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METROLOGICAL INVESTIGATION AND CALIBRATION OF REFERENCE STANDARD BLOCK FOR ULTRASONIC NON-DESTRUCTIVE TESTING

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Abstract

Ultrasonic Non-Destructive Testing (NDT) is a powerful tool used for testing, verification, and inspection of material, especially for quality control and assurance. The key applications are the identification of flaws, cracks, irregularities, defects, and estimation of material thickness. The standard documents available for ultrasonic NDT are used as a guideline for the specifications and certification of the calibration reference standard block (RSB). The method for metrological characterization of the testing blocks is not specifically addressed in standard documents and is left to the wisdom of metrologists working in the ultrasonic calibration laboratories to adopt the suitable one. The ultrasonic flaw detector (UFD) is used most widely in ultrasonic NDT. The International Institute of Welding (IIW) V1 RSB standard is used as a reference to ascertain the functionalities of UFDs. In this article, we have proposed a new methodology for calibration of RSB and evaluation of associated measurement uncertainty along with influencing parameters. The proposed method conforms to the international standard ISO 2400:2012 and Indian standard IS 4904:2006 for validation purposes. According to these standards, the clauses for RSB e.g., dimension and quality of material have been examined. The expanded measurement uncertainty in thickness, ultrasonic longitudinal velocity, ultrasonic attenuation, parallelism and perpendicularity is ±0.068 mm, ±6.70 m/s, ±0.22 dB, and ±0.066 mm, respectively. The measurement uncertainty of these parameters is well within as per clauses stipulated in the standard documents except the ultrasonic longitudinal velocity for the IS standards.

Keywords: ultrasonic non-destructive testing, reference standard block, ultrasonic pulse-echo technique, calibration method.

1. Introduction

Ultrasonic *Non-Destructive Testing* (NDT) is extensively utilized in the fields such as aerospace, concrete testing, composite structures, material structures damage detection, and visualization of flaws. It ensures the product's structural integrity, quality, and reliability, especially

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in assessment of materials, due to its inherent advantages of not affecting or damaging the item being tested. The ultrasonic NDT technique is one of the most widely used and well-accepted for metrological characterization as well as for industrial applications including dimensional measurements [1–7]. In the past few decades, this method has also been preferred as there is no need to access both sides of the material [8, 9]. For the inspection of the materials, the *ultrasonic pulse-echo* (UPE) technique is preferred. In the UPE method, a short-duration electrical pulse applied to the ultrasonic transducer generates an ultrasound which enters the test piece, travels through the medium, and reflected from the test piece is received by the same transducer [10]. The received signal is in the form of echoes that contains information about ultrasonic transit time and signal amplitude decay. The obtained signal contains relevant information regarding the flaws present in the material as well as the dimensions of the material. The UPE method is extensively used in contact and immersion modes. The generalized UPE system consists of a pulser for the generation of the ultrasound, a transmitter/receiver probe, and an oscilloscope [11–15]. The dimensional measurements are performed by measuring the transit time of ultrasonic waves traveling through the material. In the immersion method, the material is submerged in the liquid, most likely water. This technique is preferred due to its inherent advantage over the contact UPE method as there is no direct contact between the probe and the material [16, 17]. The effect of variation in the thickness of the couplant layer is greatly improved in the immersion technique in comparison with the contact method [18]. *Ultrasonic flaw detectors* (UFDs) are used as universal pulse-echo-based systems for ultrasonic NDT. As the name suggests, UFD is utilized for the detection of flaws or any kind of defects in homogeneous materials. The functionality of the UFDs may suffer due to the deterioration of electronic components or repair. The quality of the NDT is maintained by the validation of the UFD. A reference standard is used for the validation of the desired parameters of the UFD. The ultrasonic *reference standard block* (RSB) is developed in conformity with ISO 2400:2012 and IS 4904:2006 used as a reference for the pulse-echo devices. The certification of the RSB itself is a challenge and requires critical consideration of ultrasonic parameters along with methodology. Both the standards (ISO 2400:2012 and IS 4904:2006) stipulate the requirements of the RSB such as material quality and dimensional tolerances. The literature review in this field reveals that the methodology of material characterization of such RSB is rarely available. Therefore, a proper and robust calibration procedure needs to be explored, applied, and adopted. Thus, the proposed methodology would provide a calibration approach for the metrological characterization of the RSB. The characterization includes the investigation of the effects of influencing parameters involved in the measurements. Metrological traceability of the measurements was established using a known calibration instrument traceable to the National Primary Standards of the *National Physical Laboratory* (NPL), India [19–24].

