Evaluation of the BCIT Hybrid Test Method

In the Acoustic Performance of Windows

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Evaluation of the BCIT Hybrid Test Method In the Acoustic Performance of Windows

Abstract

This thesis presents validation of the British Columbia Institute of Technology (BCIT) Hybrid Test Method, a novel approach for measuring the sound transmission loss of building envelope elements, with an emphasis on double-glazing windows. The BCIT Hybrid Test Method was developed to be a more accessible and cost-effective alternative to the ASTM E90 test. The ASTM E90 test method is typically used in advanced research stages and requires two reverberant chambers. The limitations of the ASTM E90 test method, such as limited access to test sites for the industry, underscore the need for innovative and cost-effective alternatives for acoustic testing. The BCIT Hybrid Test Method, which combines elements of the ASTM E966 standard (2011) and the ISO 15186-1 standard (2016) standards, addresses this need by offering a more locally available, less expensive, and flexible method for scanning multiple variables in the design and investigation stage of research and development. The efficacy of the BCIT Hybrid Test Method was assessed using window samples from Centra Window Manufacturer Ltd. The research examined the BCIT Hybrid Test Method's ability to accurately detect variations in different test windows, including changes in the frame or the glazing system. Consideration was given to factors such as glass thickness, interpane spacing, and the use of laminated or symmetrical glass in insulated glass units (IGUs). Equations from Quirt’s (1982) study on double-glazing windows were employed to investigate mass-air-mass resonance frequency and critical frequency and to evaluate the accuracy of the BCIT Hybrid Test Method. The results demonstrated the validity of the BCIT Hybrid Test Method in measuring the sound transmission loss of windows, emphasizing its potential for use in early-stage window research.

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1. Introduction

1.1. Impact of Noise Pollution

The growing concern over noise pollution has prompted the implementation of strict measures to ensure the well-being of individuals, particularly in densely populated urban regions. Extended exposure to unwelcome sound, commonly known as noise, has been associated with a range of health problems, including hearing issues, increased stress levels, raised blood pressure, and even psychological conditions like anxiety and depression (Goines & Hagler, 2007). As urban areas expand, noise pollution presents a significant challenge, affecting the quality of life in residential, educational and communal environments (Berglund, 1998). Consequently, regulations have been established to uphold acceptable noise levels, aiming to enhance public health.

The Canada Mortgage and Housing Corporation (CMHC) booklet from 1981 provides guidelines for permissible noise levels in different living spaces. For example, it recommends the ambient noise levels below 35 dB for bedrooms, up to 40 dB for living and recreational areas, and a maximum of 45 dB for spaces like kitchens and bathrooms (CMHC Booklet, 1981). These recommended numbers emphasize the importance of managing noise intrusion to safeguard human health and well-being.

One useful approach for reducing noise pollution in different living spaces is to prevent noise from entering interior areas through the building envelope which is the physical boundary between the outside and the interior conditions. In this context, the assessment and improvement of the acoustic performance of building elements, such as windows, has become crucial for mitigating noise intrusion. Although primarily designed for visual purposes, windows inadvertently allow sound to pass through more than walls and other major building envelop components, making them vulnerable points for noise infiltration and potentially undermining the overall acoustic integrity of a structure (Bradley & Birta, 2001). Hence, the evaluation and enhancement of the acoustic quality of windows assume crucial importance in mitigating noise intrusion.

1.2. Complexity of Window Acoustic Quality Assessment

Transmission loss is a key indicator of how well windows transmit sound. It can quantify airborne sound insulating properties of windows for each one-third octave band. The higher the value, the more capable the structure is at reducing sound penetration. The sound transmission loss of a window is affected by many parameters, such as the physical and material properties of the windows, the air gap between them, the frequency and direction of the sound waves, and the type of sound source. The window frame, opening style, gaskets, and other factors can also have a significant impact on the noise transmission through windows (Maraqa et al., 2018). Therefore, a comprehensive understanding of the factors that influence the acoustic quality of windows is required.

1.3. Need for New Methods and Hybrid Approaches

A large body of research has been focused on developing quasi empirical and theoretical models for predicting the transmission loss characteristics of single and double leaf partitions (Sharp 1973, Quirt 1983, Long 2006). However, the complicity of this matter and its dependence on several factors, causes the assessments of windows to be dependent on experimental measurements as well (Fahy, 2007). Several standard methods for measuring the transmission loss of windows have been established that can be divided into field, laboratory, or semi laboratory methods. The ASTM E90 test method is a standard method executed for the publication of window manufacturer's data and is primarily applied when the project is advanced in the research and development stage. However, it requires large and expensive test chambers that are not readily available or affordable for many situations where transmission loss tests are needed (Barnard & Rao, 2004). Also, access to the ASTM E90 test sites is limited for industry. In the earlier stages of research, a local, more available method that is less expensive to construct and more flexible method is desired to scan multiple variables in the design and investigation stage of research and development. Given the limitations of the ASTM E90 test method, innovative and more cost-effective alternatives for acoustic testing are imperative.

1.4. Research Objective and Scope

The BCIT Hybrid Test Method, presents a potential solution as an innovative method for evaluating the acoustic performance of the windows. This hybrid method integrates components from two standards: the ASTM E966 (Standard Guide for Field Measurements of Airborne Sound Attenuation of Building Facades and Facade Elements) (2011) and the ISO 15186-1 (Measurement of sound insulation in buildings and of building elements using sound intensity-Part 1: Laboratory measurements methods) (2016).

One important benefit of this method is that it uses a sound intensity probe for measurements of the interior side of the window, which eliminates the need for a reverberant room on the source side and allows the use of any room as the receiving room that meets the requirements of the field indicator and the background noise indicated in the ISO 15186-1 (2016). The BCIT Hybrid Test Method also follows the ASTM E966

(2011) procedures for the measurements of the source side and allows the use of an outdoor environment instead of the source room under specific conditions.

The primary objective of this thesis was to explore and validate the BCIT Hybrid Test Method as an innovative approach to assess window acoustic performance and to confirm that the method is beneficial to window manufacturers in terms of evaluating the acoustic performance of their products in the research and development stages. For the evaluation of the BCIT Hybrid Test Method, windows from the Centra company were utilized in this thesis. The previous studies in this field related to the effect of glass thickness, interpane space, laminated glass and symetricall glazing, were used to assess the accuracy of this method.

2. Literature review

2.1. Sound transmission

Sound transmission is the process of sound energy propagating from a source to a receiver through a medium or a structure. When the structure acts as the receiver, it subsequently radiates the sound. In this thesis, the focus is on airborne sound transmission. This process occurs when sound travels through a fluid medium, such as air or water, and reaches a solid barrier. The amount of sound energy that is transmitted by a barrier or a partition between two spaces is quantified by the sound transmission loss (TL), which is expressed in decibels (dB) and defined as the difference in sound power levels between the incident and the transmitted sound fields (Hopkins, 2007).

2.2. Sound Transmission Theory

The theory of sound transmission through barriers or partitions originated from the need to control airborne sound, which is one of the common types of noise in many applications. Airborne sound can be reduced by placing a barrier or a partition such as a wall, a door, or a window, between the sound source and the receiver. The effectiveness of the barrier or the partition in reducing the airborne sound, depends on its ability to block or attenuate the sound energy that passes through it, which can be measured by its sound transmission loss. Sound transmission loss varies with the frequency of the sound and depends on several factors, such as the material properties, the thickness of the building elements and the angle of incidence of the sound wave (Bies & Hansen, 2003). To predict and measure sound transmission loss, various models and methods have been developed over the years, each with its own advantages and limitations. Some of the most common models are based on physical principles, such as the mass law and the coincidence theory; while others are based on statistical assumptions, such as the statistical energy analysis (SEA) (Hopkins, 2007). These models and methods have enabled engineers and architects to design and optimize sound transmission loss for various applications.

For a single panel (in the case of windows, this would be the glass panel) when an airborne sound wave is incident on the panel, part of the sound will be reflected and another part will be absorbed by the panel. The ratio of these parts depends on the panel acoustic impedance; a measure of how much resistance a material offers to the sound wave passing through it (Long, 2006), relative to air's (Ginn et al., 1987). Some of the absorbed energy will be converted into heat, while the remainder will propagate through the panel to the receiving room's boundaries. At this boundary, the relative impedances of the panel and the air will once again influence the proportion of energy transferred into the receiving space (Ginn et al., 1987).

The sound transmission factor (τ) is a dimensionless quantity that reflects the ratio of the sound power levels on both sides of a panel. It is a useful measure of the sound insulation performance of a panel when there is a noise source on one side. The sound transmission factor is defined by Equation 1:

$$\tau = \frac{W_t}{W_i} \tag*{(Eq. 1)}$$

where W_t is the sound power level in the receiving room that has been transmitted through the element and W_i is the incident sound power level, both measured in watts (Sharp, 1973).

As it was mentioned, the transmission coefficient is a dimensionless ratio. It can vary from 0 to 1, which is hard to compare and interpret. However, transmission loss is a logarithmic scale and can easily compare large differences. Transmission loss is expressed in decibels (dB) and can be calculated as follows (Hopkins, 2007):

$$TL = 10 \log \left(\frac{1}{\tau}\right) \qquad \textit{(Eq. 2)}$$

Although transmission loss is frequency dependent, single-number ratings were developed to provide an easier way to quantify and understand the general behavior of building envelope assemblies including windows and doors for quick comparison. Such ratings are calculated from the sound transmission loss data. Two single-number ratings which are used to classify building envelope assemblies for commercial and technical purposes are sound transmission class (STC) rating, and the outdoor indoor transmission class (OITC). The STC rating is calculated according to the standard the ASTM E413 (the ASTM, 2016), while the OITC rating is calculated according to standard the ASTM E1332 (the ASTM, 2010). The frequency range for the STC rating is from 125 to 4000 Hz which is within speech frequency range, whereas the frequency range for the OITC rating is between 80 Hz and 4000 Hz. Thus, OITC rating can better express the low frequency environmental noise and it covers the range of the human hearing (ASTM, 2010). It is noteworthy that windows are most commonly employed to separate indoor spaces from external environments. In such cases, there is often a need to guard against noise sources like vehicular traffic and aircraft, which can have significantly different noise spectra compared to typical residential noises (the ASTM, 2010). As a result, it is more practical to view the STC rating as a rough guideline rather than a precise indicator when selecting window configurations. (Quirt, 1988).

The sound transmission through a glass panel varies throughout the audio frequency range. Figure 1 from Long, (2006) depicts the curve showing sound transmission loss versus frequency for a single thin panel that can be classified into five zones: Stiffness controlled zone, resonance controlled zone, mass controlled zone, damping controlled zone and Shear controlled zone.

