

Article

Sizing Uncertainty in Time-of-Flight Diffraction by Monte Carlo Modeling

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Abstract

This study provides a method to estimate of the sizing error of Time-of-Flight Diffraction (TOFD) using a calibration/inspection procedure and a TOFD instrument in accordance with ISO 10863 and ISO 16828. This estimate is based on Monte Carlo simulations using distributions of the underlying error sources. The objective is to estimate the distribution of the flaw height sizing error and to rank the factors affecting the sizing error in a TOFD inspection. The proposed method is demonstrated on a T-shaped carbon steel welded connection with wall thickness 40 mm and flaws with flaw height 5 mm from the back wall. This is a common detail in welded bridges and TOFD is a frequently used inspection technique for fatigue cracks in such a detail. This demonstration case poses two practical challenges. First, for some old bridges, there are no reference blocks of the same material for calibration. This could possibly lead to errors propagated from the calibration. Second, the practice of inspecting the weld by scanning parallel to the weld bead may result in uncertainty of the flaw location relative to the instrument midplane. We found that the errors propagated from calibration are irrelevant for the case of study, and the major contributors to the flaw height sizing error are the uncertainty in picking time-of-flight on the ultrasonic signal and the position of the flaw with respect to the midplane of the TOFD instrument. This last factor is also the main contributor to the systematic underestimation of the flaw height (95% sizing error interval of -1.1 mm in the considered inspection scenario).

Keywords: TOFD; sizing accuracy; measurement uncertainty; welding flaws; Monte Carlo; bridge inspection



Academic Editor: Jie Zhang

Received: 27 July 2026

Revised: 14 September 2026

Accepted: 24 September 2026

Published: 1 October 2026

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1. Introduction

The accuracy of the prediction of the remaining fatigue life relies on accurate sizing of flaws. The T-shaped welded connection consisting of two fillet welds between the stiffener and the bottom flange of the main girder, as shown in Figure 1, is a fatigue-critical detail that occurs in the majority of existing steel bridges. In these welds, flaws with small flaw height are regularly observed.

These flaws can grow into fatigue cracks, finally endangering the structural integrity of the bridge. Using experimental fatigue crack growth curves for fillet welds [1], one can derive the relationship between crack sizing error and remaining fatigue life error, as shown in Figure 2. These curves show the sensitivity of the prediction of remaining fatigue life to the flaw height sizing error: an undersizing error of 0.5 mm in a flaw with a true

height 5 mm leads to an unconservative overestimation of 20 % of the remaining fatigue life. This could potentially lead to unexpected structural failures.

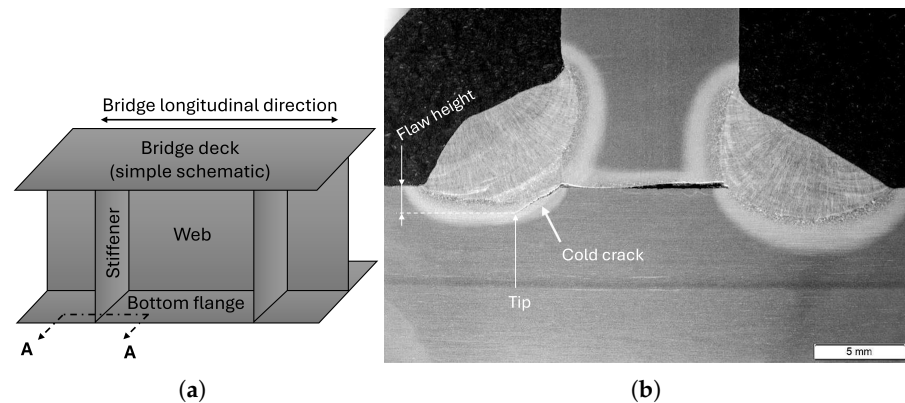


Figure 1. Flaw in a welded connection in a steel bridge. (a) Main girder of a steel bridge. (b) Metallographic photo (section A-A) of a specimen removed from of an actual bridge in the Netherlands at the location of a flaw detected by TOFD.

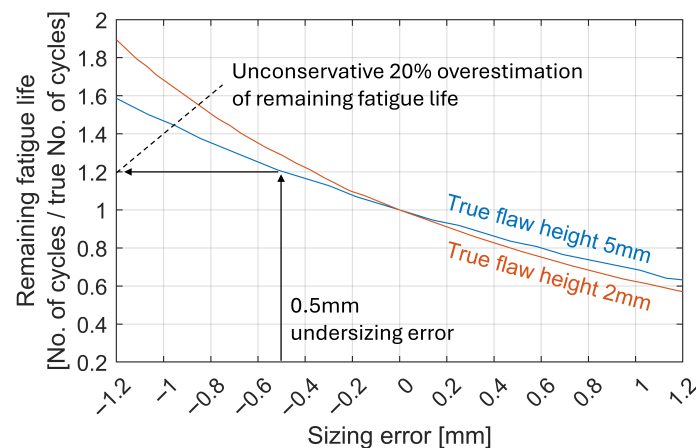


Figure 2. Sensitivity of fatigue life prediction to flaw sizing error using experimental measurements in [1].

In bridge inspections, flaws are sized using nondestructive evaluation. An established ultrasonic technique is Time-of-Flight Diffraction (TOFD). Figure 3 shows a cross-section of the TOFD measurement instrument on a test object. The source probe fires an ultrasonic pulse and the receiver probe records the ultrasonic signal that typically contains these echoes of interest: the lateral wave (LW) which follows a path just below the inspection surface, flaw echoes (FLs) diffracted by the flaw tips and the back wall (BW) echo reflected at the back wall. The instrument setup (e.g., wedge angle, probe center separation) is prescribed [2] to ensure good illumination of the region of interest.

Assuming that the flaw is in the midplane between the two probes and the ultrasonic pulses departs/arrives at points on the inspection surface known as index points, the flaw depth (d , unit mm) may be calculated by [2]

$$d = \frac{1}{2} \sqrt{c_{stl,obj}^2 \cdot (t_{FL,obj} - t_{LW,obj})^2 + 4 \cdot c_{stl,obj} \cdot (t_{FL,obj} - t_{LW,obj}) \cdot s} \quad (1)$$

where s (unit mm), is the probe center separation. $c_{stl,obj}$ (unit mm/ μ s) is the sound velocity in the test object. $t_{LW,obj}$ and $t_{FL,obj}$ (unit μ s) are the times-of-flight of the LW and FL echoes, respectively.

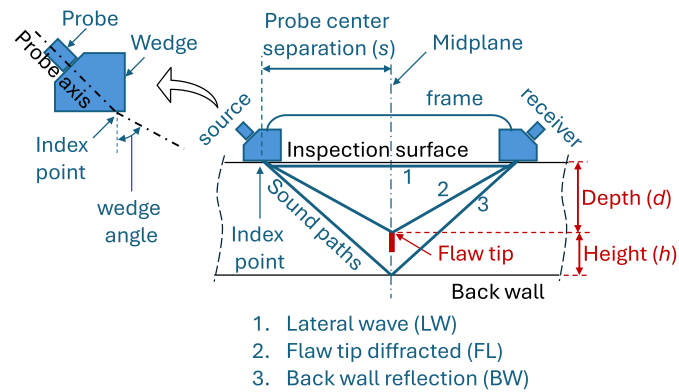


Figure 3. Principle of Time-of-Flight Diffraction (TOFD).

Figure 4 shows the inspection scenario of interest in this study: a T-shaped welded connection with flaws such as weld imperfections (slag inclusions, cold cracks and pores), potentially growing into fatigue cracks. The flaws may appear in any position between the weld toe and the weld root. The practice is to scan each weld bead with the instrument midplane matching the projection of the stiffener side-wall on the inspection surface. This minimizes deviations from the assumption of flaw in the midplane. However, a midplane deviation between -4.6 mm and 14.6 mm remains. This is calculated for a distance between the weld toe and the weld root of 10 mm, and a scanning guiding accuracy limited by ISO 16828 [2] to 10% of the probe center separation (defined for a wall thickness 40 mm), while ignoring the uncertainty in the projection of the stiffener side-wall on the inspection surface.

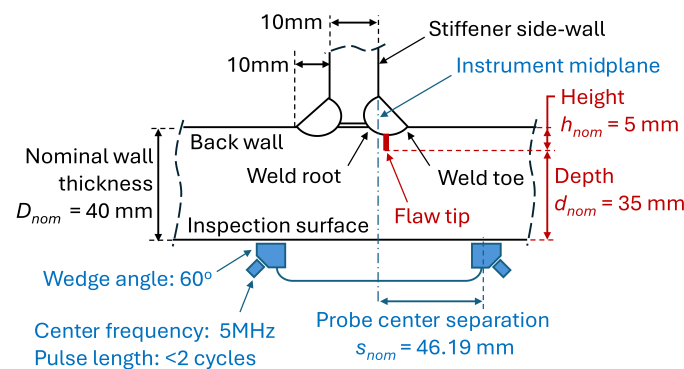


Figure 4. Schematic of the inspection scenario (dimensions in nominal values).