The authors address this issue in the article by proposing a methodology for the metrological characterization of RSB. This article discusses the various standard clauses and their experimental validation in detail.

2. Ultrasonic IIW V1 RSB

For the assessments of UFDs, the IIW V1 block plays a crucial role. The block is used to evaluate various parameters of UFDs in laboratory or on-site conditions. The RSB is originally designed and proposed by the *American Society for Testing and Materials* (ASTM). The shape, dimension, and surface finish conform to the ISO 2400:2012 [25]. The standard reference block is made of fine-grained low carbon steel with a low attenuation coefficient. It is made from wrought

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material having no internal flaws. Brushing and hardening are prohibited on the surface of the block. The standard guidelines include ultrasonic velocity in the block and marking for the probe. Figure 1 shows the structural and dimensional details of the standard IIW V1 block [26–29]. The IS 4904:2006 is an Indian standard adopted by the *Bureau of Indian Standards* (BIS) for RSB. The experimental calibration procedure for this block is developed at NPLI as per the requirements of IS 4904:2006.

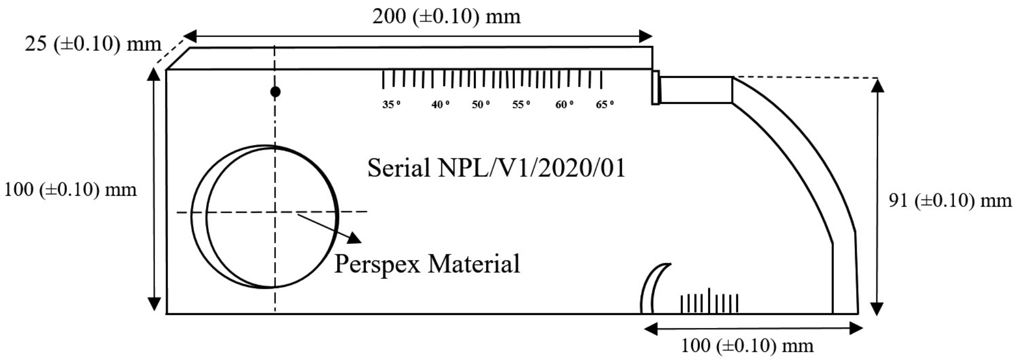

Fig. 1. Ultrasonic IIW V1 RSB (side view), used for the functional validation of UPE devices.

In this article, the methodology for estimation of different parameters using the ultrasound such as dimension, surface parallelism, perpendicularity, time of flight, and effect of grain size on ultrasonic attenuation have been described and studied using two approaches, UPE contact, and immersion methods. The clauses documented in the IS 4904:2006 standard to ensure the quality and reliability of block material are also discussed [25]. Clause 3 is especially for the material's quality, processing, and homogeneity while Clause 4 stipulates the dimensional aspect.

2.1. Clauses for material quality and dimension

The RSB shall be of low or medium carbon steel and crushed to normalize for the fine grain structure stated in Clauses 3.1 and 3.3. As per IS 4748, the grain size of the material must be uniform throughout [30]. Clause 3.2 specifies that the RSB shall be made of wrought material that is free from flaws. The final preparation of the RSB, according to Clause 3.3, should be mild grinding. Brushing and hardening the surface are prohibited. For the faces and edges, the surface roughness (R) value must not exceed 0.8 microns [31]. According to Clause 3.4, the material used in the development of the RSB must be evaluated for post-heat ultrasonic attenuation. When measuring compressional waves in the frequency range of 4 to 6 MHz, the local attenuation variation must not exceed ±1 dB (±0.02 dB/mm) of standard block dimensions. The longitudinal ultrasonic velocity in the block material must be measured with an accuracy of ±1 m/s according to Clause 3.5 and Clause 3.6 specifies that steel equivalent thickness of the perspex in the V1 block is 50 ± 0.1 mm. The dimensional Clause 4.1 specifies that both faces of the RSB should be parallel within ±0.10 mm and that adjacent faces perpendicular within ±5 mm of the arc and the dimension tolerances must be less than ±0.10 mm. The clauses of the standards are summarized in Table 1.