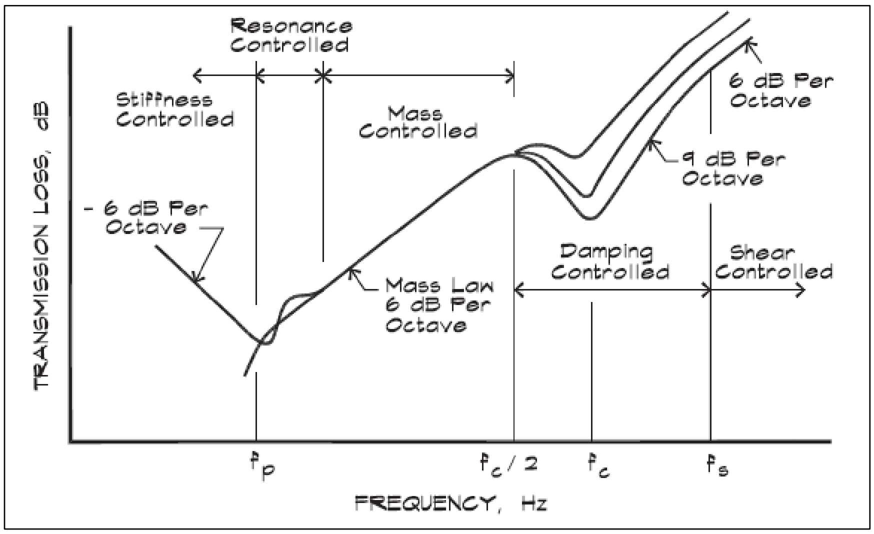


Figure 1. Sound transmission loss for a single thin pane (Long M., 2006)

Since a thin panel has qualities of stiffness and mass, it can exhibit resonance and mode effects. At frequencies lower than the lowest panel resonance (f_p), panel stiffness is the primary factor influencing sound transmission, whereas damping and mass are irrelevant. This is the first zone as depicted in Figure 1. In this region, the transmission loss of a panel is stiffness dependent and increases as the frequency decreases. A higher stiffness leads to higher transmission loss in this region as more energy is required to vibrate the panel. This also means that damping and mass are unimportant in this region. (Bies & Hansen, 2003).

The resonance-controlled area of a panel is the most critical zone for its acoustic performance, as it has the lowest sound transmission loss among the five zones. This zone is marked by a dip in the sound transmission loss curve, which occurs at frequencies around the natural frequencies of the panel. At these frequencies, the incident sound waves induce structural modes of the panel, resulting in large vibrations and high sound transmission. The position and magnitude of the dip are influenced by several factors, such as the panel's size, geometry, stiffness, damping, and edge constraint. Equation 3 can be used to estimate the natural frequencies of a simply supported panel (Bies & Hansen, 2003). The resonance-controlled area is bounded by the stiffness-controlled area at lower frequencies and the mass-controlled area at higher frequencies.

$$f_{i,n} = \frac{\pi}{2}\sqrt{\frac{B}{m}}\left[\frac{i^2}{a^2} + \frac{n^2}{b^2}\right] \quad i, n = 1, 2, 3, \ldots \qquad \textit{(Eq. 3)}$$

where B is bending stiffness, m is the mass per unit area, a is the panel width, b is the panel length and i, n are natural numbers. The fundamental panel resonance frequency happens when $i, n = 1$.

After the panel resonance zone, the third region is named the mass law zone. The mass law states that the transmission loss of the panel is proportional to the mass per unit area of the plate and the frequency of the sound, and inversely proportional to the angle of incidence of the sound. In this region, the transmission loss is expected to increase by 6 dB per octave (Bies & Hansen, 2003).

The extension of this zone is from about the frequency of twice the lowest resonance frequency up to about the critical frequency. This extension depends on a number of factors, including the mass per unit area of the panel, the stiffness of the panel, and the damping of the panel, as well as the speed of sound in the surrounding medium (usually air). Increasing the stiffness of the panel will cause the mass law region to start at higher frequencies. This is because a stiffer panel will have a higher natural frequency of vibration, and therefore will not start to vibrate until a higher frequency is reached. As a result, the beginning of the mass law region will be shifted to higher frequencies where the sound transmission loss of the panel is primarily determined by its mass per unit area. Conversely, decreasing the stiffness of the panel will shift the mass law region to lower frequencies. On the other hand, increasing the stiffness of the panel can cause the coincidence dip to appear at lower frequencies and consequently this will limit the extension of the mass law region (Bies & Hansen, 2003).

Another effective factor on mass law is the angle of incidence of the sound in the source room. By neglecting the stiffness and damping for a thin infinite panel, the sound transmission loss in the mass law region is governed by the Equation 4 as follows (Long, 2006):

$$TL = 10\ log\left[\frac{\omega^2 m^2}{4(\rho c)^2/cos^2\theta}\right] \qquad \textit{(Eq. 4)}$$

where, ω is the angular frequency, m is the mass per unit area, ρ is the density of air, c is the speed of sound, and θ is the angle of incidence.

However, In practice, panels are not of infinite extent and results obtained by using the predicted equations do not agree well with the results measured in the laboratory. Sharp (1973) showed that good agreement between the prediction and measurement of sound transmission loss in the mass law range is obtained for single panels by considering the limiting angle of about 85° and therefore the mass law can be written as Equation 5 that is known as field incidence transmission loss to fit best to the measured data below the critical frequency (Sharp, 1973).

$$TL = 20\log_{10}(fm) - 47 \qquad \textit{(Eq. 5)}$$

where m is the mass per unit area of the panel and f is the frequency of the incident sound.

A dip in the sound transmission loss curve of a single thin panel can be seen at frequencies above the mass law region which corresponds to the coincidence frequency. This region is known as the fourth zone. When a panel is subjected to an excitation, it can vibrate and generate bending waves that propagate along the panel. As the frequency of the excitation increases, the speed of propagation of the bending waves also increases. When the bending waves in the panel reach a certain frequency, there exists a critical frequency where the speed of propagation of the bending waves in the panel is equal to the speed of sound in the surrounding medium. This reduces the sound transmission loss of the panel, resulting in a dip in the sound transmission loss curve. The critical frequency for a panel was predicted by Equation 6.

$$f_c = \frac{c^2}{2\pi m}\left(\frac{12\rho^{3(1-\sigma^2)}}{E}\right)^{1/2} \qquad \textit{(Eq. 6)}$$

where f_c is the coincidence resonance, c is the speed of sound in air, m is the mass per unit area of panel, E is Young's modulus of elasticity, σ is the Poisson's ratio and ρ is the density of the panel material.

Above the coincidence frequency region, the sound transmission loss in a thin panel is controlled by the shear impedance, which occurs at high frequencies. In the case of thin panels, this frequency is typically much higher than the frequency range used in building acoustics (greater than the 4000 Hz one-third octave band). Also, at frequencies higher than the coincidence region, transmission loss via building materials is often high and requires no particular consideration (Long, 2006).

It can be summarized that for a thin panel to have a high sound transmission loss throughout a broad frequency range of audible frequencies, it must have a large mass and low rigidity and stiffness. In other words, having sufficient mass cannot lead to the full potential sound transmission loss in an element since the high stiffness of a panel can reduce the frequency range between resonance and coincidence frequency, consequently impinging on the sound transmission loss curve. The natural frequency of a panel is determined by its stiffness and mass. The stiffness of the panel affects its ability to resist deformation when subjected to an external force. A panel with high stiffness resists deformation more than a panel with low stiffness, resulting in a higher natural frequency. This can be found in Equation 3 as well. Additionally, as can be seen in Equation 6, increasing the stiffness of a panel decreases its critical frequency. Therefore, when a panel has high stiffness, it can reduce the frequency range between resonance and coincidence, which can negatively impact the sound transmission loss curve (Ginn et al., 1987).

However, it is not possible generally to reduce the stiffness of an existing element. Occasionally the impact of the stiffness may be mitigated by increasing the damping of the element. Damping affects mostly the resonance and coincidence dips. Higher damping can reduce the magnitude of the dips in the sound transmission loss curve. These dips affect the overall acoustic performance of the panel, which means the smoother the transmission loss curve, the higher the overall acoustic performance of the panel as shown in Figure 1 (Ginn et al., 1987). In the frequency range where the mass law applies, there is essentially little impact of damping on the sound transmission loss (Ginn et al., 1987).

2.3. The transmission loss of windows

The theory of sound transmission loss in a thin single panel has been discussed. The aim of this section is to apply the understanding of sound transmission loss from a single thin panel to windows. This necessitates focusing on the unique characteristics of window assemblies and their impact on sound transmission loss. Some of the important considerations regarding windows, in the context of sound transmission loss, are as follows: Firstly, the glass panels exhibit significant stiffness with a limited range; secondly, windows typically have restricted dimensions, leading to deviations from mass law principles; thirdly, the interleaf spacing within windows is confined; additionally, the use of absorptive materials is mainly restricted to the perimeter of the interleaf cavity, while the presence of baffle and niche effect also has an impact on the sound transmission loss in windows. Numerous research efforts have been undertaken to understand and specifically predict window transmission loss (Quirt, 1982; Quirt, 1983; Quirt, 1988). The subsequent sections explore some of the notable outcomes derived from investigations focusing on windows.

2.3.1. Single-glazed windows

Different factors can impact the sound transmission loss of a single-glazed window including properties of glass, glass thickness, window size, the frame and edge constraint. Numerous studies have been done about evaluating the acoustic performance of windows. In one study Quirt (1982) carried out a series of tests on single glazed windows with glass thicknesses of 3 mm, 4 mm, and 6 mm. In these tests, the sound transmission loss was shown to increase noticeably with increasing glass thickness at the frequencies below the coincidence dip, while the critical frequency reduced with increasing glass thickness. However, the STC rating of the single-glazed windows in this research showed much less dependency on the mass per unit area of the glass comparing it to the mass law expression. In part, this may be explained by the decrease in the critical frequency with raising the mass per unit area of the glass, so that for heavier glass the coincidence dip has a greater effect within the frequency range affecting the STC rating. However, even at frequencies appreciably below critical frequency, the change in the sound transmission loss was less than 6 dB by doubling of mass per unit area of the glass. Nilsson predicted in his study a very similar reduced dependence of the sound transmission loss on the mass per unit area of the glass for small panels (Quirt, 1982).

In another study by Maraqa et al. (2018), the sound transmission loss of twenty-one different windows was investigated. This research indicated that in single-glazed windows, changes in glass thickness had a small effect on the sound transmission loss and the changes in the sound transmission loss were less than what was predicted by mass law. Also, changing the glass thickness had a negligible effect on the STC ratings (Maraqa et al., 2018).

Similar results were obtained by Tadeu et al. (2001) in their experiments of the effect of the glass thickness on the sound transmission loss in windows. In their experimental evaluation of sound transmission loss of single, double and triple-glazed, they used a simplified analytical model that could predict the sound transmission in the windows using mass law and sound reduction index and they compared the results of these theoretical models with laboratory test measurements. They found out that the sound transmission loss at a lower frequency usually is higher than the calculated transmission loss obtained by the mass law. They also observed that the measured sound transmission loss dropped dramatically below mass law prediction at higher frequencies around the coincident dip (Tadeu et al., 2001).

The transmission loss of a single-glazed window can be improved by increasing the mass of the glass; however, this solution has limitations considering the cost, space and structural issues. To tackle these problems, one approach to achieve better sound transmission loss in windows is to add another layer of glass.

2.3.2. Double-glazed windows

When higher insulation is needed, using double-glazed windows is one method employed for increasing sound transmission loss through a building envelope. In double-glazed windows, there are two layers of glass separated by an air gap which may be filled with air, argon or krypton. When sound waves propagate through the window, they can interact with the glass panes and the air in between them, leading to different types of resonances and transmission loss effects (Ginn, 1987).