In this inspection scenario, the relevant flaw size information used in the prediction of the remaining fatigue life is the flaw height (h , unit mm), defined as the through-wall distance between the back wall and the flaw tip (see Figure 3). This is calculated as the difference between the flaw depth and the wall thickness. The latter is calculated by Equation (1) using the time-of-flight of the BW echo ($t_{BW,obj}$) in place of $t_{FL,obj}$.

Calibration of the measurement instrument using a reference block with known wall thickness and the times-of-flight of the LW and BW determines an effective probe center separation that minimizes the flaw depth sizing error caused by uncertainty in sound velocity and variable wedge delay (time-of-flight along the path between the probes and the inspection surface) [3].

Reference blocks should be representative of the test object in terms of grain structure, sound velocity, wall thickness, and surface conditions, all with tolerances defined in international standards [2,4]. In bridge inspections, a representative reference block is difficult to obtain for a variety of reasons. Some bridges are old or constructed before the invention of TOFD; hence, no reference blocks remain. Material specifications of the time

of construction are now obsolete and the materials are no longer manufactured. Removing material from the bridge to manufacture a reference block is often not allowed and reference blocks are not made for each element type of each bridge. In this scenario, reference blocks are manufactured from materials which are believed to be comparable to the test object and which have a wall thickness that might differ from the wall thickness of the test object, possibly leading to sizing errors propagating from the calibration.

In addition to the mentioned factors (uncertain flaw position and differences between the test object and the reference block), uncertainties in the parameters in Equation (1) ($c_{stl,obj}$, s , $t_{FL,obj}$ and $t_{LW,obj}$) also contribute to the sizing uncertainty.

There is limited information about the flaw height sizing uncertainty of TOFD in the literature. One study quantified the contributions of some factors to the sizing uncertainty in a TOFD inspection under controlled laboratory conditions [5]. They arrived at the flaw height sizing uncertainty ± 0.20 mm (expressed in terms of expanded uncertainty, i.e., a band that is expected to encompass a large portion of the values that could reasonably be attributed to the measurand [6]) and indicated probe center separation as the most relevant contributing factor to the sizing uncertainty. However, this study does not consider aspects present in a TOFD inspection performed in an operational environment. For example, the authors used a static instrument which enables careful control of the flaw position on the instrument midplane, rather than a scanning procedure as applied in practice. Some studies report the mean and standard deviation of the sizing error compiled over several inspection scenarios (measurement of several flaw types in test objects with a wide range of characteristics; see Table 1). However, sizing error may be scenario-specific. Most other authors report the sizing error in individual measurements and hypothesize the main contributors to the sizing uncertainty (uncertainties in location and irregular nature or morphology of the flaw [7], uncertainties in measuring the diffracted signal's transit times or times-of-flight [8]). These factors are included in this study, except for the flaw morphology, because the scope of this study is limited to flaws with a sharp tip. The sizing uncertainty of TOFD is also mentioned in standard BS 7910 [9]: a through-wall height sizing error of ± 0.5 mm down to ± 0.1 mm has been reported from trials.

Table 1. Flaw height sizing uncertainty (reported in the literature).

Scenario	Mean (Bias)	Standard Deviation
Planar flaws [3]	0.52 mm	1.8 mm
Non-planar flaws [3]	−0.32 mm	1 mm
All flaw types [10]	0.55 mm	0.88 mm

The current study uses time-of-flight calculation by ray-tracing embedded in a Monte Carlo framework to evaluate the flaw height sizing uncertainty of a TOFD inspection, including instrument setup, calibration, and inspection procedures that would be adopted in an operational environment. Scenario-specific distributions for model parameters are used; therefore, probability plots of the sizing error and the most relevant factors affecting the sizing uncertainty in that specific inspection scenario may be evaluated. The method is partially validated through TOFD experiments in a block with an artificial notch. The nominal wall thickness $D_{nom} = 40$ mm and the notch height (flaw height) $h_{nom} = 5$ mm are selected based on the inspection scenario of interest (Figure 4). A notch perpendicular to the back wall is selected on the basis of the flaw of interest having a sharp tip, such as a cold crack or fatigue crack. Model parameters to address aspects of an inspection in an operational environment are included, e.g., scanning guiding accuracy. Unlike previous studies [5,7], this paper intends to address all potential causes of sizing error in a practical inspection, and ranks these causes from high to low contribution.

2. Methods

2.1. Inspection Model

The inspection model, summarized in Figure 5, calculates the flaw height sizing error resulting from an inspection procedure that would be used in an operational environment. It starts with the instrument setup, followed by calibration using a reference block and inspection of the test object.

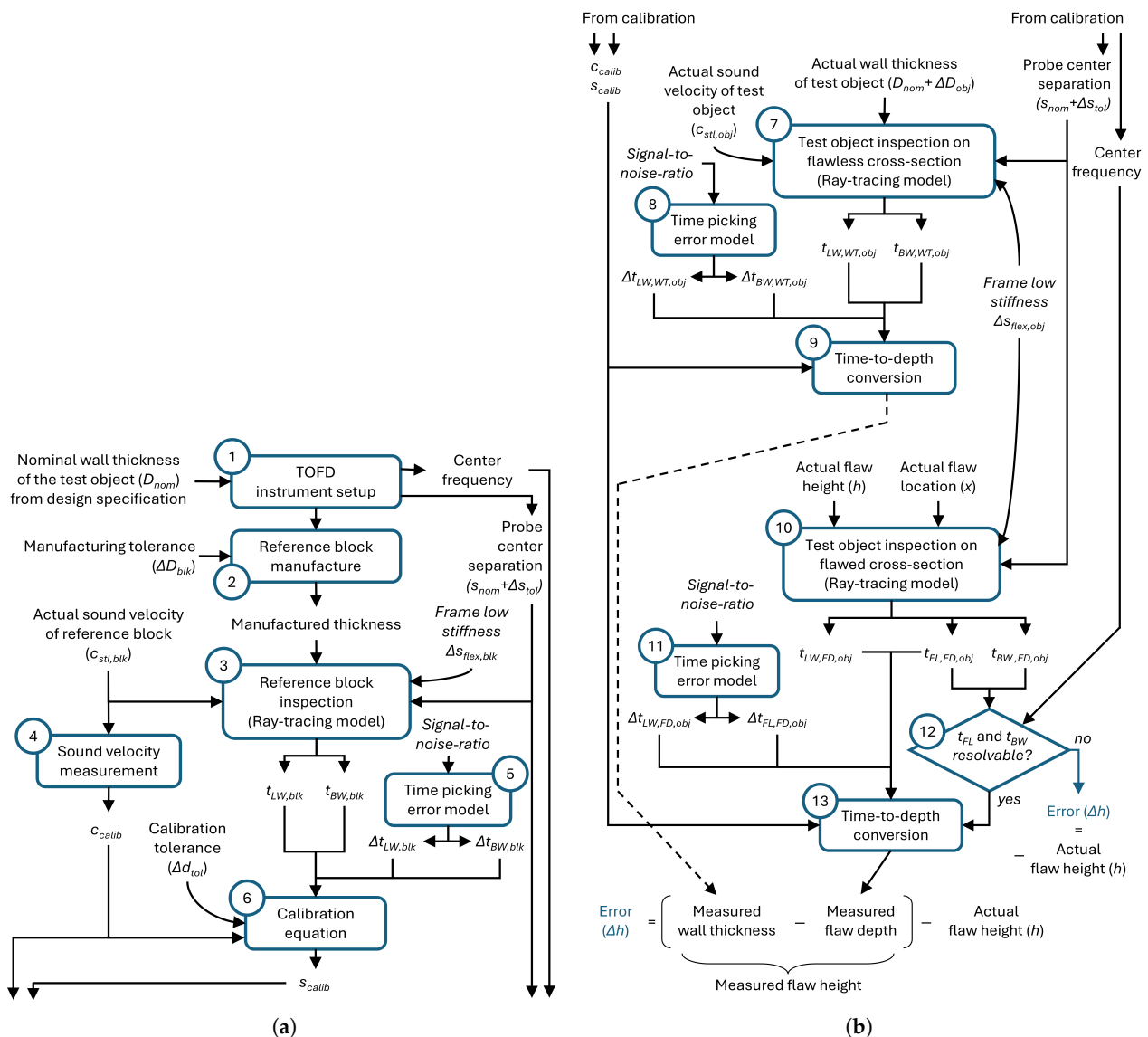


Figure 5. Diagram of the inspection model. (a) Instrument setup and calibration. (b) Inspection of the test object.

In Step 1, the nominal probe center separation and the probe/wedge specifications (see Figure 4) are defined based on the nominal wall thickness of the test object according to ISO 10863 [4].