Table 1. Summary of clauses and their acceptance criteria as per IS 4904:2006 and ISO 2400:2012.

Parameter	Clause (IS 4904:2006)	Clause (ISO 2400:2012)	Parameter Details	Acceptance Level (IS 4904:2006)	Acceptance Level (ISO 2400:2012)	Remarks
Material	3.1 3.2 3.3	4.1 4.3	Material, surface finish, and heat treatment	Low or medium carbon steel	Steel or equivalent grade	For both clauses the R-value equivalent to 0.8 micron
	3.4	–	Variation in attenuation	±1 dB (±0.02 dB/mm)	–	–
	3.5	5	The ultrasonic velocity of longitudinal waves	±1 m/s	5920 ± 30 m/s	–
	3.6	–	Thickness of perspex	50 ± 0.1 mm	–	ISO does not include any requirement for the plastic insert
Dimensions	4.1	4.2	Dimensions of the RSB	±0.10 mm	±0.10 mm	IS include parallelism and perpen-dicularity in the RSB
	4.2	4.4	Marking	Zero marking done on both side	Reference marks shall be permanently marked	–

3. Working principle and experimental setup for the ultrasonic calibration of RSB

The UPE method was used for the characterization of RSB. The experimental set up has the facility to align the ultrasonic transducer to receive the maximum amplitudes of the reflected signal. The maximum amplitude corresponds to the normal incidence of the beam to the surface of the sample. In the UPE method, the simple way to estimate ultrasonic velocity is by using (1)

$$c(T) = 2d/t_d\,, \tag{1}$$

where c is the ultrasonic propagation velocity in the sample as a function of temperature T, d is the thickness of the sample and t_d is ultrasonic wave transit time in the sample. Here, $2d$ is due to the double path (to and from) travelled by ultrasound.

The ultrasonic flaw detector estimates the depth of flaws or cracks or measures the thickness of the sample by using ultrasonic propagation velocity in the sample specified by the user. One way of measuring the propagation velocity is to measure the thickness and ultrasonic transit time as indicated in (1). The UFDs are generally not suitable for the estimation of transit time and a special arrangement is required for its measurement.

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3.1. Calibration approach to thickness measurement

The accuracy of the thickness measured by the UFD is mainly dependent on the accuracy of an ultrasonic velocity fed into the UFD. Therefore, the thickness of the RSB is measured by other means. A Vernier caliper, a screw gauge, and a digital height gauge (all three manufactured by Mitutoyo) were used that are traceable to the National Standard of Length and Dimensional Metrology of NPLI for the measurement of thickness. The thickness was measured with three approaches to determine the best. The measurements were performed repeatedly 20 times by each method for a better statistical estimate and measurement uncertainty. The average thicknesses measured with the Vernier caliper, screw gauge, and height gauge were found to be 25.09 mm, 25.05 mm and 24.99 mm, respectively. Fig. 2 shows the variations in the sample thickness measurement while using the Vernier caliper, screw gauge, and height gauge. The standard deviation of the measurements performed using the Vernier caliper was found the highest with ±0.02 mm compared to the screw gauge as ±0.01 mm. The lowest scatter in the measurement was observed in the case of the height gauge with a standard deviation of ±0.001 mm. Also, the average thickness obtained with the height gauge is lower in comparison with values obtained using the screw gauge and the Vernier caliper. This may be due to the inherent limitation of the Vernier caliper in holding the RSB. The additional limitation of using the Vernier caliper is that it may produce permanent marks or damage on the RSB surface due to the sharp edges of the jaws.