Two significant factors that contribute to decreases in the sound transmission loss in double-glazed windows are the resonance frequency of the mass-air-mass system and the critical frequencies associated with each individual pane of glass (Hopkins, 2007). These frequencies are caused two noticeable dips in the sound transmission loss curves of the double-glazed windows. At the frequencies below the mass-air-mass resonance frequency, the two glasses of the window with the mass per unit area of m_1 and m_2 can be treated as a single glass with a mass per unit area of m=m_1+m_2 (Fahy, 1987). In these frequencies, damping has a negligible effect on the transmission loss.

The mass-air-mass resonance happens when the leaves of the panel are linked by the spring produced by the air in the cavity. At this frequency, a sharp drop in the transmission loss curve can be detected. Therefore, the mass-air-mass resonance can have a significant effect on the sound transmission loss of the whole assembly. The overall acoustic performance of double-glazed windows improves as their mass-air-mass resonance frequency is sufficiently low (Ginn, 1987). Quirt (1982) in his study about the double-glazed windows pointed out that Equation 7 can be used theoretically to predict the mass-air-mass resonance frequency.

$$f_{mam} = \frac{1}{2\pi}(\rho_o c^2)^{1/2}\left(\frac{m_1+m_2}{m_1 m_2 d}\right)^{1/2} \qquad \textit{(Eq. 7)}$$

where m_1 and m_2 are mass per unit area of each panel, d is the interpane spacing, ρ_o is the density of air and c is the speed of air.

Increasing the mass per unit area of each glass pane, increasing the width of the cavity and using glass panes of same weights are among the solutions to reduce this frequency.

The amount of reduction in sound transmission at mass-air-mass resonance frequency in the sound transmission loss curve of a double-glazed window, is damping dependence

(Fahy, 1987). The depth of the mass-air-mass resonance dip can increase by using the square shape IGU with identical width and height even when the glass panes are not the same thickness or one glass pane is laminated. Mass-air-mass resonance frequency and the depth of its dip can also be affected by the dimension of the window (Hopkins, 2007). The mass-air-mass resonance frequency is angle dependent and this phenomenon exists for any angle of incidence (Fahy, 2007).

Figure 2 depicts the mass-air-mass resonance frequency of a double panel with the panes having equal mass per unit area. This figure shows the dependency of the mass-air-mass resonance frequency with the cavity depth and the mass per unit area of the panes of glass (Hopkins, 2007).

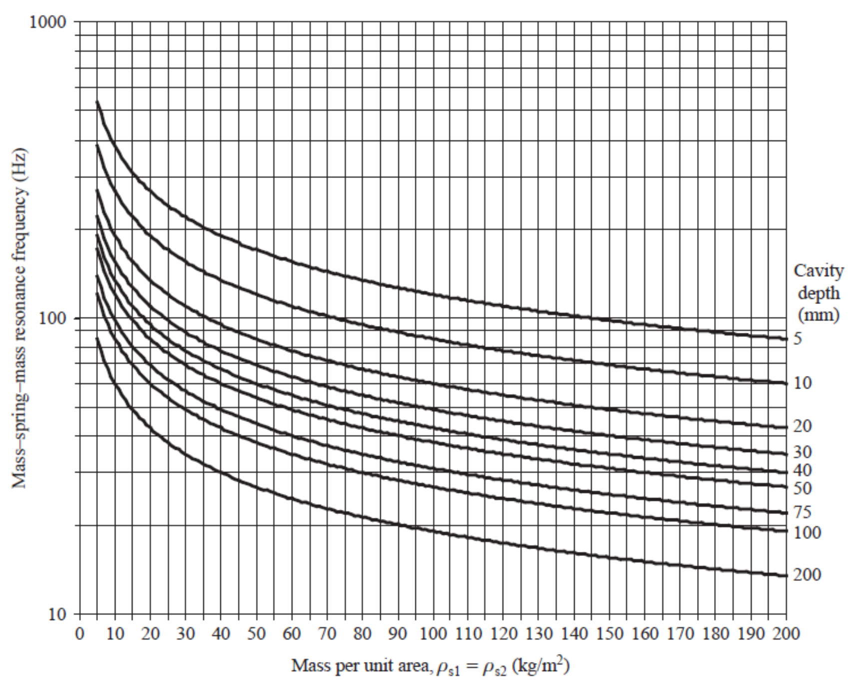


Figure 2. Mass–spring–mass resonance frequencies for a plate–cavity–plate system where the cavity is filled with air, and both plates have the same mass per unit area (Hopkins, 2007)

When the frequency of the incident sound is higher than the resonance frequency, the sound transmission loss of a double-glazed window increases at a faster rate than it would for a single glass of the same weight. For N separate panels, the ideal theoretical transmission loss goes up by 6(2N-1) dB for each octave (Long, 2006). However, within the frequency range between mass-air-mass resonance and critical frequency, cavity resonances can lower the transmission loss (Ginn, 1978). Adding absorptive material to cover the surface of the frame around the perimeter of the cavity can reduce the negative effect of these frequencies (Quirt,1988). Therefore, within this frequency range, the sound transmission loss can be greatly affected by the spacer and sealant used. This is because of how they impact structural coupling around the edge of the panes (Hopkins, 2007). However, if there are openings or cracks around the frame of a window that can be opened, any benefit from choosing a unit with low structural coupling can be lost. These openings usually lower sound transmission loss in mid and high frequency ranges (Hopkins, 2007). Using sulphur hexafluoride gas instead of air can increase the sound transmission loss of double and triple-glazed windows between the mass-air-mass resonance frequency and critical frequency. This is because this gas has a slower phase velocity and is denser (Hopkins, 2007). Figure 3 depicted an example of the effect of different gas fills in an IGU.

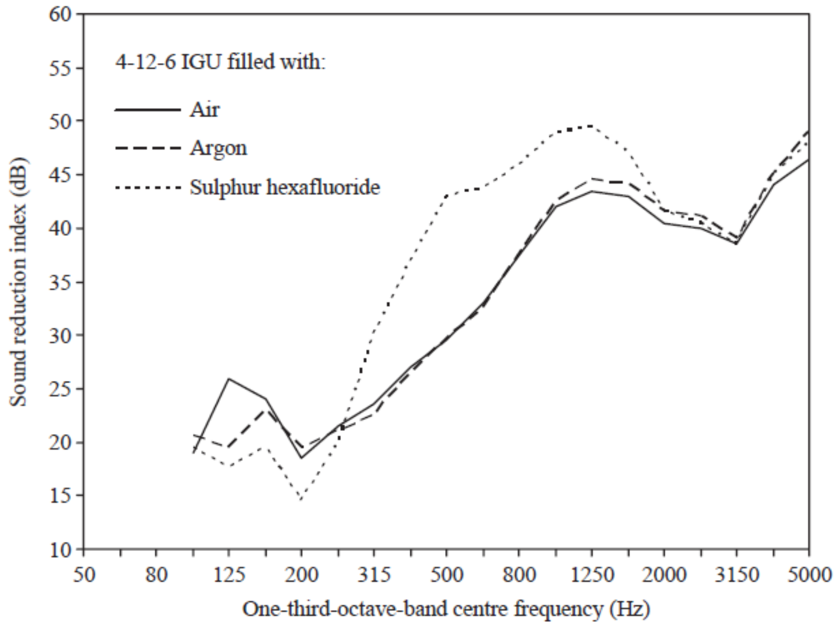


Figure 3. Effect of using different gases on the sound transmission loss of an IGU (Hopkins 2007)

At coincidence frequency another dip in the sound transmission loss curves of double-glazed windows can be observed. The coincidence resonance happens for each glass pane of the window and is independent of glass pane distances. However, the mass per unit area of each glass pane and damping can significantly affect the coincidence dip.

One common strategy employed to control the coincidence dip is to ensure that the panes in an insulated glass unit have varying thicknesses. This approach aims to avoid the occurrence of a single, excessively deep critical frequency dip. Research by Hopkins (2007) found that using panes with identical thicknesses often leads to a noticeable dip at the critical frequency. By introducing differing thicknesses, two shallower critical frequency dips can be achieved, improving sound insulation significantly. An ideal thickness ratio of approximately 2, as suggested by Quirt, 1988, maximizes this effectiveness. In double-glazed windows like single-glazed windows, sound transmission loss also depends a lot on damping when the sound frequency is near or above the coincidence frequency. Employing one laminate and one non-laminate pane can be advantageous, as the higher internal damping of the laminate glass contributes positively to mitigating critical frequency dips. Damping is not just about the glass's losses; it also includes how much sound energy is absorbed by the seals around the window and how much is transmitted to the supporting structure (Quirt, 1982).

Olynyk (1968) in his study about the overall acoustic performance of double-glazed windows, suggested that the main factors determining the sound insulation of double window constructions include the similarity or dissimilarity of leaves, glazing thickness, air space depth, and sound absorption treatments (Olynyk, 1968).

2.3.3. Triple-Glazed windows

In the last decade, as the attention to the thermal insulation increased and the demand for energy saving raised, the use of triple-glazed became popular (Quirt, 1983). The general principles for triple-glazed windows are the same as those for double-glazed windows.

In triple-glazed windows, having three panes of glazing creates a mass-air-mass-air-mass system, which is pictured in Figure 4. As it can be seen, it consists of three masses and two air springs and as a result, two resonance frequencies that can be seen in Equation 8 (Long, 2006).

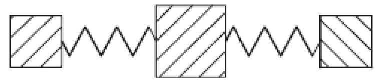


Figure 4. General model of a three pane system (Long, 2006)

$$f_{\alpha,\beta} = \frac{1}{2\pi}\sqrt{3.6\rho_0 c_0^2}\sqrt{a \pm \sqrt{a^2 - b}}\ (f_\beta > f_\alpha) \qquad \textit{(Eq. 8)}$$

where $a = \frac{1}{2m_2}\left(\frac{m_1+m_2}{m_1 d_1} + \frac{m_2+m_3}{m_3 d_2}\right)$, $b = \frac{M}{m_1 m_2 m_3 d_1 d_2}$ and $M = m_1 + m_2 + m_3$

Due to the mass-spring system for a triple panel, raising the middle and inner panels' mass does not have an equivalent effect on the panel's mass-spring interaction in comparison with increasing the outer glass pane’s mass in the triple-glazed window. According to Xin and Lu (2011), imbalanced masses create greater sound transmission loss if the incident sound panel is heavier. Vinokur (1996), conducted measurements that showed the same results when the incident sound panel was heavier. A comparison between triple panel and double panel partitions by Xin et al. (2011), suggests that the difference in performance of these two groups is not significant when the total masses of the two partitions are equivalent. However, the large number of system parameters in triple panel partitions provides more design flexibility for tailoring their noise reduction capabilities in triple-glazed windows. This study also mentioned that the soundproofing capability of a triple-panel partition increases as panel dimensions decrease (Xin et al., 2011).

In another research on the acoustic performance of the triple windows, Quirt (1983) found that when the total space between the glass panels in the triple-glazed matches the spacing of the double-glazed units, the results are very similar. However, the triple-glazed windows provide higher sound transmission loss at frequencies below the mass-air-mass resonance and in the vicinity of the coincidence dip (Quirt, 1983). Similar results were obtained from a study conducted by Tadeu on double and triple glazed windows (Tadeu, 2001).