The calibration of the instrument occurs in Steps 2 to 6. First, the calibrated sound velocity (c_{calib}) is measured by traditional pulse-echo in the reference block. Details of this measurement are provided in Section 2.4. Second, using a TOFD inspection in the reference block, the effective probe center separation (s_{calib}) is determined such that the wall thickness measured by TOFD matches the manufactured wall thickness of the reference block. The calibration is modeled by rearranging Equation (1):

$$s_{calib} = \frac{4(D_{nom} + \Delta D_{blk} + \Delta D_{tol})^2 - c_{calib}^2(t_{BW,blk} - t_{LW,blk})^2}{4c_{calib}(t_{BW,blk} - t_{LW,blk})} \quad (2)$$

Here, D_{nom} (unit mm) is the nominal wall thickness of the reference block. The manufactured wall thickness, $(D_{nom} + \Delta D_{blk})$ includes the manufacturing tolerance (ΔD_{blk} , unit mm). In Step 3, times-of-flight are calculated based on the manufactured wall thickness. The wall thickness measured by TOFD ($D_{nom} + \Delta D_{blk} + \Delta D_{tol}$) includes the calibration tolerance (ΔD_{tol} , unit mm). ΔD_{blk} and ΔD_{tol} are specified by the ISO standard 10863 [4].

The TOFD inspection of the test object takes place in Steps 7 to 13. As the instrument scans the test object, it records ultrasonic signals at consecutive positions. Two ultrasonic signals are used: one without flaw in Steps 7 to 9 to measure the wall thickness of the test object, and one containing a flaw in Steps 10 to 13 to measure the depth of the flaw tip. The two ultrasonic signals are supposed to be from neighboring instrument positions; hence, their times-of-flight are calculated adopting the same values of sound velocities and thickness.

Lastly, the flaw height sizing error (Δh , unit mm) is calculated as the difference between the measured height and the actual height. In Step 12, if the difference between the time-of-flight of the FL and the BW echo is less than the pulse period (2 cycles at the nominal frequency of the ultrasonic probes 5 MHz), the echoes are considered unresolvable from each other, and the flaw is undetectable. This assumption is in agreement with the descriptions of spatial resolution and dead zones in ISO 16828 [2]. In such a scenario, the error (Δh) is set to the negative actual flaw height.

The model allows for temperature differences between the calibration and the inspection of the test object. The envisioned scenario is that of a calibration performed indoors, at a temperature of 20 °C, and an inspection performed outdoors at a temperature ranging from 0 °C to 50 °C [4]. The sound velocities of the material layers considered for the test object (wedge, steel, coupling fluid, and paint) are updated according to the temperature difference between the reference block and test object (−20 °C to +30 °C) using fixed rates of change of sound velocity with temperature: $dc/dT_{wedge} = -1.83 \text{ m/s } ^\circ\text{C}$ [11] for wedge material, $dc/dT_{coupling} = 3.28 \text{ m/s } ^\circ\text{C}$ [12] for coupling fluid and $dc/dT_{steel} = -0.82 \text{ m/s } ^\circ\text{C}$ [13] for low-carbon steel.

The following sections describe the ray-tracing model used to calculate times-of-flight (Steps 3, 7 and 10), the model to calculate the error in picking times-of-flight (Step 5, 8 and 11), and the model of the measurement of sound velocity (Step 4).

2.2. Ray-Tracing Model

Although more accurate times-of-flight can be calculated by wave-equation-based modeling, these are computationally expensive for Monte Carlo simulations, which require a large number of realizations of the inspection model. Alternatively, ray-based methods require less processing power. The ray-tracing model calculates times-of-flight by assuming that the ultrasonic pulses depart/arrive at the center of the probes and follow a ray path to a scatterer with refraction at the interfaces between different material layers according to Snell's law [14], as shown in Figure 6.

The considered material layers (wedge, coupling fluid, paint and steel) are assumed to be homogeneous with a uniform thickness and a uniform sound velocity. This is a reasonable assumption for the addressed inspection scenario because a minimal percentage of the propagation path occurs inside the heat-affected zone where post-weld material anisotropy is expected (see Figure 4), and the temperature gradient is expected to be small due to the small volume of material inspected (approximately $40 \times 30 \times 140 \text{ mm}$).

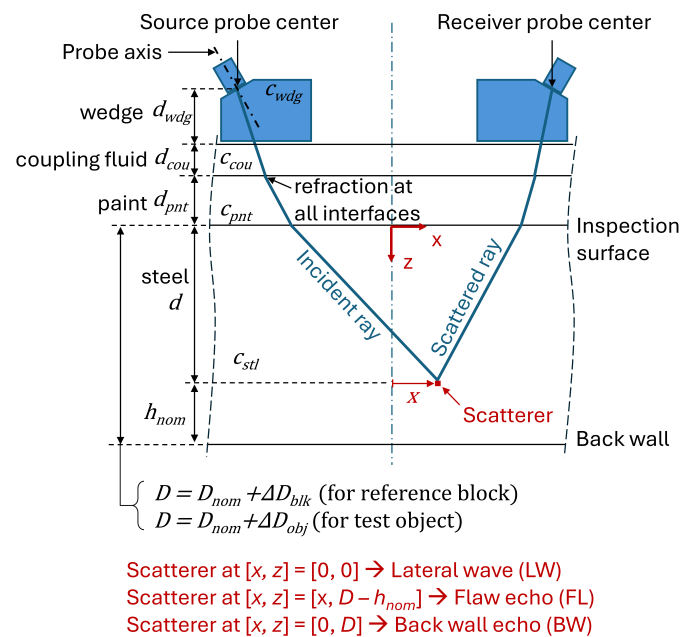


Figure 6. Diagram of the ray-tracing model (picture is not to scale).

Reflections and reverberations in the thin coupling fluid and paint layer are ignored. Simulations using a 2D finite difference method [15] of TOFD inspection in test objects with a paint layer thickness in the range of interest (0.4 to 1.3 mm) show that sound waves traveling in the thin paint layer pollute the ultrasonic signal with additional echoes. These echoes arrive shortly after the lateral wave and show a decaying amplitude. Disregarding them is reasonable for the addressed inspection scenario because high attenuation is observed in ultrasonic signals of real bridges, which causes these additional echoes to disappear before the arrival of the FL (see [16], Figure 13).

The surface roughness is ignored. 2D simulations of test objects with surface roughness R_a 6.3 μm and 12.5 μm [4] show that the time-of-flight of the echoes changes by less than 0.015 μs . Moreover, 2D finite difference models overestimate the influence of surface roughness because they do not capture the averaging effect of the varying roughness profile in out-of-plane direction [17]. This justifies disregarding surface roughness.

The ray-tracing method calculates the time-of-flight of the leading edge of the echo, whereas time-of-flight is picked at the first zero crossing of the echo in an actual ultrasonic signal. This makes time-picking waveform-dependent. In the inspection scenario of study, the flaws have a sharp tip and are concentrated in a small angular range of the field-of-view of the probes (defined by midplane deviation limited to the range from -4.6 mm to 14.6 mm and height 5 mm). In this scenario, the variation in the waveform is deemed small, and hence the associated time-picking uncertainty is ignored.

2.3. Model for the Noise-Caused Uncertainty in Time-Picking

Noise, which is inevitable in an inspection, influences the zero crossings of the echoes, and thereby contributes to time-picking uncertainty. Two sources of noise are present, namely electronic and grain scattering noise. The first is characterized by a broad frequency band, whereas the latter is limited to the frequency band of the ultrasonic probe. FL, LW and BW echoes differ regarding the dominant noise source and signal-to-noise ratio (SNR). In this study, SNR is defined as the ratio between the maximum amplitude of the echo and the standard deviation of a time window of the ultrasonic signal without echoes.

Table 2 shows the dominant noise source and the assumed SNRs. The upper limits are based on the SNRs observed using the experimental setup described in Section 2.6 in controlled laboratory conditions. The lower limits are based on information provided by an inspection company active in bridge inspections: 9 to 12 dB is practically considered as the minimum acceptable SNR in a TOFD inspection.

The ranges in Table 2 capture the overall trend: high-amplitude BW echoes present higher SNR than low-amplitude FL echoes. There is a potential correlation between the FL and BW echo because these SNRs depend on the same level of grain noise. Since the correlation coefficient is unknown, no correlation is considered in the main results presented hereafter, whereas the sensitivity is demonstrated by a separate evaluation with full correlation.

Table 2. Dominant noise source and assumed signal-to-noise ratios.

Echo	Dominant Source	SNR Range	Distribution Type
LW	Electronic	12–30 dB	Uniform
FL	Grain	15–27 dB *	Uniform
BW	Grain	12–45 dB	Uniform

* Valid for a flaw tip at the intersection of the probe's axes.