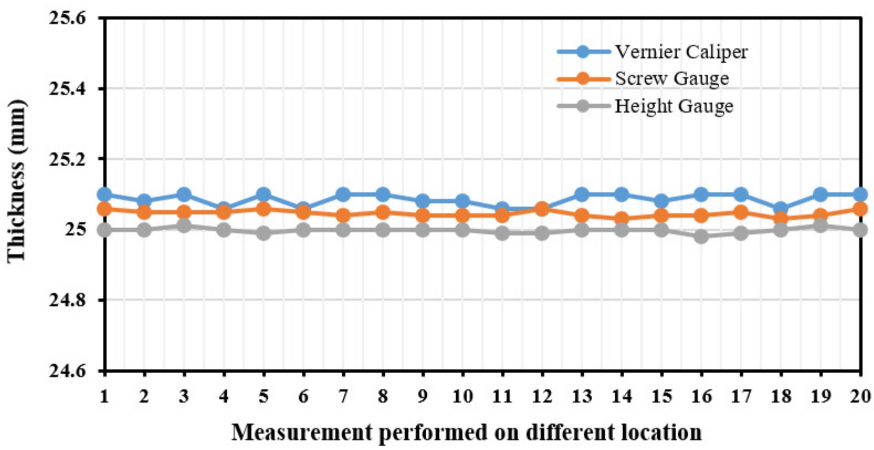

Fig. 2. Thickness measurement variation of the RSB by using the Vernier caliper, screw gauge, and height gauge.

3.2. Calibration approach for longitudinal ultrasonic velocity

The ultrasonic propagation velocity in the block at a fixed temperature is given by (1). There can be two approaches to measure the ultrasonic propagation velocity as described herein;

3.2.1. Ultrasonic velocity calibration using UFD and thickness of the RSB

The experimental setup for the ultrasonic velocity measurement consists of a UFD (Olympus: Epoch 1000), a test probe with a nominal frequency of 5 MHz (model EN-1225, 10 mm diameter), lubricant oil/water as couplant, and a test specimen. To estimate the correct ultrasonic velocity in the RSB, an estimated or any nearby value of velocity (c_1) is fed into the UFD. In the present case, for mild steel, the longitudinal velocity of 5900 m/s was considered. As the ultrasonic propagation time at a particular location in the RSB is constant, the UFD indicates the corresponding thickness as d_1.

$$c_1 = \frac{2d_1}{t_d}, \tag{2}$$

where d_1 is the thickness measured by the UFD at the fed velocity c_1. Now, as t_d is an ultrasonic time delay (transit time) in the block material and remains constant.

$$t_d = \frac{2d_1}{c_1}, \tag{3}$$

Considering d_2; the actual thickness of the block measured has measurement traceability to the National Standard. So, the actual propagation velocity (c_2) is related by

$$t_d = \frac{2d_2}{c_2}. \tag{4}$$

From (3) and (4), we have:

$$\frac{d_1}{c_1} = \frac{d_2}{c_2}, \tag{5}$$

$$c_2 = \frac{d_2 c_1}{d_1}. \tag{6}$$

Taking into consideration the estimated nearby ultrasonic velocity (c_1), thickness (d_1) displayed on the UFD and the measured traceable thickness (d_2) of the RSB, the actual ultrasonic propagation velocity (c_2) in the RSB is calculated. As ultrasonic propagation velocity measurement is affected by the change in the temperature, the path length measurement is also becomes affected by the variations in the temperature. Therefore, the temperature needs to be monitored with the best possible accuracy. Being a metrology laboratory, the temperature in the laboratory is maintained at 25° (±2°) and relative humidity at 55% (±10%) as per the ISO 17025 standard [32].

According to IS 4904, the ultrasonic propagation velocity of the compressional wave in the RSB material must be specified with the accuracy of ±1 m/s.

3.2.2. Ultrasonic velocity calibration using transit time and thickness of RSB

The ultrasonic propagation velocity through the RSB material is also measured using (1). The ultrasonic time of flight (twice the transit time) through the sample has been measured using a digital storage oscilloscope (DSO, Model: Lecroy; WaveSurfer 42Xs) having a time measurement resolution of 100 ps and being traceable against the National Standard of Time and Frequency metrology of NPLI. The UFD (Model: Sonatest; MasterScan 300) has been used for the excitation of the ultrasonic probe in the pulse-echo mode. It has a facility to provide the radio frequency output signal which is fed to the DSO. The adjustment in the DSO is made to carry out the time delay measurement between two successive echoes. Fig. 3 shows the typical arrangement for the ultrasonic time of flight measurement in the RSB.