2.3.4. The effect of Laminated glazing on transmission loss

Laminated glass is produced by permanently bonding two sheets of glass together using a relatively soft interlayer, such as polyvinyl butyral (PVB) or polymethyl methacrylate (PMM). This type of glass offers several advantages, including high damping achieved by constraining an interlayer between two plates and a reduction in bending stiffness compared to solid plates. The internal loss factor (the ratio of the energy dissipated by the material to the total energy passing through it) of a laminate plate is also high due to energy losses associated with shear deformation of the interlayer, which makes it useful for attenuating bending wave motion. However, the material properties of laminate glasses are more complex compared to solid glasses, as both the bending stiffness and the internal loss factor vary with frequency and temperature. As a result, it is more reliable to measure these properties rather than attempting to predict them based on the individual properties of the interlayer and plates (Hopkins C., 2007).

Quirt (1982) likewise found that laminated glass can provide much higher transmission loss than solid glass, however, as damping is temperature dependent, the amount of transmission loss is not consistent throughout the year Quirt (1982). In another study by Yoshimura and Kanazawa (1984), the effect of temperature on laminated glass was examined and the experimental results were compared with theoretical results. The experimental results showed that by raising the temperature the transmission loss does not change dramatically except around coincident frequency (Yoshimura and Kanazawa,1984).

In a study by Sun et al. (2006) four different types of laminated glass samples were designed and tested using analytical and experimental approaches. The sound transmission loss of laminated glass was investigated. The results showed that laminated glass provides a significant improvement in sound transmission loss compared to monolithic glass, due to the damping properties of the PVB interlayer. The study also found that the sound transmission loss of laminated glass is affected by the thickness of the glass and the PVB layers and the density of the PVB interlayer. The study showed the sound transmission loss increases when the polymer has a higher density (Sun et al., 2006).

Maraqa et al. (2018) found that the use of laminated glass significantly reduced sound transmission through the window compared to nonlaminated glass. Specifically, the use of double-glazed with a laminated glass layer resulted in a better reduction in sound transmission for higher frequencies. The results of this study suggest that the use of laminated glass can be an effective strategy for reducing sound transmission through windows in urban environments (Maraqa et al., 2018).

Compared to a single pane of glass with the same thickness, laminate glass offers several advantages. Firstly, it shifts the critical frequency to a higher frequency while reducing the depth of the critical frequency dip due to its higher damping capabilities. Placing the laminate pane in an insulated glass unit on the side with the higher temperature can help maximize its internal losses at higher temperatures. This consideration depends on the climate and could be indoors or outdoors. Temperature effects for a single pane of laminate glass are especially significant near, at, and above the critical frequency. Therefore, it is important to keep this in mind when comparing measured sound insulation data from the laboratory and the field, as well as when making comparisons between measurements on different laminates (Hopkins C., 2007).

2.3.5. The Effect of temperature on the transmission loss of windows

According to Konstantinov et al. (2020), Polyvinyl Chloride (PVC) windows are subject to temperature deformations due to the temperature difference between outdoor and indoor air, which can affect their sound insulation performance. It was found that the sound insulation of PVC windows starts to deteriorate only when the outside temperature falls below 0 °C. At -20°C outside, the sound transmission loss of a PVC window is 3 dB lower than the sound transmission loss of the same window measured under typical circumstances (+20 °C). The reduction in sound insulation at negative outdoor temperatures is attributed to the reduction of the tightness of the flaps joining the window frame due to temperature deformations of window profiles and the reduction of the elasticity of window seals. These findings suggest that the tightness of PVC windows diminishes as a consequence of temperature deformations of profiles, and as a result, the acoustic performance of these windows decreases (Konstantinov et al., 2020).

The temperature has also an effect on the airtightness of the windows. Miskinis et al. (2019) investigated the sound, thermal, and air tightness properties of typical wooden windows used in Baltic and Scandinavian countries. The authors conducted laboratory tests to determine the sound transmission loss, thermal transmittance, and air permeability of the windows. The study aimed to assess whether airtight wooden windows in these regions always possess good acoustic and thermal properties. The results showed that the air permeability of the windows had a significant impact on both their acoustic and thermal properties. The study also revealed that the thermal insulation and acoustic performance of wooden windows were not necessarily related. The authors concluded that the airtightness of wooden windows should be taken into consideration when designing buildings in these regions, to achieve optimal acoustic and thermal performance (Miskinis et al., 2019).

2.3.6. The Effect of frame of a window on its sound transmission loss

Tadeu and Mateus (2000) that window frames can notably affect the sound insulation of buildings. found that the sound insulation performance of window frames is influenced by factors such as their material, shape, and size. In particular, the use of metal frames was found to reduce the sound insulation performance, while the use of PVC frames was found to improve it (Tadeu & Mateus, 2000). Bradley and Birta (2000) observed consistent results in their study while comparing the acoustic capabilities of casement windows with sliding windows. According to their findings, casement windows demonstrated superior sound transmission loss (Bradley & Birta, 2000).

2.3.7. The effect of airtightness in windows on the transmission loss of the windows

Regarding the effect of airtightness Park and Kim (2015) in their study, investigated the effect of window frame airtightness on acoustic properties. The authors installed airtight structure reinforcements to an existing window frame to decrease the Air Changes per Hour (ACH) of the window, which resulted in measurable improvement in acoustic performance. The authors suggested that this approach could be applied to passive house installations, as these aim for greater airtightness and should therefore have better sound reduction than traditional installations. The study demonstrates that increasing the airtightness of window frames can lead to improved acoustic properties (Park & Kim, 2015).

2.4. Problem statement, scope and hypothesis

In the early stages of research for any new window product, it is desirable to have a more accessible and cost-effective test method to evaluate the acoustic performance of different products. Tests such as the ASTM E90 are better suited for use in the advanced stages of research and development due to their high cost and low accessibility. Consequently, window manufacturers need reliable substitute test methods in their early stages of research and development, when they need to run multiple tests.

This research explored an alternative field-lab technique, referred to as the BCIT Hybrid Test Method, which combined the ASTM E966 and the ISO 15186-1 standards for use in product development. The study evaluated the acoustic performance of windows using the BCIT Hybrid Test Method to investigate whether this method could accurately detect changes in the frame or the glazing system of the test windows. The results from the BCIT Hybrid Test Method were evaluated in accordance with the theoretical predictions discussed in the literature review of this thesis.

The BCIT Hybrid Test Method approach has the advantage of using an intensity probe and consequently is capable of investigating windows and their acoustic performance in a more detailed manner. This method allows for the assessment of various factors such as glass pane thickness, air cavity depth, laminated glasses, and the effect of symmetrical glazing on mass-air-mass resonance frequency, critical frequency, and the depth of these dips in the sound transmission loss curves of the tested windows.

The hypothesis of this research was that the BCIT Hybrid Test Method could provide a reliable, cost-effective, and accessible means of assessing the acoustic performance of windows in the early stages of product development. The method was expected to accurately identify alterations in the frame or the glazing system of the test windows, providing valuable insights for manufacturers.

The scope of this research was limited to the evaluation of the BCIT Hybrid Test Method using sample windows donated by Centra Manufacturers. The measurements were carried out in two phases, with each phase involving a different series of windows. The results from these measurements were then compared with the theoretical predictions to validate the BCIT Hybrid Test Method.

The insights gained from this phase were instrumental in shaping the second phase of the research, where the remaining test windows from Centra 2600 series with the same size and configuration from the window test of the first phase, underwent testing using the same methodology and procedure as the first phase. The objective was to compare the results of these windows to understand the effect of different glazing systems and also to investigate the effect of using foam insulated profiles on the sound transmission loss of the windows. This method potentially allows for a more comprehensive understanding of the impact of various factors on the sound insulation performance of windows, paving the way for more efficient and effective window designs in the future.

3. The BCIT Hybrid Test Method Procedure

For this study, a modified version of the BCIT Hybrid Test Method was used. This method was originally developed in 2017 as part of a Master of Applied Science (MaSc) and a Master of Engineering (MEng) research project (Tamanna, 2017; Stehling, 2017). It combines two different standard methods of calculating the sound transmission loss for a building specimen. Specifically, it follows the guidelines of the Flush method in the ASTM E966 (2011) standard for measuring the outside sound pressure level, and in the receiving section, it adheres to the ISO 15816-1 (2016) standard for measuring sound intensity level. The method has been revised in this study to enable a comparison of the test results with those achieved by the ASTM E90 test method. A visual representation of this test method can be found in Figure 5.

The ASTM E966 standard is a method for conducting field measurements of airborne sound attenuation, specifically designed for building facades and facade elements. The ASTM E966 standard includes six different measurement prosedures, each tailored for different outdoor incident sound fields. The flush microphone method is the method employed in this thesis. This standard calculates the outdoor-indoor noise reduction (OINR), which is the difference in sound pressure level between the free-field level outdoors, without the structure, and the resulting sound pressure level inside a room. In controlled circumstances, this standard can measure the outdoor-indoor transmission loss for a single facade element, such as a window. For accurate results, the test element should have a significantly lower transmission loss than the rest of the facade. Also, a loudspeaker should be employed as the noise source for these tests. The results derived from this method depend on the angle of incidence of the sound field. However, by taking measurements at various angles of incidence and averaging the energy of the results, an approximation of the diffuse field transmission loss, as measured between two rooms, can be achieved. Figure 5 provides a schematic depiction of this standard test method. In this standard test method, the receiving room must form an enclosed space with hard wall, ceiling, and floor surfaces and deffusing objects, and have a volume of at least 40 m^3 for outdoor-indoor transmission loss (OITL) measurements. The room sound absorption should be measured and must not exceed a certain limit, which depends on the room volume and the type of measurement.

The ISO 15186-1 standard is a test method for laboratory measurement of airborne transmission loss of building partitions and elements by using sound intensity. In this test method, the sound power radiated by the test specimen is measured directly by the use of an intensity probe with the scanning method or discrete point method. One advantage of this standard test method is that the receiving room in this method can be any room meeting the requirements of the field indicator; the difference between the sound pressure level, L_p, and the normal sound intensity level, L_{In}, on the measurement surface, both being time and surface averaged that should be less than 10 dB for each one-third octave band, and the background noise that should be at least 10 dB less than both the measured sound pressure level and sound intensity level. However, the sound source space and the test opening should follow the same criteria as per standard ISO 140-1. This test method needs a deffused field in the receiving side. The schematic representation of this standard test method is illustrated in Figure 5.