The SNR of the FL echo shown in Table 2 refers to a flaw located at the intersection of the probe axes. For other flaw positions, the SNR is adjusted proportionally to the squared root of the product of the P-wave intensity fields of the source and receiver probes, I_{src} and I_{rec} , respectively. The former is calculated from a simulation of the TOFD inspection by a 2D model using the finite difference method [15].

$$I_{src}(x, z) = |(v_x \sigma_{xx} + v_z \tau_{xz}, v_z \sigma_{zz} + v_x \tau_{zx})| \quad (3)$$

where v_x and v_z (unit m/s) are particle velocities, σ_{xx} and σ_{zz} (unit Pa) are normal stresses, and τ_{xz} and τ_{zx} are shear stresses at each point (x, z) of the model grid accumulated over all time steps of the simulation. The latter (I_{rec}) is obtained by mirroring the intensity field of the source probe on the instrument midplane. This adjustment decays the SNR values for flaws positioned away from the intersection of the probe axes.

The time-picking error is calculated by adding noise signals to the echo of interest (LW, FL or BW, all modeled as single-cycle wavelet with frequency set to the probe center frequency) to realize the SNR and the dominant noise source, followed by picking the zero crossing. This time-picking error is added to the times-of-flight calculated by the ray-tracing model explained in Section 2.2.

The model ignores the variability of the amplitude of the diffracted pulse with the angles of incidence/diffraction at the flaw tip. This is a reasonable assumption because the variability of the magnitude of the diffraction coefficient (measured by the coefficient of variation) is 6 times smaller than the variability of the ultrasonic beam profile for the area of the test object where a flaw of height 5 mm is expected in the studied inspection scenario. The diffraction coefficient is calculated for the pressure wave-mode for a notch normal to the back wall [18].

2.4. Model for the Measurement of Sound Velocity

To measure the sound velocity using a pulse-echo technique, the ultrasonic probe is placed directly on the (unpainted) inspection surface of the reference block. The actual sound velocity is measured using the nominal wall thickness and picked times-of-flight of two successive BW echoes in the ultrasonic signal. This measurement is modeled by

$$c_{calib} = \frac{2D_{nom}}{\frac{2(D_{nom} + \Delta D_{blk})}{c_{stl,blk}} + \Delta t_{BW1,blk} + \Delta t_{BW2,blk}} \quad (4)$$

where c_{calib} is the measured sound velocity, $c_{stl,blk}$ is the actual sound velocity at 20 °C, and D_{nom} is the nominal wall thickness. $\Delta t_{BW1,blk}$ and $\Delta t_{BW2,blk}$ (unit μs) are the noise-caused time-picking uncertainties of the first and second BW echoes in the ultrasonic signal, respectively, calculated as described in Section 2.3. The SNRs for the first and second BW echoes are assumed to be uniformly distributed with ranges of 12 to 40 dB and 12 to 33 dB, respectively.

2.5. Monte Carlo

The Monte Carlo simulation estimates the distribution of the flaw height sizing error by repeatedly evaluating the inspection model. In each Monte Carlo trial, the variables of the model are sampled from assumed or calculated distributions, which are summarized in Tables 3 and 4.

The distribution of the flaw height sizing error calculated by this Monte Carlo framework is conditioned to the flaw being detectable and sizable, which is checked in Step 12 of the inspection model (see Figure 4).

The Monte Carlo framework is implemented in Matlab R2024b [19] adopting Marsenne twister [20] as the pseudo-random number generator algorithm. The influence of each individual variable on the sizing uncertainty is studied by running a Monte Carlo simulation in which only the variable of interest has non-zero variance. The variable that produces the largest standard deviation is the one that contributes the most to the flaw height sizing error. This approach ignores the contributions from the interactions among the individual variables, i.e., it ranks the most important variables by the isolated rather than total contributions of the variables to the sizing uncertainty.

The maximum error is obtained by running a Monte Carlo simulation with variance in all variables simultaneously.

2.6. Experimental Setup

An experimental TOFD setup is used to validate the models for the noise-caused time-picking error and for the measurement of sound velocity. These models are selected for validation because they calculate custom distributions for variables in the Monte Carlo simulation.

The measurement instrument uses probes with a center frequency of 5 MHz, a wedge angle of 60°, and a probe center separation of 46.2 mm (see Figure 4). The test object is a carbon steel block with a wall thickness of 39.5 mm without a weld and with a vertical notch with height 5 mm from the back wall, width 0.5 mm (perpendicular to the scanning direction) and length 40 mm (parallel to the scanning direction). Another carbon steel block with wall thickness 40 mm is used as the reference block.

Table 3. Variables considered in the Monte Carlo simulation (geometry).

Symbol	Description	Nominal Value	Range	Distribution Type	Reference
d_{wdg}	Wedge thickness	5 mm	± 0.05 mm	Uniform	Fine machining tolerance [21]
$d_{cou,obj}$	Coupling fluid thickness on the test object	0 mm	0 to 0.5 mm	Uniform	Maximum allowed surface waviness [4]
$d_{cou,blk}$	Coupling fluid thickness on the reference block	0 mm	0 to 0.10 mm	Uniform	Surface waviness derived from manufacturing tolerance [4]
$d_{pnt,obj}$	Paint layer thickness on the test object	0 mm	0.368 to 1.3 mm	Uniform	Acceptance criteria for the measurement of dry film thickness [22] of paint systems typically adopted in steel bridges (corrosivity category “C5”, durability “vh” [23,24])
ΔD_{blk}	Manufacturing tolerance for the reference block	0 mm	± 0.05 mm	Uniform	ISO standard 10863 [4]
ΔD_{obj}	Variation in the wall thickness on the test object	0 mm	± 1.6 mm (95% scatter band)	Custom	Measurements on actual manufactured steel plates [25]
Δs_{tol}	Probe center separation assembly tolerance	0 mm	± 0.05 mm	Uniform	Assumed caliper uncertainty
x	Flaw midplane deviation	0 mm	−4.6 to 14.6 mm	Uniform	Scanning guiding accuracy [2] and distance from weld root to toe
ΔD_{tol}	Calibration tolerance, i.e., acceptable error in depth when calibrating the instrument	0 mm	± 0.2 mm	Uniform	ISO standard 10863 [4]
$\Delta s_{flex,blk}$	Probe center separation variation on the reference block due to clearances/stiffness of the instrument frame	0 mm	± 0.05 mm	Uniform	Hole/shaft fit H8/f7 in the wedge/frame interface [26]
$\Delta s_{flex,obj}$	Probe center separation variation on the test object due to clearances/stiffness of the instrument frame	0 mm	± 0.05 mm	Uniform	Hole/shaft fit H8/f7 in the wedge/frame interface [26]

Table 4. Variables considered in the Monte Carlo simulation (sound velocity, time-of-flight and temperature).

Symbol	Description	Nominal Value	Range	Distribution Type	Reference
c_{wdg}	Sound velocity (wedge)	2.59 mm/ μ s	± 0.05 mm/ μ s	Uniform	Nominal value from the literature [27], range is an assumption
c_{cou}	Sound velocity on the coupling fluid	1.47 mm/ μ s	± 0.05 mm/ μ s	Uniform	Nominal value from the literature [28], range is an assumption
c_{pnt}	Sound velocity on the paint layer	2.45 m/s	± 0.05 mm/ μ s	Uniform	Assumption
$c_{stl,obj}$	Actual sound velocity of the steel on the test object	5.92 mm/ μ s	± 0.05 m/s	Uniform	Scope of ISO standard 10863 [4]
$c_{stl,blk}$	Actual sound velocity of the steel on the reference block	5.92 mm/ μ s	± 0.05 mm/ μ s	Uniform	Scope of ISO standard 10863 [4]
$\Delta c_{measur,blk}$	Error in measuring sound velocity on the reference block	0 mm/ μ s	± 0.009 mm/ μ s (95% scatter band)	Custom	Model for sound velocity measurement in Section 2.4
$\Delta t_{LW,blk}$	Time-picking uncertainty for LW on the reference block	0 μ s	± 0.014 μ s (95% scatter band)	Custom	Model for time-picking uncertainty in Section 2.3 using SNR range from Table 2
$\Delta t_{BW,blk}$	Time-picking uncertainty for BW on the reference block	0 μ s	± 0.007 μ s (95% scatter band)	Custom	Model for time-picking uncertainty in Section 2.3 using SNR range from Table 2
$\Delta t_{LW,FD,obj}$	Time-picking uncertainty for LW when measuring flaw depth on the test obj.	0 μ s	± 0.014 μ s (95% scatter band)	Custom	Model for time-picking uncertainty in Section 2.3 using SNR range from Table 2
$\Delta t_{FL,FD,obj}$	Time-picking uncertainty for FL when measuring flaw depth on the test obj	0 μ s	± 0.013 μ s (95% scatter band)	Custom	Model for time-picking uncertainty in Section 2.3 using SNR range from Table 2
$\Delta t_{LW,WT,obj}$	Time-picking uncertainty for LW when measuring wall thickness on the test object	0 μ s	± 0.014 μ s (95% scatter band)	Custom	Model for time-picking uncertainty in Section 2.3 using SNR range from Table 2
$\Delta t_{BW,WT,obj}$	Time-picking uncertainty for BW when measuring wall thickness on the test object	0 μ s	± 0.007 μ s (95% scatter band)	Custom	Model for time-picking uncertainty in Section 2.3 using SNR range from Table 2
ΔT	Difference between the temperature of the reference block (20 °C) and the test object	0 °C	−20 to 30 °C	Uniform	Scope of ISO standard 10863 [4]

Figure 7 shows the experimental setup during Steps 7 to 13 (see Figure 5) and the experimental ultrasonic signals. Six inspections are performed on the test object, namely, three with a midplane deviation of 0 mm and three with a midplane deviation of 10 mm.