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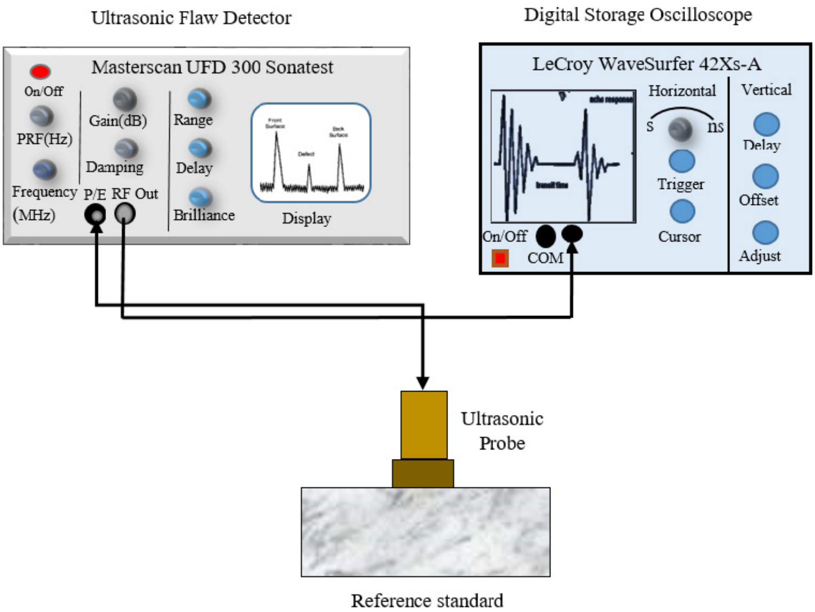

Fig. 3. Experimental setup for measurement of ultrasonic wave transit time in the RSB.

3.3. Calibration Approach for Ultrasonic Attenuation

Ultrasonic attenuation in the RSB needs to be calibrated as stipulated in Clause 3.4 of the IS 4904:2006 standard. Measurement of ultrasonic attenuation is carried out in the immersion system to reduce the effects of coupling. The typical immersion arrangement with a UFD is shown in Fig. 4. The immersion method includes the generation of ultrasound the in the propagation medium; where the RSB is submerged in the water (at room temperature) as shown in Figs. 4a and 4b. The scanning tank having stroke length ranges $(810 \times 408 \times 291)$ mm is used. The X and Y axes have step resolution of ±0.01 mm. The positioning system is used to move the ultrasonic probe and scan the sample in the desired direction and particularly for the specific location. There is a provision to tilt and rotate the transducer within the range of ±35° and ±180°, respectively. The system is used to control the position of the probe in all axes. A commercial immersion probe (model Sonatest LIH4-25 SP 351) is used. While using the normal beam approach, the water path length should always be larger enough to receive the desired number of echoes from the block and can estimated by (7) [33, 34].

$$d_w = \frac{n d_s c_w}{c_s}, \tag{7}$$

where d_w is the separation between the ultrasonic probe and the sample surface (water path), n is the desired number of echoes from the sample received between two water-block interface echoes, d_s is the thickness of the sample, c_w is the ultrasonic velocity in water at the measured temperature and c_s is the ultrasonic propagation velocity in the RSB material.

The separation between the test object and the probe has been chosen to be 80 mm, which results in the effective reception of about 12 echoes between the two interface (water-solid) echoes on the UFD screen. Gain control is also adjusted to obtain the back wall echo well within the screen range.