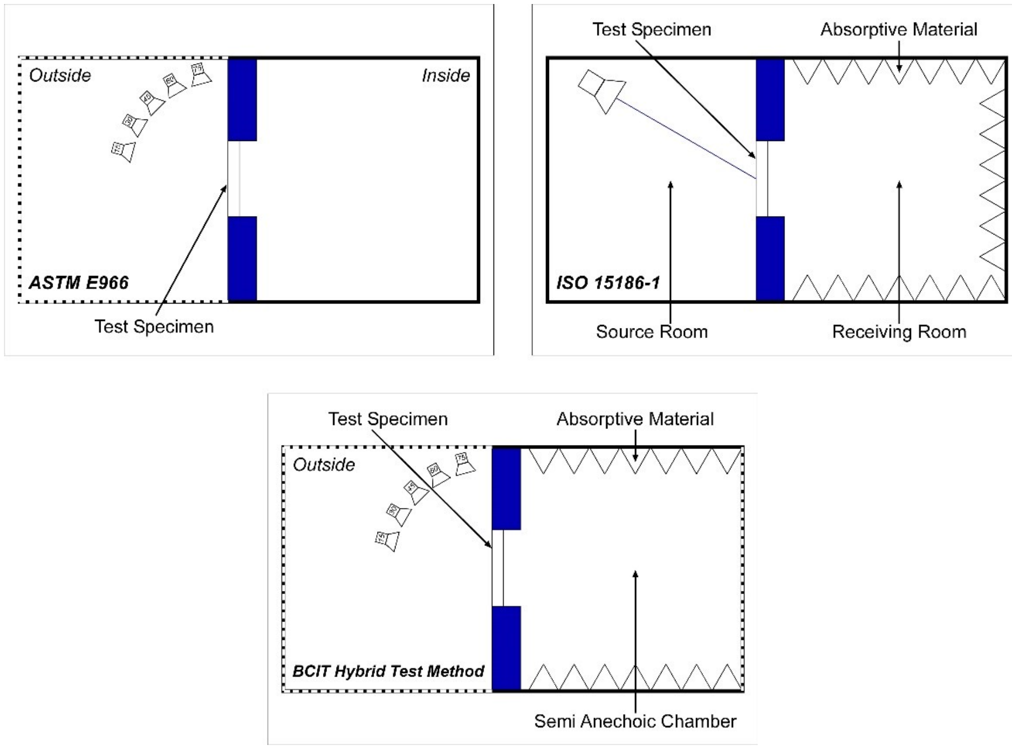


Figure 5. Schematic Representation of the BCIT Hybrid Test Method Applying ASTM E966 and ISO 15186-1 Standards

Some fundamental steps should be taken to use this method properly. One step is related to preparing the intensity probe by warming up the instrument, calibrating of probe, examining the probe’s functionality and selecting the correct measurement surface. The explanation of these preparations can be found in Section 3.2.

By employing the ASTM E966 standard method for the exterior side measurements of this study, outside environment was used as the source side with a loudspeaker. Also, using the ISO 15186-1 standard method for the interior side measurements in this study, gave the BCIT Hybrid Test Method the advantage of restricting the receiving side requirements to the interior background noise and the field indicator. In the subsequent sections, a detailed explanation of the BCIT Hybrid Test Method will be presented, which was divided into two primary categories based on measurements taken externally and internally.

In Figure 6, a schematic layout plan view was provided, depicting the test wall, window specimen, partitions, and the exit door situated near the test wall. It is important to highlight that the measurements for this study were exclusively carried out on the test windows and not for the test wall.

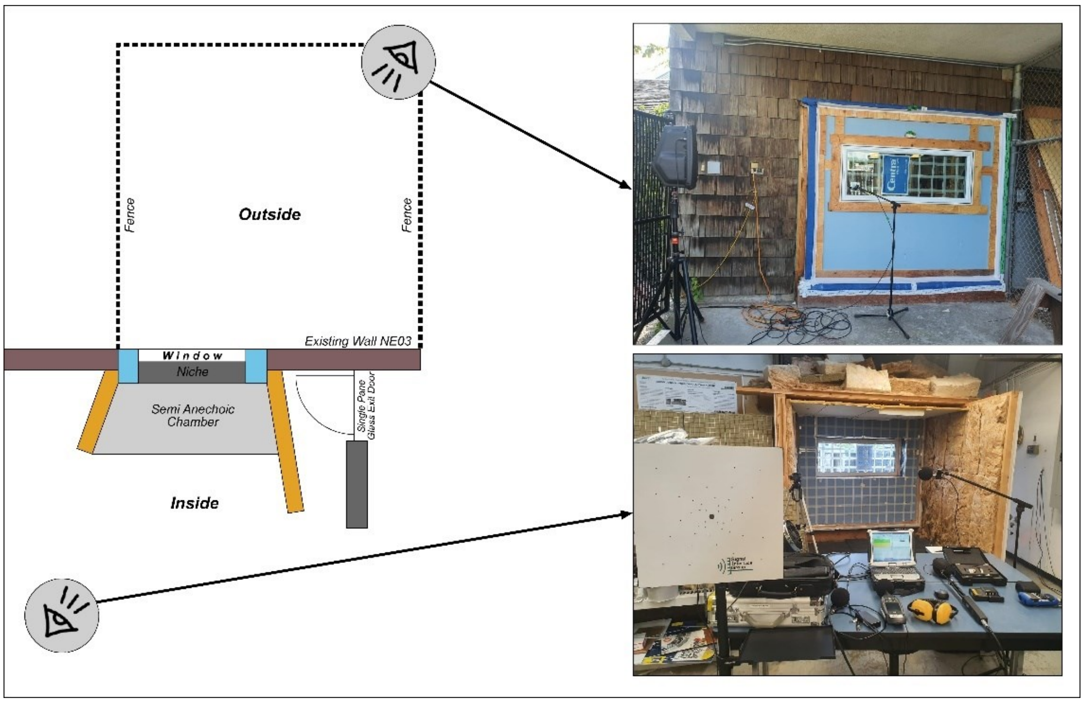


Figure 6. Test Wall and Surrounding Elements

The test windows were mounted on a test wall which was a part of the exterior envelope of the Centre for Architectural Ecology building of the British Columbia Institute of Technology. As depicted in Figure 7, to isolate the test wall from its opening and to reduce the flanking paths, resilient materials were employed.

Figure 7. Resilient materials over the plate (Stehling, 2017)

On the interior side of the wall as depicted in Figure 8, a partial enclosure was constructed, consisting of two side partitions and a ceiling. This enclosure was designed to reduce extraneous noise and reflections, apart from the testing source itself. To ensure a more reliable analysis and facilitate effective comparisons of measurement results between different window samples, the study made efforts to maintain consistency in various variables. These variables included window sizes, window types, installation methods, and the equipment used for measurements. By controlling these variables, the study sought to increase the confidence level in comparing sound transmission loss data obtained from the various test windows conducted throughout the research.

Figure 8. Interior Partial Enclosure for Noise Reduction and Reflection Control

3.1. Measurement of outdoor sound pressure level

When measurements were conducted to determine the external sound pressure level of windows using the BCIT Hybrid Test Method, the factors that are outlined in the ASTM E966 (2011) were considered. These factors included outside background noise, the characteristics of loudspeaker sound emission, sound incidence angles, the ratio of the distance between the noise source and the nearest and furthest parts of the test surface, measurement duration, and the designated measurement points across the window's surface. In the following sections, detailed information about each of these factors will be provided and discussed.

3.1.1. Loud speaker position

To measure the external sound pressure level, a single loudspeaker, compliant with the ASTM E966 (2011) standard, was employed. Verification of the loudspeaker's directional characteristics at 2000 Hz occurred before each set of measurements was conducted in this thesis. Testing was carried out to ensure that, at the frequency of 2,000 Hz, the radiated sound pressure level did not exceed a 6 dB deviation from the on-axis sound pressure level up to an off-axis angle of 45 degrees.

To conduct outdoor tests, the ASTM E966 (2011) stipulates that the loudspeaker must be directed towards the window at five distinct angles relative to the vertical plane perpendicular to the window's center. These angles are 15, 30, 45, 60, and 75 degrees, as illustrated in Figure 9, following the standard guidelines. In this thesis, these positions are evenly spaced on a circular path around the window's center, maintaining a distance of 210 cm from the window's center. During the testing of various windows, the position of the external sound source remained constant for each test and for each direction of sound incidence.

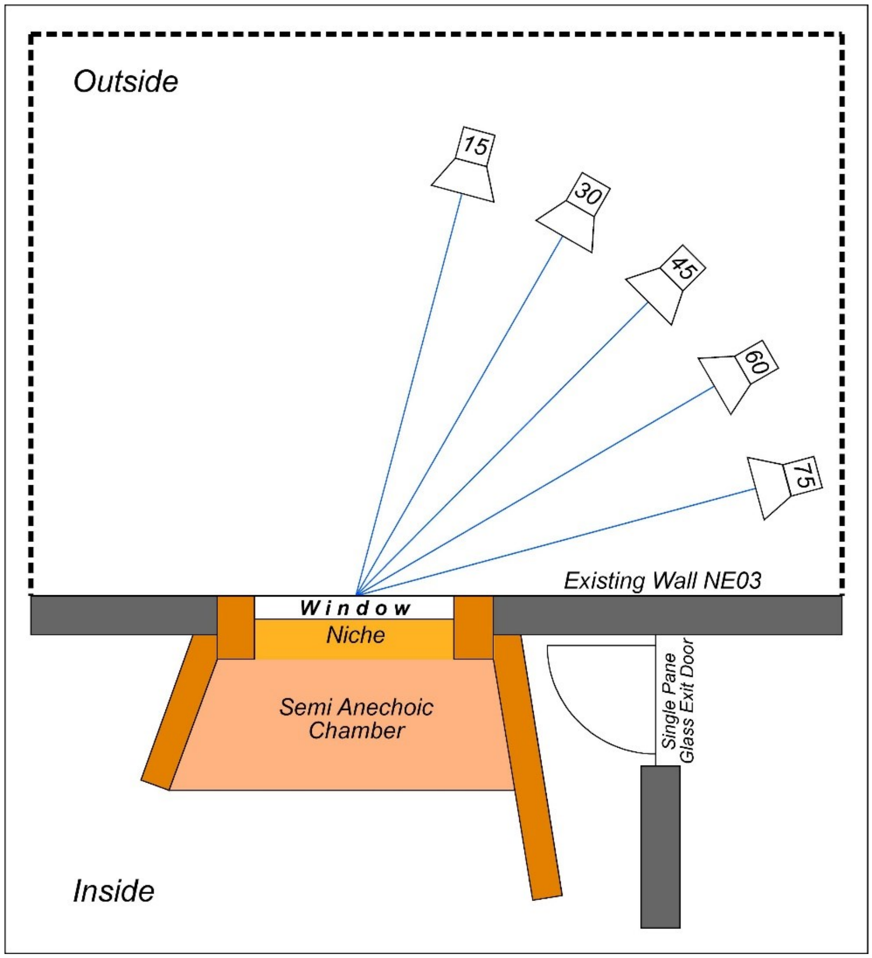


Figure 9. Loudspeaker positions for outdoor measurements

To ensure minimal sound pressure variation across the specimen exterior surface, the loudspeaker's axis was directed towards the center of the window and positioned in the vertical plane through the center of the window, perpendicular to it. In addition to this criterion, another factor was considered in determining the loudspeaker's position for the evaluation of the exterior part of the window: the ratio of the distances between the center of the loudspeaker and the farthest and nearest parts of the test surface. Figure 10 shows the longer and shorter distances, represented by A and B, respectively. As per the ASTM E966 (2011), each loudspeaker position should have a ratio of B to A is less than 2. Table 1 presents these dimensions and information about the loudspeaker's distance from the window's center in the measurements of this thesis. With the exception of the 75-degree position, the mentioned ratio was less than 2 for all loudspeaker locations. For the 75-degree position, however, this ratio was 2.17, which is still close to 2. In Table 1 the position of the loudspeaker (X, Y and Z) is measured according to Figure 11 based on Figure 3 of the ASTM E966 (2011) standard.