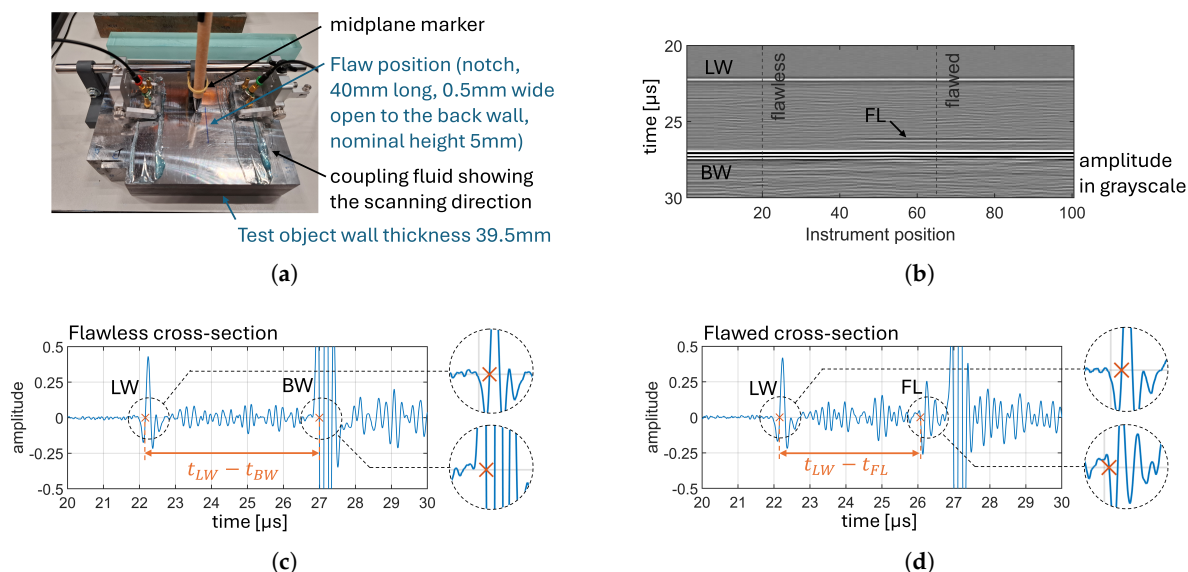


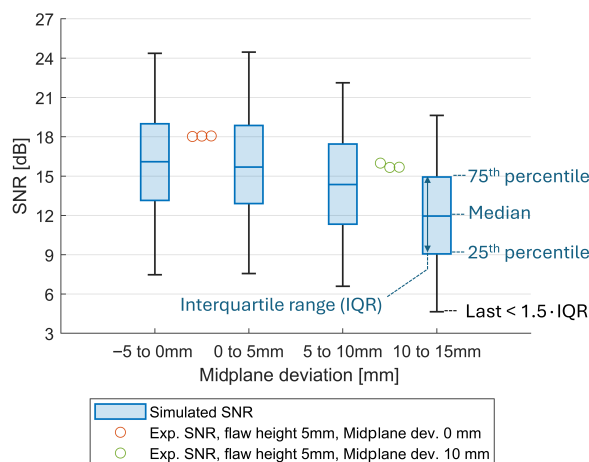
Figure 7. Experimental setup and time-picking principle. (a) TOFD instrument on test object. (b) Ultrasonic signals stacked side-by-side (B-scan). (c) Ultrasonic signal to measure wall thickness, the x marks indicate the first zero crossings. (d) Ultrasonic signal to measure flaw depth.

3. Results and Discussion

3.1. Validation of the Model

The models for the noise-caused time-picking error and for the measurement of sound velocity are validated by comparing their predictions with the experiments.

In Figure 8, the simulated SNR distribution for the FL echo (assumed distribution according to Table 2) after adjustment for flaw positions is categorized by ranges of midplane deviation and the distribution of each category is represented by a box plot. The box plots indicate a decay of the simulated SNR with increasing midplane deviation, which is in good agreement with the decay of the SNR observed experimentally (see dots in Figure 8).



Median: separates the higher half from the lower half of the data.

25th percentile: 25% of data is below this level.

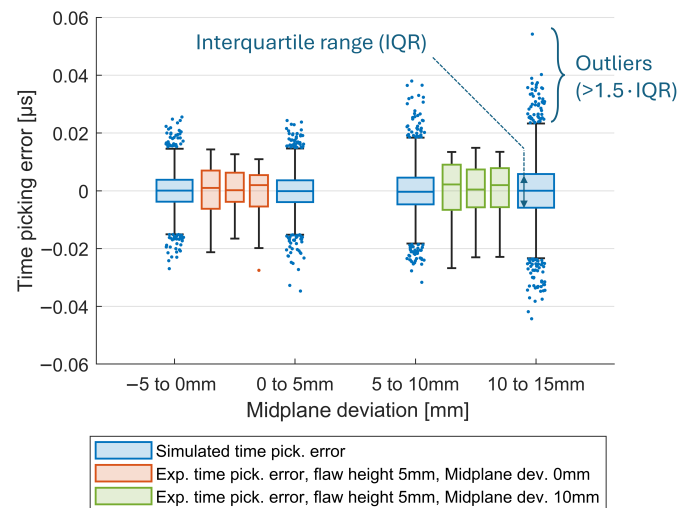
75th percentile: 75% of data is below this level.

Interquartile range (IQR): contains the 50% of the data which lies between the 25th and the 75th percentiles.

Outliers: data that lies beyond 1.5 · IQR. The last non-outlier is marked.

Figure 8. Modeled and experimental signal-to-noise ratio (SNR) of the FL echo.

Figure 9 shows box plots of the experimental and simulated time-picking uncertainty of the FL echo categorized by intervals of midplane deviation. In the simulated time-picking uncertainty (which uses the SNR distribution according to Table 2), the effect of adjustment by the beam profile is perceived as a higher time-picking uncertainty for flaws away from the midplane of the instrument. This is also observed in the experimental time-picking.



Outliers: data that lies beyond $1.5 \cdot \text{IQR}$.

Figure 9. Modeled and experimental time-picking uncertainty of the FL echo.

Figure 10 shows the cumulative probability plot of the measured sound velocity obtained by a Monte Carlo simulation of the pulse-echo inspection. An empirical cumulative probability plot is also shown. The empirical curve is calculated using measurements of sound velocity made by placing the ultrasonic probe at eight different points in the test object. The variability of the experimental measurements is the result of uncertainties in the measurement of wall thickness and time-picking. The overlapping of the curves suggests that the simulation captures the observed experimental variability well.

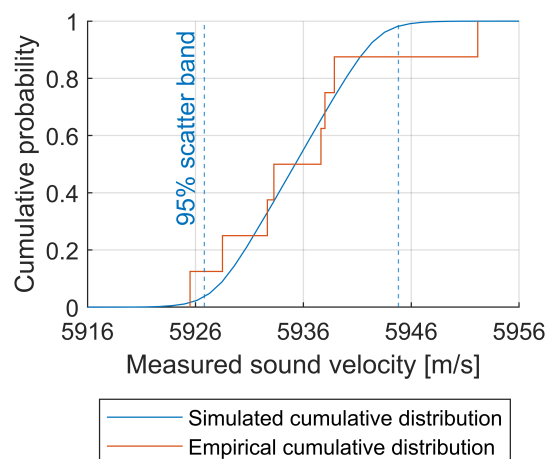


Figure 10. Cumulative probability plot of the measured sound velocity.

3.2. Quantity of Trials in Monte Carlo Simulations

This study uses estimates of three statistics of the flaw height sizing error calculated by Monte Carlo simulations: the standard deviation and the lower and upper bounds of the 95% scatter band. The uncertainty of these estimates improves with increasing number of trials in a Monte Carlo simulation. The uncertainty of an estimate is defined here as twice its standard deviation.