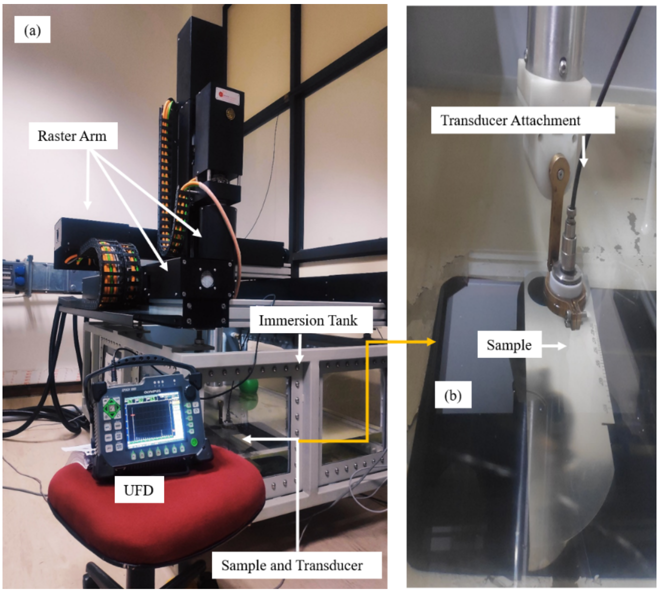

Fig. 4. a) Experimental setup for the immersion method, b) close view of the RSB and the transducer used in the immersion tank.

The amplitude attenuation coefficient of plane waves for pure water at 23° was computed using the following formula [35]

$$\frac{\alpha}{f^2} = 2.3 \times 10^{-4}/\text{MHz}^2\text{cm}, \tag{8}$$

where α is the ultrasonic attenuation coefficient and f is the nominal frequency of the ultrasonic probe. The ultrasonic attenuation in water for a separation distance of 80 mm is found to be 0.028 dB at a frequency of 4 MHz. Normally the attenuation coefficient increases with an increase in the probe frequency. When it comes to pure absorption, the sound reduction is proportional to the square of the frequency, and when it comes to the attenuation due to dispersion, the sound reduction is proportional to the square of the frequency. At low frequencies, these components have a direct proportionality with attenuation due to absorption. The phenomenon of scattering occurs at frequencies when the wavelength approaches the grain size.

The following formula is used for the estimation of the attenuation coefficient in terms of relative echo height [36].

$$\alpha = \frac{20}{d} \ln \frac{H1}{H2}, \tag{9}$$

where d is the total beam path length in the sample and $H1$, $H2$ are the echo heights of Echo 1 and Echo 2, respectively. Fig. 5 shows the attenuation values over the entire RSB, at a probe frequency of 4 MHz. In the reference block, along thickness (25 mm) the measurements were performed at different locations covering almost the entire block. Total 14 locations were identified for the measurement. The average value of the measured attenuation was found to be 29.87 dB (±0.03 dB overall variation in the block).

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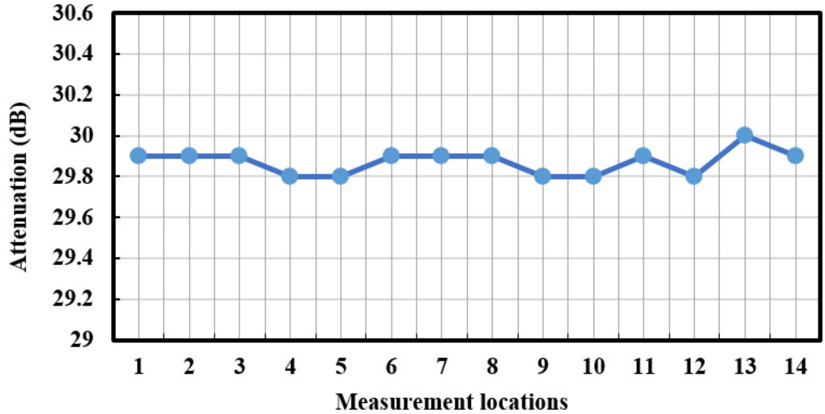

Fig. 5. Measured ultrasonic attenuation in the RSB.