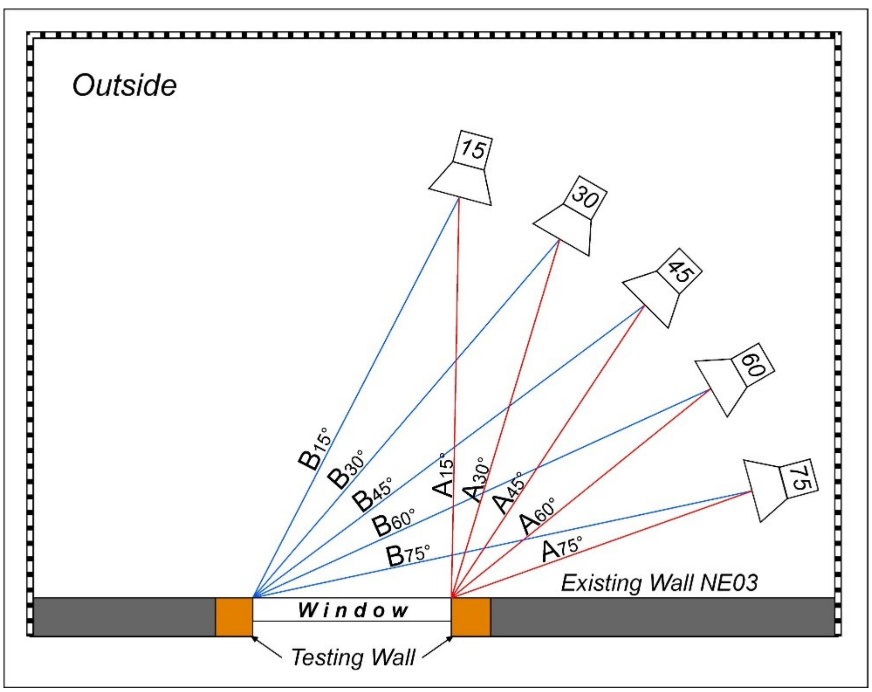


Figure 10. Various positions of the speaker

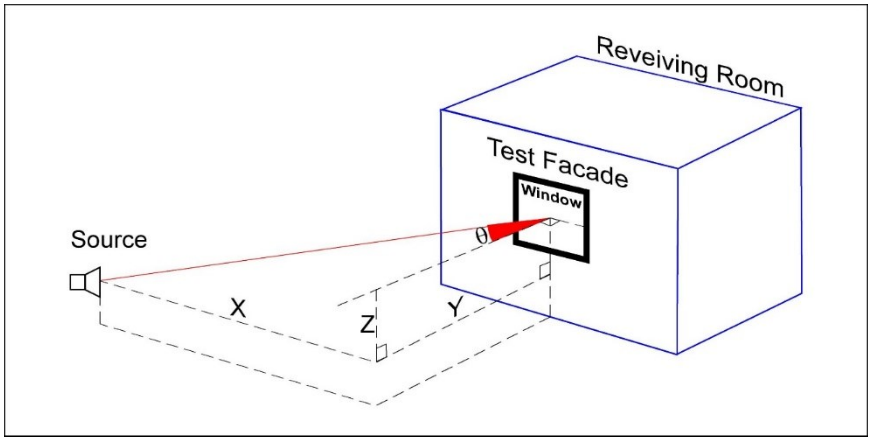


Figure 11. The geometry of the loudspeaker from the center of the window

Angle	15	30	45	60	75
X	54.35	104.6	118.5	181.5	209.5
Y	209.9	181.9	148.5	105	54.3
Z	0	0	0	0	0
A	204.6	183.3	162.9	145.2	132.9
B	244.1	260.5	273.7	283.5	289.5
B/A	1.2	1.4	1.7	2	2.17

Table 1. Details of Loudspeaker Positions at Various Angles

3.1.2. Microphone positions

To measure the sound pressure level incident on the outside surface of the window, a small condenser microphone, with a diameter of 12.5 mm (1/2”), was positioned parallel to the window surface. The microphone was mounted close to the specimen surface, but not so close that it would obstruct airflow through the microphone grille or touch the surface. A thin windscreen, with a thickness of 1.5 mm, covered the end of the microphone. To comply with the referenced standard for the exterior measurements, days with clear weather with no precipitation or significant winds were selected for the time of performing all the tests.

As illustrated in Figure 12, the entire diaphragm of the microphone was positioned within 17 mm of the glass surface, in accordance with the flush method described in the ASTM E966 (2011) standard.

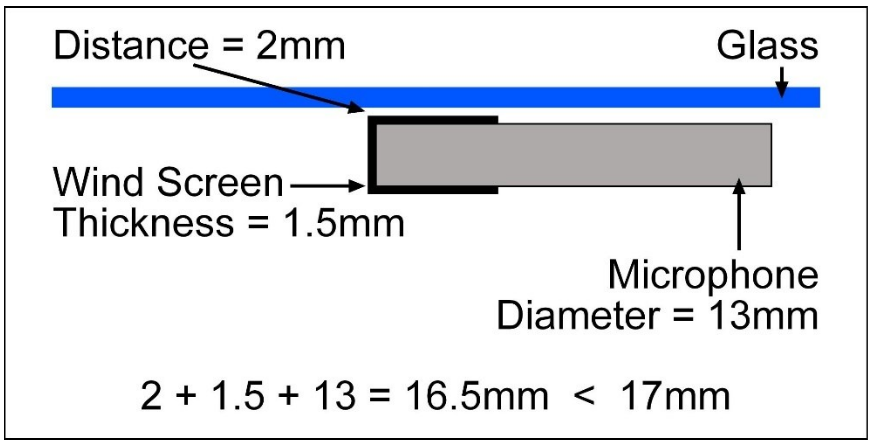


Figure 12. Position of the microphone versus the glazing

Placing the microphone so close to the surface of the specimen for measuring sound pressure level increases the sound pressure on the specimen by a factor of two, as described in the ASTM E996 (2011). In practice, this effect has been found to result in a 5 dB increase (the ASTM E966, 2011). This increase has been considered in calculating the sound transmission loss of the windows in the BCIT Hybrid Test Method. The microphone was connected to a sound analyzer software; Samurai, a Windows program that performs measurement and analysis functions, to receive and analyze the data recorded by the microphone. According to Figure 13, the microphone was placed at the center and 4 other locations on the outside surface of the specimen near the corners of the glazing for each position of the loudspeaker.

Figure 13. The 5 different Positions of the microphone for measuring the outside noise level

The sound pressure level was measured sequentially for each of these five positions of the microphone depicted in Figure 13. The duration of each measurement was 30 seconds. This step then was repeated for each position of the loudspeaker with the same procedure. It should be mentioned that the method applied in this thesis for measuring the sound pressure level (measuring the sound pressure level of each point of the window sequentially), was a departure from the ASTM E966 (2011) standard as the recommended method in the referenced standard is to do the measurements simultaneously.

3.1.3. Calculation of Outside Sound Pressure Levels

To calculate the average outside sound pressure level for each speaker position, Equation 9 was used, keeping the loudspeaker fixed for all microphone locations.

$$L_{p,average} = 10\log\left(\frac{1}{n}\sum_{i=1}^{n} 10^{L_{Pmic(i)}/10}\right) \qquad \textit{(Eq. 9)}$$

where L_p is the averaged outside sound pressure level for each speaker position, $L_{Pmic(i)}$ is the sound pressure level at the i_{th} microphone position and n is the number of microphone locations.

The same equation and procedure were applied to each speaker position by moving the loudspeaker and repeating the measurements. This way, the corresponding L_p was obtained for each speaker position. Figure 14 depicted the calculated sound pressure level for each loudspeaker position for window test 5.

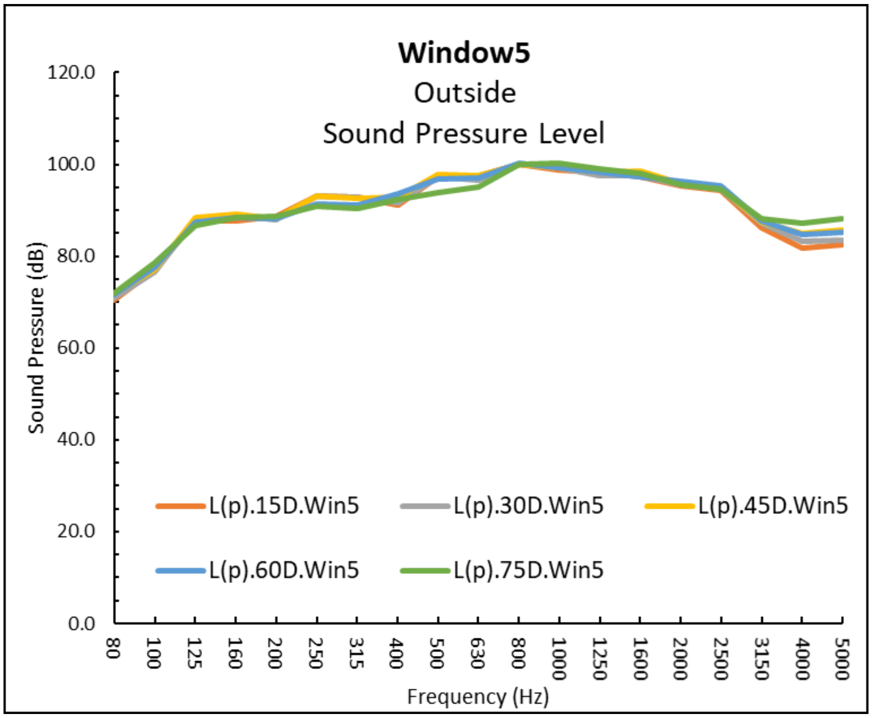


Figure 14. Measurement of the exterior sound pressure level for Window test 5

3.1.4. Measuring and evaluating the outside background noise level

To compare the measured sound pressure level at each microphone position on the outside surface of the window with the corresponding outside background noise level, another assessment was conducted on the exterior measurements. The outside background noise level was measured when the loudspeaker was off for each microphone position. The duration of these measurements was 60 seconds. Then, the sound pressure level was measured at the same microphone position when the loudspeaker was on. The average sound pressure level for the background noise was calculated using Equation 9. The difference between the average sound pressure level for background noise and for the average sound pressure level when the loudspeaker was on for each one-third octave band was calculated. The standard recommendation for this difference is a minimum 10 dB for each one-third octave band. This procedure was repeated for each loudspeaker position. Figure 15 shows the difference between the average background noise and the average sound pressure level for each one-third octave band, for each loudspeaker position in accordance with the window test 5. This figure showed that the background sound pressure levels were acceptably low for the use of the measurement standard.