In this study, the standard deviation of each estimate is calculated by resampling results from a Monte Carlo simulation with 10^5 trials to mimic the execution of 10^4 Monte Carlo simulations with a predetermined number of trials. The improvement of the uncertainty of the three estimates with the number of Monte Carlo trials is shown by the curves in Figure 11.

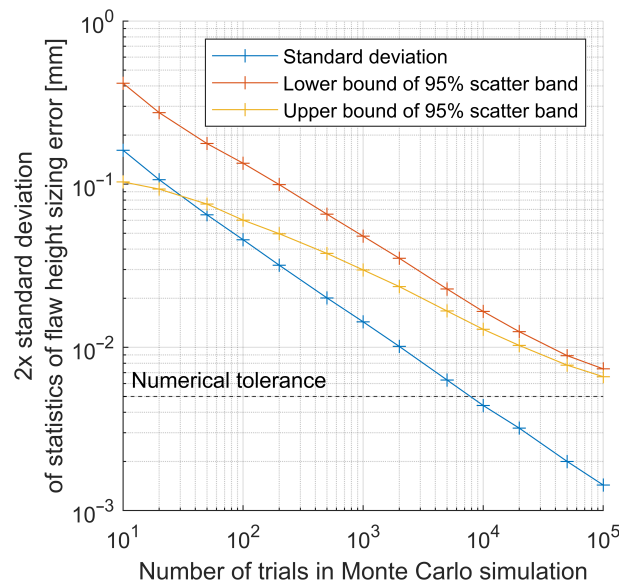


Figure 11. Convergence of the Monte Carlo simulation.

In the Monte Carlo simulations in this study, 10^4 trials are deemed sufficient to rank the error sources. The uncertainty of the estimate of the standard deviation is below the numerical tolerance 0.005 mm, which provides two decimal significant digits [6]. A total of 10^5 trials are used to determine the maximum size error. The estimates of the upper and lower bounds have one significant decimal digit. This matches the number of decimal significant digits of TOFD sizing uncertainty reported in published standards (± 0.5 mm to ± 0.1 mm [9]).

3.3. Most Influential Error Sources

Figure 12 shows the standard deviation of the flaw height sizing error ($\sigma_{\Delta h}$, unit mm) when the variable (or group of variables) indicated on the horizontal axis has non-zero variance. The assumed SNR is described in Table 2. The SNR of FL and BW echo are uncorrelated in these simulations. A sensitivity study assuming full correlation does not impact the calculated probability plot of flaw height sizing error. The nominal flaw height is 5 mm. Figure 12a addresses the scenario of midplane deviation ranging from -4.6 mm to 14.6 mm (considering the scanning guiding accuracy of ± 4.6 mm and the uncertain position of the flaw along the 10 mm between the weld root and toe). The midplane deviation (x , unit mm) appears to give the largest contribution to the flaw height sizing error. Figure 12b addresses the scenario of controlled midplane deviation, that is, the midplane deviation is limited to the scanning guiding accuracy of ± 4.6 mm. In this case, the contribution of the midplane deviation reduces significantly and the time-picking uncertainties ($t_{LW,FD,obj}$, $t_{FL,FD,obj}$, $t_{LW,WT,obj}$ and $t_{BW,WT,obj}$) appear to give the largest contribution to the flaw height sizing error.

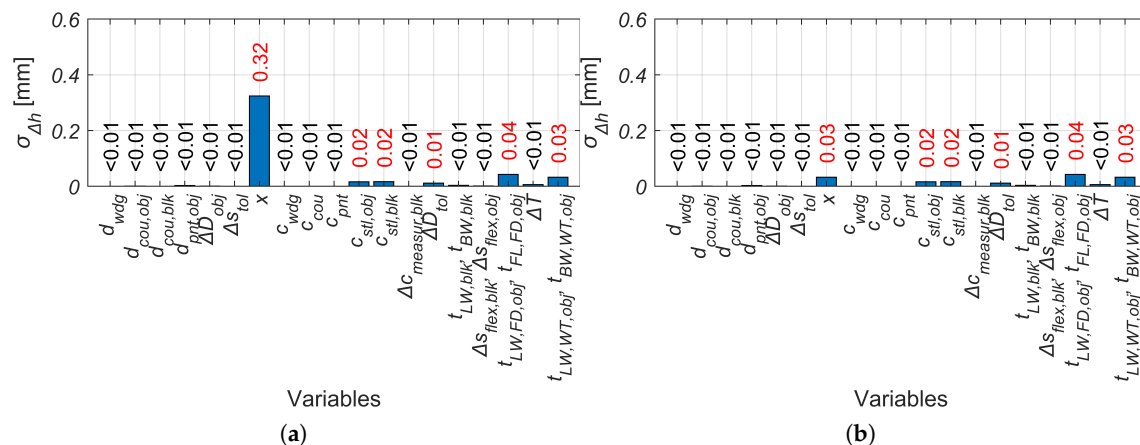


Figure 12. Comparison of standard deviations of the flaw height sizing error. (a) Nominal flaw height 5 mm and midplane deviation range -4.6 mm to 14.6 mm. (b) Nominal flaw height 5 mm and midplane deviation range ± 4.6 mm.

Given the relevance of midplane deviation to the sizing error in the first scenario, curves indicating the flaw height sizing error for selected values of midplane deviation are shown in Figure 13. The curves are calculated using the nominal values indicated in Tables 3 and 4, i.e., the variances are set to zero.

The flaw height sizing error curves are compared against the flaw height sizing errors obtained experimentally. For this, the calibration and the inspection are performed six times: three times with the flaw located approximately in the midplane and three times with the flaw located with the midplane deviation ≈ 10 mm. To reduce errors caused by differences between the test object and the reference block, the instrument is calibrated in an area of the test object without flaws. The experimental measurements match the simulated flaw height sizing error, and the measurements adopting the midplane deviation set to zero are within the sizing uncertainty of a TOFD inspection under controlled laboratory conditions: ± 0.20 mm [5].

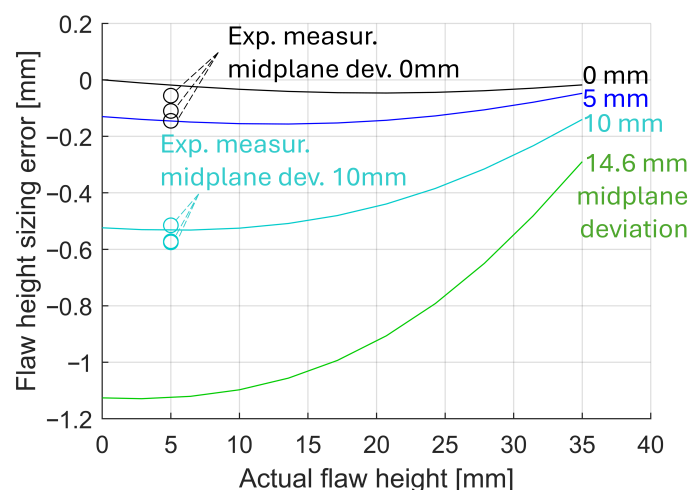


Figure 13. Flaw height sizing error due to midplane deviation.

The curves indicate that the error caused by midplane deviation is particularly relevant for flaws with flaw height < 10 mm from the back wall, reaching a flaw height sizing error of -1.1 mm for a flaw at 14.6 mm from the midplane. Simulations adopting other nominal flaw heights indicate that the midplane deviation remains the most relevant error source for the range of nominal flaw heights from 2 to 25 mm. For nominal flaw heights < 2 mm,

flaws with large midplane deviation fall into the dead zone and are missed. For nominal flaw heights > 25 mm, the decreasing sensitivity of the flaw height sizing error to the midplane deviation and the increasing sensitivity to time-picking error make the latter the most relevant error source.

Simulations adopting alternative distribution types of the midplane deviation in the inspection scenario of study indicate that the importance of this parameter to the flaw height sizing error is insensitive to the distribution type.

Approaches to minimize the midplane deviation exist. One approach involves an additional scan perpendicular to the weld bead [4] for every flaw detected in the scan parallel to the weld bead. However, this makes inspection slow and unpractical. Another approach uses times-of-flight of the flaw echoes recorded by an instrument equipped with multiple receivers to calculate locus curves (possible flaw locations). The flaw height is then determined at the intersection of these locus curves [29]. This requires additional processing algorithms, the accuracy of the technique is unknown, and it is not commonly applied in practice.

3.4. Maximum Sizing Error

Figure 14 shows simulated probability plots of the flaw height sizing error for a nominal flaw height of 5 mm for the two scenarios of midplane deviation: range from -4.6 mm to 14.6 mm (Figure 14a), and range ± 4.6 mm (Figure 14b). Each probability plot addresses a different level of time-picking uncertainty, defined by different SNRs, i.e., the SNR of the FL and BW echo are set to a different level to mimic the inspection of a steel grade with a different grain size.