3.4. Calibration approach for parallelism and perpendicularity measurement

Clause 4 is related to the parallelism and perpendicularity of the RSB. The clause recommends that the opposite faces of the block should be well within ±0.1 mm in terms of dimensions. The RSB was placed inside the water-filled ultrasonic immersion tank to measure the parallelism of faces in the thickness mode (*i.e.* 25 mm side of the block). Parallelism of the two faces is assured by measuring the thickness of the RSB using the corresponding depth of the two consecutive block echoes. The variations in the RSB thickness are measured by scanning the sample at various locations as shown in Fig. 6. The average thickness measured was 25.01 mm along with the overall thickness variation well within 0.06 mm.

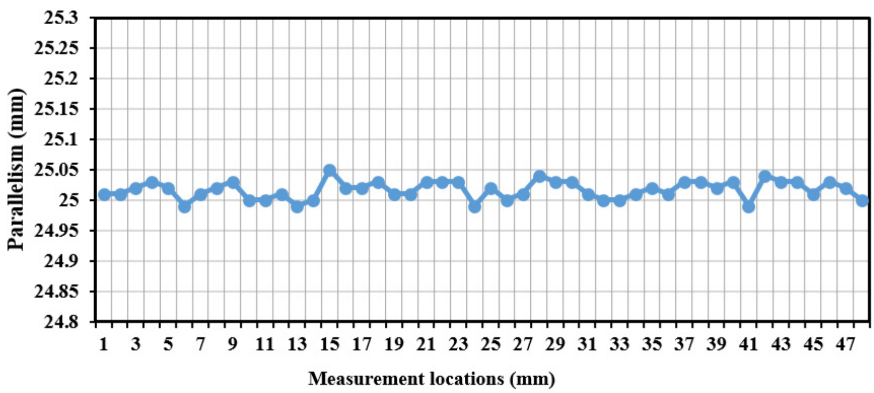

Fig. 6. Measured thickness variation for estimation of parallelism in the RSB.

The perpendicularity between the two faces of the RSB was ascertained by fine alignment of the ultrasonic transducer along the angular and rotational axes to achieve the maximum echo response. If there is any deviation in the alignment during perpendicularity compared to that of the parallelism alignment, it is considered as angular error in perpendicularity. Once the transducer alignment was over the same procedure was also repeated for the perpendicularity assessment in term of thickness variation but this time the sample was kept in the vertical position (*e.g.*, 100 mm side of the block). The angular alignment variation was extremely small (0.05°) so it was neglected. The variations in the thickness of the RSB were recorded and are shown in Fig. 7. The average thickness measured was found as 99.93 mm with overall thickness variations well within 0.05 mm.

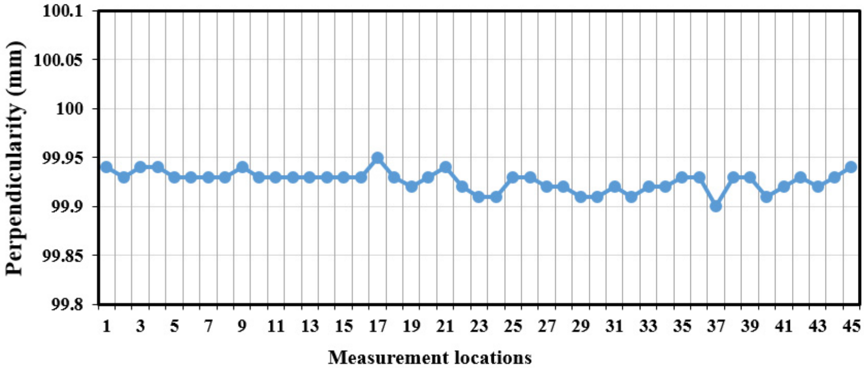

Fig. 7. Measured thickness variations for estimation of perpendicularity in the RSB.