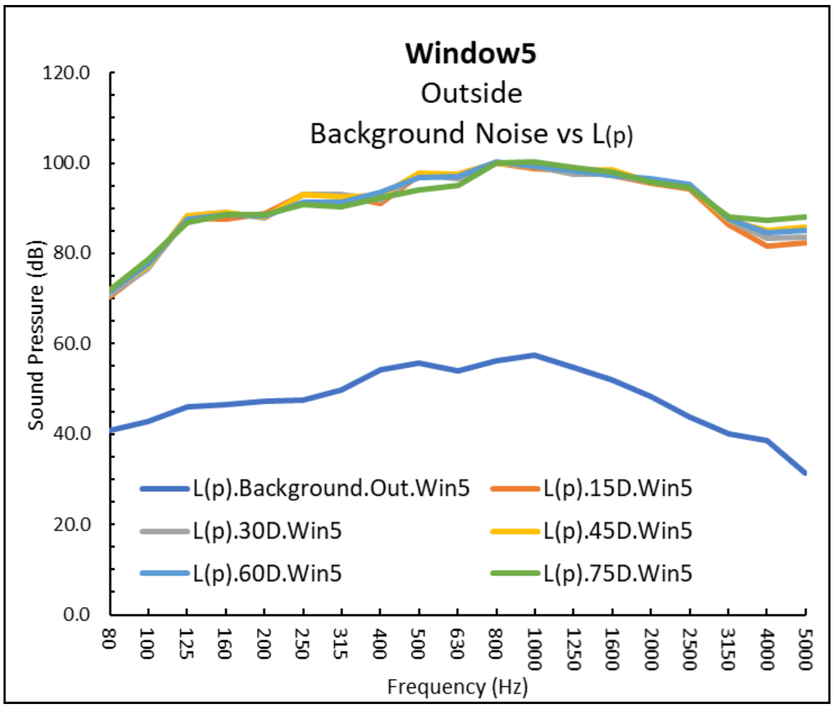


Figure 15. Verification of Sound Pressure Level Accuracy through Background Noise Calculation for window test 5

3.1.5. Qualification of the sound pressure variation for the outside surface of test windows

In accordance with section 8-2-4 of the ASTM E966 (2011) standard, a preferred sound pressure variation of 3 dB across the surface of the test specimen is recommended. To check this factor, the sound pressure level of 5 different points (four points on near the corners of the glass and one on the center of the window) on the outer surface of the window was measured sequentially when the speaker was on. In these measurements, the microphone was positioned within 17 mm distance from the surface of the window as the rest of the measurements. After doing the measurements for all positions of the microphone, the maximum and minimum amount of the measured sound pressure level for each one-third octave band were calculated. The difference of these results for one of the test windows is depicted in Figure 16. It should be noted that in most frequencies, this value exceeds 3 dB, which is a departure from the standard. Despite adjusting the speaker’s position and its direction towards the window surface during various measurements, the issue of exceeding the 3 dB value at certain frequencies, and consequently the departure from the standard, remained unresolved.

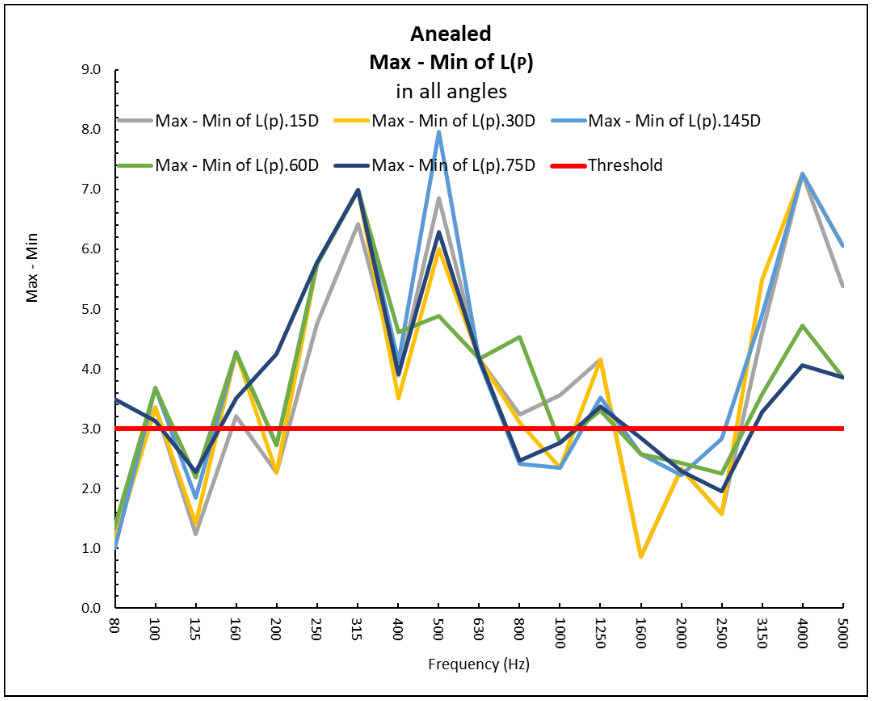


Figure 16. Difference between the maximum and minimum of Sound Pressure Levels on Window Exterior surface for BCIT Annealed window

3.2. Interior measurements

Following the initial steps of defining the average sound pressure level for the exterior surface of the window, a separate series of measurements was carried out to determine the interior sound intensity level of the window surface. The interior sound intensity levels were measured according to the ISO 15186-1 (2016) standard in this study by using an intensity probe and the scanning method was applied. In the ISO 15186-1 (2016) the source room should meet the requirements of the ISO 140-3. However, since the test element in this study was a window and the source room here, was an outdoor environment, the source room conditions and the sound defuse source room specified in the ISO 140-3 could not be satisfied in this study. Therefore, instead of the ISO 140-3 standard, the ASTM E966 (2011) standard was used in this thesis to generate the exterior sound levels. This was a departure from the ISO 15186-1 (2011) standard in the development of the BCIT Hybrid Test Method.

It is worth noting that the measurements of the interior side of test windows were not conducted simultaneously with the exterior measurements due to the available lab infrastructure, which was a departure from both standards; the ASTM E966 (2011) and the ISO 15186-1 (2016). This difference in methodology should be taken into account when interpreting the results of the study. Both of these standards require that the outside and inside measurements be taken at the same time. However, due to the limitations of the available lab equipment at the time, this was not possible.

The sound intensity level at the interior side of the window was measured using a GRAS Intensity Probe model 50 AI, following the procedures of the ISO 15186-1 (2016) standard. The probe used the P-P method and had two microphones facing each other with a spacer between them. A 12 mm spacer was used for all tests as recommended by the standard (the ISO 15186-1, 2016). To measure and record the sound intensity level in the receiving section, a software named Samurai was employed. A 4-channel sound book MK2, connected to a laptop with a Windows 7 system ran this software. Figure 17 shows a preliminary draft drawing of the arrangement and interconnection of the instruments, their positions and connections.

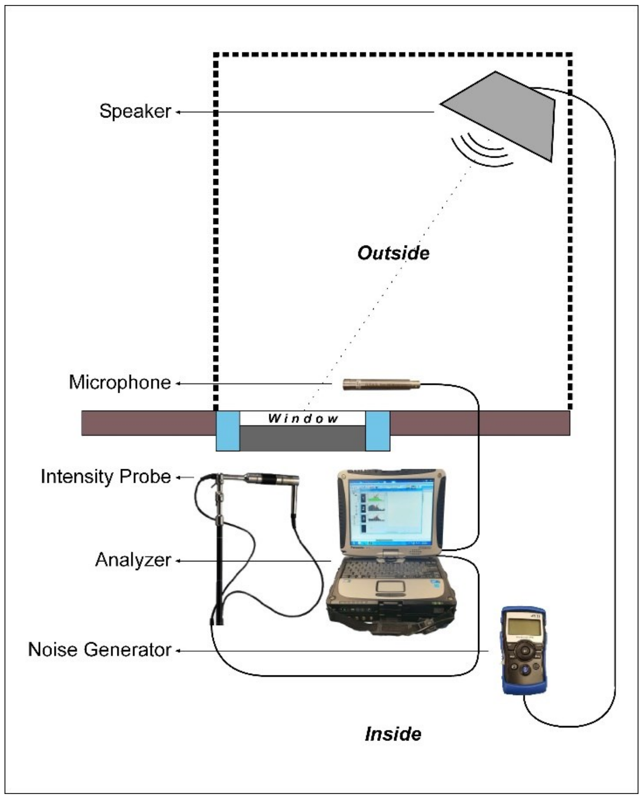


Figure 17. Draft Drawing of Instrument Placement and Interconnections

Before starting the main measurements, all the instruments were calibrated. The calibration process consisted of several steps. Firstly, the software was calibrated. Secondly, each microphone on the probe was individually calibrated using a Larson Davis CAL200 Calibrator. Finally, the probe, which comprised two microphones, was calibrated.

This final calibration involved phase calibration and pressure-residual index calibration, and a GRAS sound intensity calibrator type 51AB was employed for this purpose.

The measurement surface in this study was defined as a flat surface of the niche opening parallel to the surface of the window test from the interior side as shown in Figure 18, since in this study, the test windows were installed flush with the outside face of the wall. As the depth of the niche was 28 cm this surface was located within 0.3 m from the surface of the window, which is the requirement of ISO 15186-1 (2016). Also, the measurement surface was defined as the entire surface of the test windows as depicted in Figure 19, including the glass and the frame. This enabled a comparison of the sound transmission loss measurements from the BCIT Hybrid Test Method with the ones from the ASTM E90 standard method.

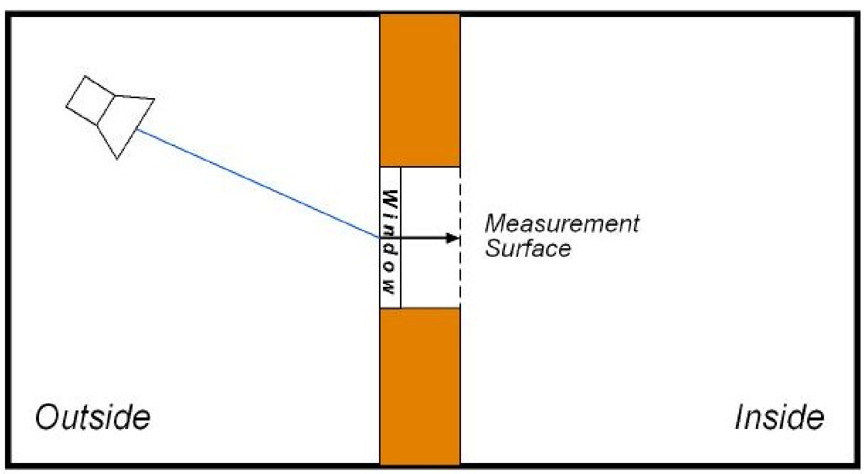


Figure 18. Single measurement surface

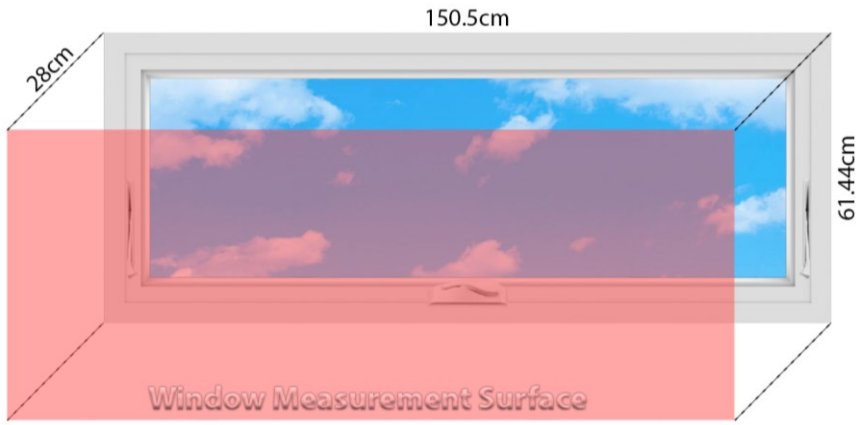


Figure 19. The whole window measurement surface

The sound intensity level on the interior surface of the window was measured when there were no microphones or other objects present on or near the exterior surface of the window. Additionally, there were no objects positioned between the window surface and the loudspeaker. These precautions were taken to ensure the accuracy of the measurements. During the measurements, two different scanning patterns were employed to measure the interior sound intensity level. These two patterns are shown in Figure 20, consisting of parallel lines with an approximate distance of 15 cm from each other.