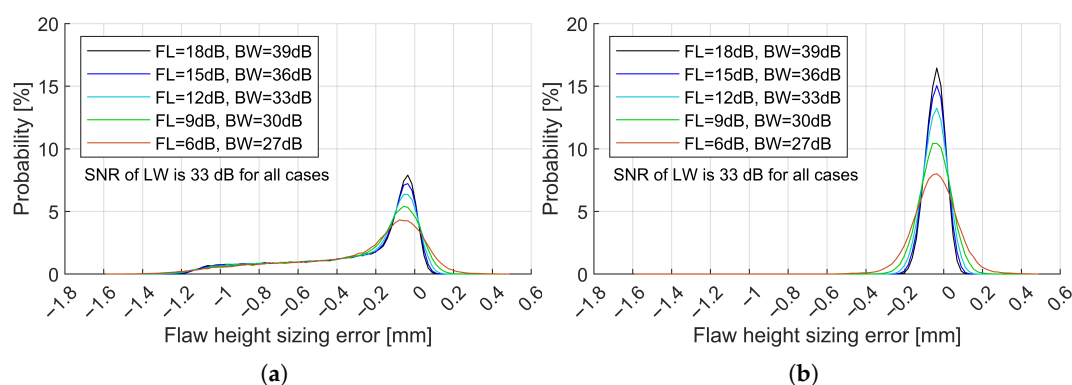


Figure 14. Probability plots of flaw height sizing error (nominal flaw height 5 mm). (a) Midplane deviation range from -4.6 mm to 14.6 mm. (b) Midplane deviation range ± 4.6 mm.

The comparison of Figure 14a,b indicates that the midplane deviation causes a bias towards underestimation of the flaw height. At the lowest SNR level evaluated, the 95% flaw height sizing error interval is shown in Table 5. The sizing uncertainty reported in the standard BS 7910: ± 0.5 mm to ± 0.1 mm [9] agrees well with the flaw height sizing error calculated in this study for the scenario with flaw position close to the instrument midplane, but it is underestimated for the scenario of large midplane deviation.

Table 5. A 95% flaw height sizing error interval for flaw height 5 mm, and the lowest evaluated SNR levels (LW:33, FL:6 and BW:27 dB).

Midplane Deviation Range	2.5% Bound	97.5% Bound
-4.6 to $+14.6$ mm	-1.1 mm	0.2 mm
± 4.6 mm	-0.3 mm	0.2 mm

Although the waveform variation is deemed small for the scenario of study (sharp tip flaws), a scenario with volumetric flaws may introduce some waveform variation. A simplified way to take the waveform variation into account is to add an additional variable in the inspection model: a time-picking uncertainty that affects only the FL echo. In an example, adopting such additional variable as uniform distribution with a range of $\pm 0.3 \mu\text{s}$, the additional time-picking error linked to waveform variation leads to additional flaw height sizing uncertainty, but still within the sizing uncertainty reported in BS7910.

3.5. Sizing Errors Propagated from Calibration

The calibration defines an effective probe center separation that minimizes the flaw depth sizing error at the depth given by the wall thickness of the reference block. At other depths, a non-zero systematic depth sizing error remains due to the variable wedge delay (see the example of the systematic depth sizing error curve in figure 2.4 in [3]). Differences between the test object and the reference block modify the shape of the depth sizing error curve. These differences are in terms of nominal wall thickness (D_{nom}), sound velocity ($c_{stl,blk}$ and $c_{stl,obj}$) and absence of a paint layer on the reference block versus presence of a paint layer ($d_{pnt,obj}$) on the test object.

In the inspection scenario of study, characterized by wall thickness 40 mm and flaws with height 5 mm from the back wall (flaw depth 35 mm), the errors caused by differences between the test object and the reference block (errors propagated from calibration) result in similar depth sizing error in the measurements of the depths of the flaw tip and the back wall (wall thickness). These depth errors cancel out when calculating the flaw height. Hence, although errors propagated from calibration are expected in the inspection scenario of study, they appear irrelevant compared to the total flaw height sizing error in Table 5.

The analysis is described in Appendix A.

4. Conclusions

We present a statistical analysis method to assess the flaw height sizing error in TOFD using ray-tracing in a Monte Carlo framework. The ray-tracing is selected because it is computationally viable for the 10^5 model evaluations in the Monte Carlo simulation. The model follows the inspection procedure typically adopted in an operational environment, including the calibration and measurements of the depth of the flaw tip and depth of the back wall (wall thickness) to calculate the flaw height. Statistical distributions specific to the inspection scenario are adopted for the model parameters. The calculated distributions of the flaw height sizing error are used to evaluate the 95% sizing error interval and to rank the error sources.

The method is demonstrated in a flat test block with an artificial notch. The dimensions are selected based on the inspection scenario of a T-shaped welded connection commonly applied in steel bridges. The geometry consists of a stiffener with thickness 10 mm welded to a flange of thickness 40 mm. The weld leg length is 10 mm. The notch on the test block is selected on the basis of the flaw of interest: sharp flaws, like fatigue cracks, with a flaw height of 5 mm from the back wall on the 40 mm flange, with uncertainty in position with respect to the midplane of the TOFD instrument (midplane deviation from -4.6 mm to 14.6 mm), and with differences between the test object and the reference block used for calibration (error propagated from the calibration).

Errors propagated from the calibration appear irrelevant for the inspection scenario of study. For flaws with height < 5 mm, the differences between test object and reference block result in similar depth error magnitude in the measurements of the depth of the flaw tip and the depth of the back wall, thus canceling out when calculating the flaw height.

The uncertain position of the flaw with respect to the instrument midplane (midplane deviation) appears to give the largest contribution to the flaw height sizing error. The flaw height sizing error caused by midplane deviation is non-linear with respect to the flaw position from the instrument midplane and increases with flaw depth. This makes small flaws near the back wall particularly susceptible. If midplane deviation is minimal, then the flaw height sizing error is in accordance with published standards. For midplane deviation originating only from the scanning guiding accuracy, which is limited by the ISO standard 10863 [4], the maximum flaw height sizing error is ± 0.3 mm (95 % scatter band). This is in good agreement with the sizing uncertainty reported in the standard BS 7910: ± 0.5 mm to ± 0.1 mm [9]. However, the midplane deviation cannot always be controlled and cannot be detected, which is a drawback of TOFD. Midplane deviation leads to a biased flaw height sizing error distribution strongly undersizing flaws. The calculated maximum flaw height sizing error is -1.1 mm to $+0.2$ mm. This large underestimation of flaw height leads to a potentially unsafe overestimation of the remaining fatigue life of the bridge. Although approaches to mitigate the midplane deviation error exist [4,29], these can be impractical.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/ndt4040029/s1>.

Author Contributions: Conceptualization, J.M.; software, D.T.G.; validation, D.T.G.; formal analysis, D.T.G.; investigation, D.T.G.; resources, A.V. and J.M.; data curation, D.T.G.; writing—original draft preparation, D.T.G.; writing—review and editing, A.V. and J.M.; visualization, D.T.G.; supervision, A.V. and J.M.; funding acquisition, J.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was carried out under project number T20006 in the framework of the Research Program of the Materials innovation institute (M2i) (www.m2i.nl) supported by the Dutch government.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Raw B-scans data presented in this study are included in the Supplementary Materials. Further inquiries can be directed to the corresponding author.

Acknowledgments: The authors acknowledge Amin Livani for the parallelization of the finite difference code used in this study.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

BW	Back wall
FL	Flaw echo
LW	Lateral wave
SNR	Signal-to-noise ratio
TOFD	Time-of-Flight Diffraction

Appendix A. Sizing Errors Propagated from Calibration

Four errors propagated from calibration are addressed. The first is related to the choice of wall thickness of the reference block. The calibration defines an effective probe center separation that minimizes the flaw depth sizing error at the depth given by the wall thickness of the reference block. For a test object of 40 mm, ISO 10863 [4] allows for a reference block nominal thickness between 32 mm and 55 mm. Taking advantage of this

wide range, a single reference block may cover a range of wall thickness of test objects scheduled for one contracted bridge inspection service. The flaw height sizing error caused by differences in nominal wall thickness between the test object and the reference block is shown in Figure A1. Two dead zone limits are indicated. These assume that echoes are resolvable if separated by a time period of one cycle and two cycles at the nominal frequency of the ultrasonic probes.