4. Results and discussion

The measurements of thickness with the Vernier caliper and screw gauge are highly dependent on the operator's ability and parallax error. The thickness measurement using a height gauge was preferred for the traceability since it had the minimum deviation as compared to the Vernier and screw gauge. Just to ascertain any error in the measurement due to the possibility of a slight bending of the block, the measurements with height gauge needed to be carried out for both sides of the RSB. The standard deviation in the measured thickness values in the case of the contact method is found to be ±0.04 mm, which is coarser than the standard deviation of ±0.014 mm obtained using the immersion method. The use of the couplant in the contact method is the major source of error, which results in dispersion in the values because it is always difficult to maintain the same level of contact pressure on the probe and couplant thickness. The longitudinal ultrasonic wave velocity was estimated using a UFD at a probe frequency of 4 MHz by considering the thickness of the RSB. The approach described in Subsection 3.2.1 was used for the estimation of ultrasonic velocity. The ultrasonic velocity was found to be 5900 m/s and 5901 m/s using the contact and immersion methods, respectively. The slightly increased velocity in the immersion approach can be attributed to the absence of excessive coupling material delay, which results in a slightly lower transit time through the RSB compared to the contact [37, 38]. When using the Subsection 3.2.2 approach, the ultrasonic transit time measured in the RSB was 4.234 (±0.002) µs, and considering the thickness of the RSB material evaluated from the height gauge as 24.99 mm, the resulting ultrasonic velocity was 5902 (±3) m/s. By using both approaches, the relative variations in ultrasonic velocity measurement are higher (3 m/s) in the case of approach 3.2.2 as compared to the UFD method described as approach 3.2.1. This is particularly because of difficulty in the estimation of transit time by using RF echoes on an oscilloscope. Although the oscilloscope has a better capability to measure the change in time of the order of 100 ps, it is extremely difficult to locate the amplitude threshold in the received signal resulting in an increased type A uncertainty. On the other hand, the ultrasonic flaw detector displays the filtered envelop-based signal which is easy to measure. Some modern UFDs have

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automatic peak amplitude detection which significantly improves measurement precision [19]. The material homogeneity along with grain size is assessed by measuring the ultrasonic attenuation variation in the RSB. The reliable attenuation measurement can only be performed using the immersion technique. The attenuation in the block measured at 4 MHz for the present setup was 29.87 dB. This value of attenuation depends upon various factors including transducer operating frequency, transduction efficiency, the separation between the transducer and the block, etc. The overall variations in the attenuation were found well within the specified limit in the Indian standard. The parallelism and perpendicularity of the faces have been ascertained by measuring the variations in the thickness measurement at various locations in the RSB. The parallelism and perpendicularity in the RSB were within the tolerance level of 0.1 mm specified in the standard. Table 2 shows the various influencing and contributing factors to measurement uncertainty.

Table 2. Uncertainty budget along with contributing factors.

Parameters Type	**RSB Thickness (Ultrasonic Method)**	**Ultrasonic Velocity (Approach 3.2.1)**	**Variation in Ultrasonic Attenuation**	**Parallelism / Perpendicularity**
Type A	±0.002 mm	±0.03 m/s	±0.03 dB	±0.01 mm
Type B	±0.01 mm (height gauge)	±2.36 m/s (height gauge traceability)	–	–
Type B	±0.01 mm (UFD thickness accuracy)	±2.36 m/s (UFD thickness accuracy)	±0.1 dB	±0.01 mm (UFD thickness accuracy)
Type B	±0.03 mm (temperature effect ±2°)	±0.15 m/s	Ignored as the only change in dB measured	±0.03 mm (temperature effect ±2°)
Combined uncertainty	±0.034 mm	±3.35 m/s	±0.11 dB	±0.033 mm
Expanded uncertainty at *k* = 2	±0.068 mm	±6.70 m/s	±0.22 dB	±0.066 mm

5. Conclusions

The article describes the validation methodology for an RSB along with the effects in the evaluation of different parameters. Particularly, in dimension measurement, the height gauge indicates a relatively better approach with the lowest standard deviation of ±0.002 mm. The immersion method is the only reasonable approach available at present for obtaining ultrasonic attenuation in the material. With the ultrasonic longitudinal velocity measurement in the RSB with ±1 m/s uncertainty as specified in IS 4904:2006 and ±30 m/s as specified in the ISO 2400:2012 while using the proposed method, the ultrasonic longitudinal velocity was ±6.70 m/s which seems reasonably fine as per international standard. The obtained result shows the RSB material is homogenous and the measurements of other parameters are in accordance with both standards. Also, this procedure can be used to validate the thickness of any reference material to achieve better accuracy.

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