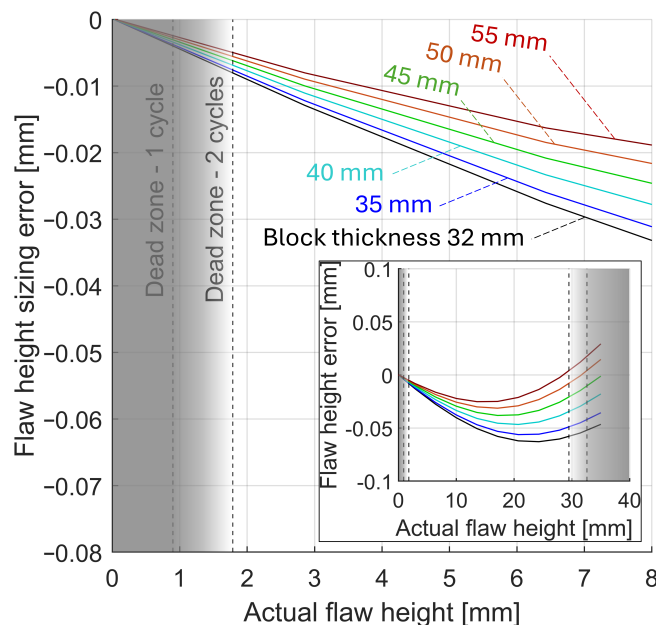


Figure A1. Error propagated by calibration: reference block thickness.

The measured wall thickness and the measured depth of the flaw tip with height up to 5 mm are affected by about the same level of depth sizing error, resulting in a small height sizing error even if the instrument is calibrated at a depth far from the depth of the flaw under inspection. This effect of depth sizing errors canceling out when measuring small flaws is also observed in the other errors propagated from calibration addressed in this study.

The second potential error source caused by the calibration process occurs when the inspection is performed on a painted test object using an instrument calibrated on an unpainted reference block. This scenario is envisioned because the removal of the paint is not mandatory [4], and therefore is usually not applied. The flaw height sizing error is shown in Figure A2. Each curve refers to a different paint thickness within the range 0.368 mm to 1.3 mm. The influence of the paint layer on the flaw height sizing error of flaws of height 5 mm appears to be negligible compared to the total error (Table 5).

The third and fourth errors propagated from calibration are errors caused by a difference in sound velocity between the reference block and the test object. In bridge inspections, this difference may be caused by: (A) differences in environmental temperature between calibration and inspection, and (B) use of a reference block made from a steel grade similar to the test object but still with a different sound velocity.

To address Scenario (A), the nominal sound velocities in Table 4 are used as the values at 20 °C when estimating times-of-flight on the reference block. When estimating times-of-flight on the test object, these sound velocities are updated for the temperature of the test object (0 °C to 50 °C [4]) using fixed rates of change of sound velocity with temperature: $dc/dT_{\text{wedge}} = -1.83 \text{ m/s } ^\circ\text{C}$ [11] for wedge material, $dc/dT_{\text{coupling}} = 3.28 \text{ m/s } ^\circ\text{C}$ [12] for the coupling fluid and $dc/dT_{\text{steel}} = -0.82 \text{ m/s } ^\circ\text{C}$ [13] for low-carbon steel. The flaw height sizing error is shown in Figure A3. Each curve addresses a different temperature of the test

object. Given the small magnitude of the flaw height sizing error for flaws of height 5 mm, the temperature at which the calibration is performed appears irrelevant.

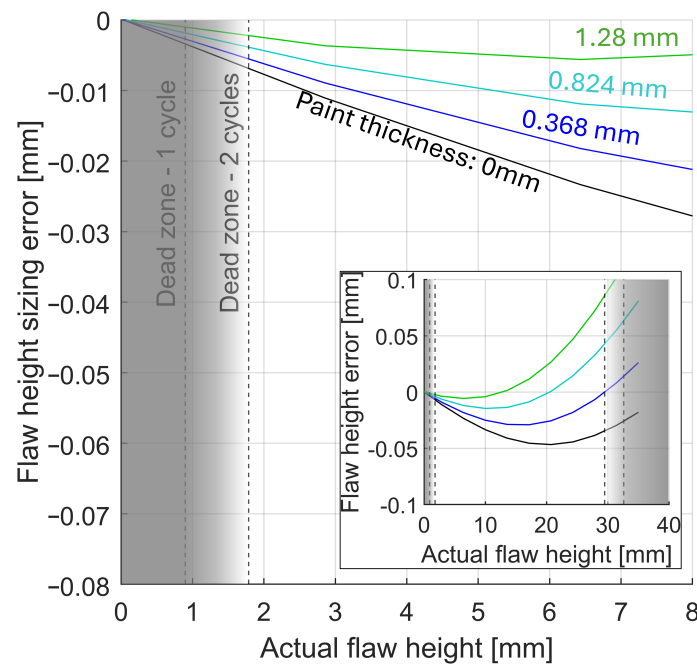


Figure A2. Error propagated by calibration: presence of paint layer on test object.

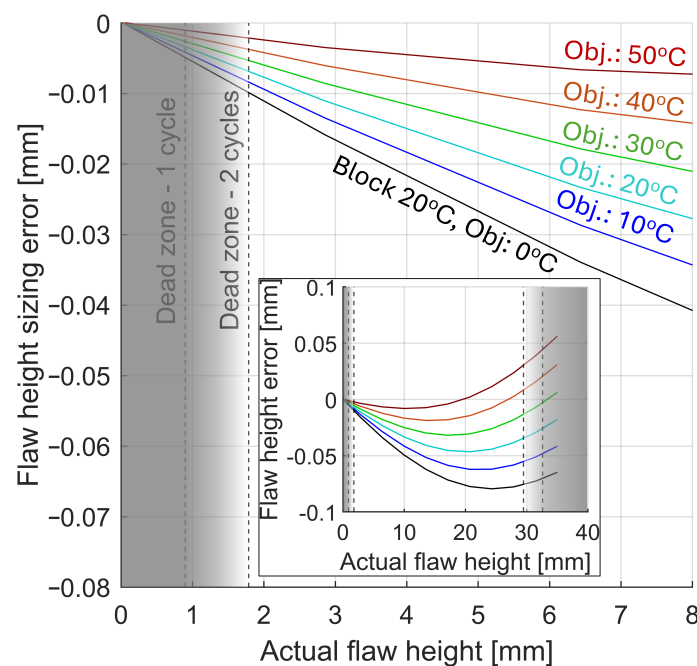


Figure A3. Error propagated by calibration: difference in sound velocity due to temperature.

To address Scenario (B), the flaw height sizing error is calculated for selected pairs of true sound velocities on the reference block and on the test object, restricted to the range 5920 ± 50 m/s [4], that is, difference in sound velocity $c_{stl,blk} - c_{stl,obj}$ in the range of -100 to $+100$ m/s. Figure A4 shows the flaw height sizing error.

The difference in sound velocity is the most relevant calibration error among those evaluated, but is still irrelevant for flaws of height 5 mm compared to the total flaw height sizing error in Table 5.

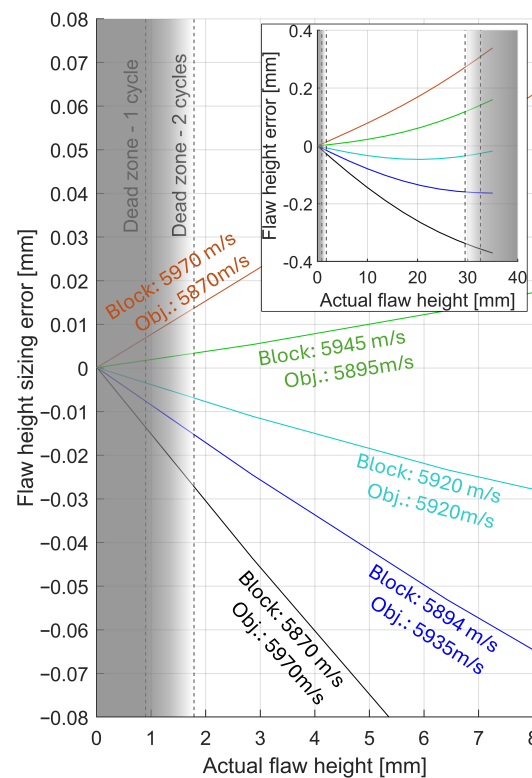


Figure A4. Error propagated by calibration: difference in sound velocity due to different steel grades in reference block and test object.

Apart from the geometry of study, namely (A) wall thickness 40 mm with a flaw with flaw root at depth 40 mm, i.e., open to the back wall, three other geometries are evaluated: (B) wall thickness 40 mm with an embedded flaw with root at depth 23 mm (close to the dead zone of the inspection surface); wall thickness 20 mm with (C) a flaw with root at 20 mm and (D) at 7 mm. In these simulations, the variables related to the errors propagated from the calibration are considered with their values selected at the extremes of the ranges in Tables 3 and 4 so that they produce the minimum and maximum error propagated from the calibration. The flaw height sizing errors for a flaw with nominal height of 5 mm are summarized in Table A1. The flaw height sizing error in all scenarios remains small compared to the total sizing error of Table 5.

Table A1. Flaw height sizing error of a flaw with height 5 mm.

Scenario	Minimum and Maximum Flaw Height Sizing Error
A	−0.08 to 0.05 mm
B	−0.06 to 0.08 mm
C	−0.10 to 0.06 mm
D	−0.02 to 0.17 mm

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