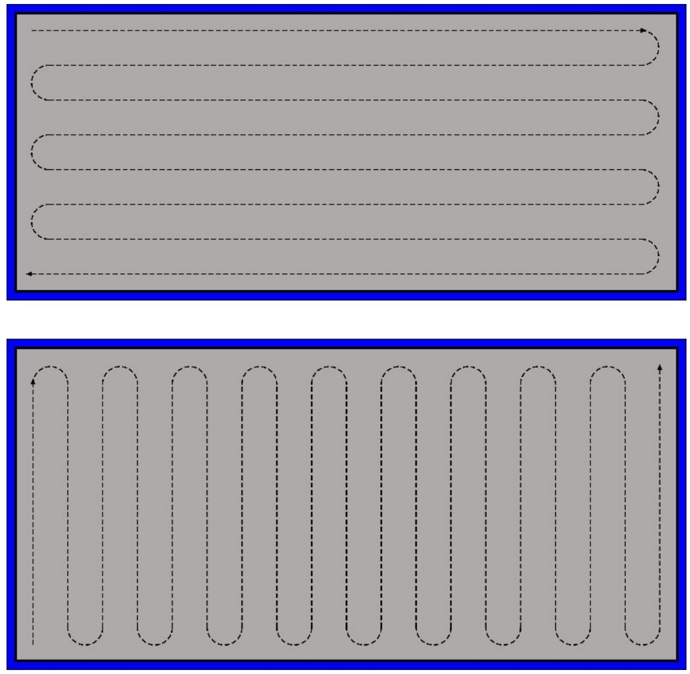


Figure 20. Two different scanning patterns used in this study

Each measurement lasted for a minimum of 30 seconds to ensure that the probe's movement speed remained below 0.2 meters per second to follow the ISO 15186-1 (2016) standard. The probe's movement along the scanning path was monitored continuously to maintain a consistent speed. The probe was always held normal to the measurement surface. The operator remained on one side of the measuring surface to avoid obstructing, reflecting, or diffracting sound towards the probe during measurements. After conducting these two orthogonal measurements, all the data related to the sound intensity level for each pair of the measurements were checked to be positive. Figure 21 depicted these measurements. Also, the difference between the two measurements was checked to ensure it was less than 1 dB for each one-third octave band as shown in Figure 22. This verification process was repeated for every loudspeaker position. If the difference between each pair of the intensity measurements for each one third-octave bands was more than

1 dB or if any data related to the sound intensity level was negative, the measurements were repeated until these measures were fulfilled to ensure an acceptable level of accuracy. If repeating the measurements could not fulfill the mentioned requirements, this was reported as a departure from the standard the ISO 15186-1 (2016).

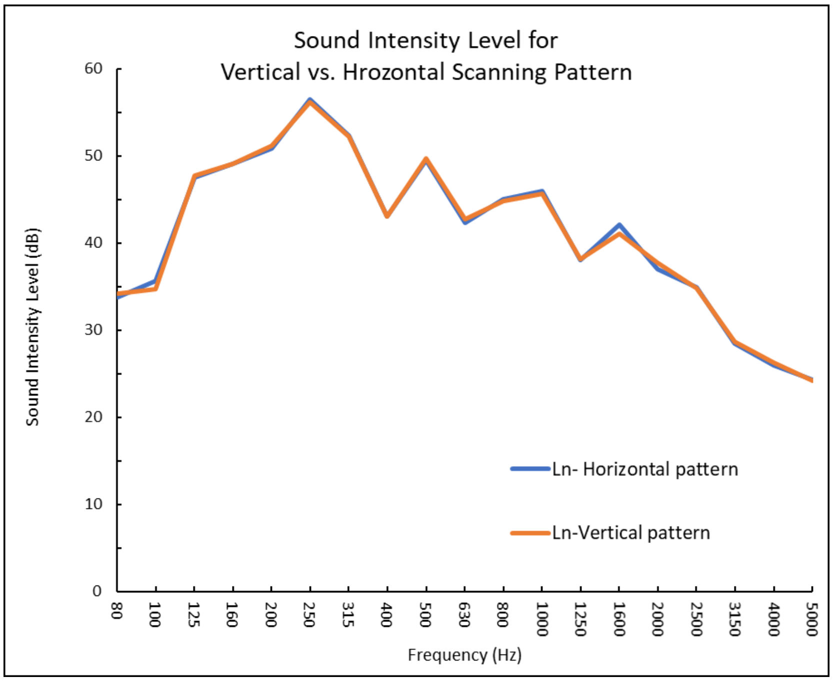


Figure 21. Comparison between Vertical vs. Horizontal Scanning Patterns for window test 5

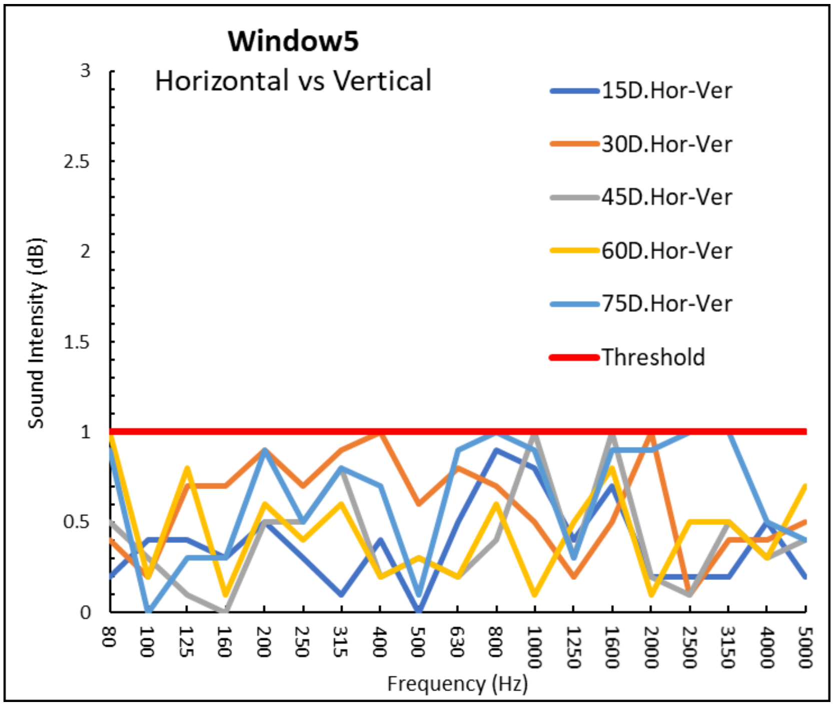


Figure 22. Difference between the Two Orthogonal Sound Intensity Measurements for window test 5

To ensure the accuracy of the measurements, the next step was related to the surface pressure-intensity index and phase for both orthogonal measurements. According to the ISO 15186-1 (2016) standard, the surface pressure-intensity indicator; F_{pI}, was checked to be less than 10 and the phase was checked to be near 0 for each one-third octave band. All these steps were performed for each one-third octave band. If any of the specified criteria were not met, the measurement process was repeated until the requirements for the measurement surface were fully met. In cases where, even after several attempts, the mentioned criteria were not satisfied by the measurements, this was documented as a departure from the standard. In the analysis and results section this is discussed.

Following the completion of all necessary steps, the two final accepted measurements of the normal sound intensity level of the interior surface of the window for two separate orthogonal scans were arithmetically averaged using Equation 10 (the ISO 15186-1, 2016).

$$L_{In} = \frac{L_{In1}+L_{In2}}{2} \qquad \textit{(Eq. 10)}$$

where $L_{In(i)}$ is the normal sound intensity level measured in the ith scan of the specimen surface.

The outcome of the arithmetical averaging process by using Equation 10 was the measured sound intensity level for the interior side of the window. This measurement corresponded to a fixed position of the loudspeaker outside. This procedure was repeated for each loudspeaker position to obtain the corresponding sound intensity level for each loudspeaker position outside. The resulting values were used for the subsequent analysis. In Figure 23 it can be seen that for each position of the outside noise source, the sound intensity level for the interior side of the window was calculated.

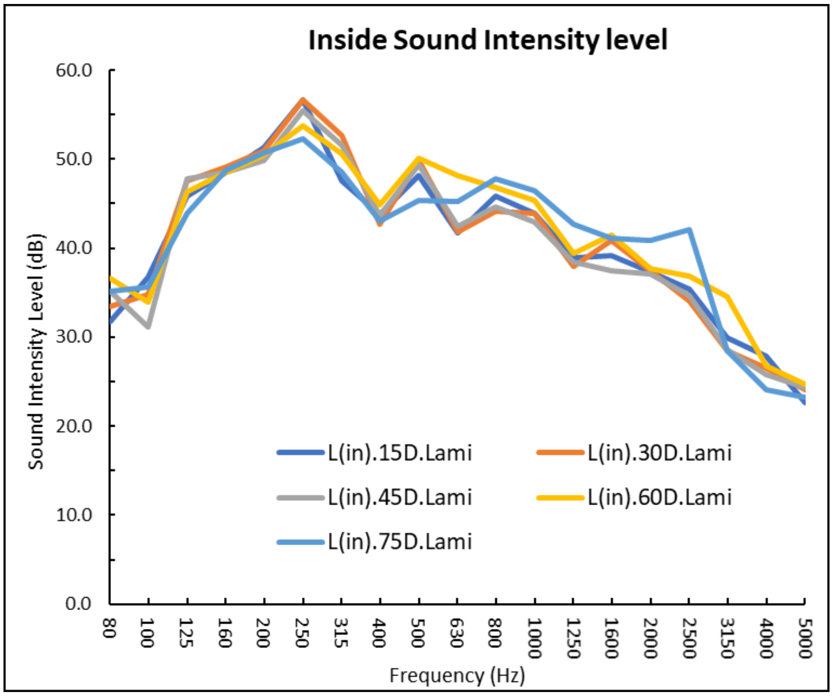


Figure 23. Averaged Interior Sound Intensity Level for each position of the loudspeaker for window test 5

3.2.1. Calculation of sound intensity measurements

To calculate the sound transmission loss of the window related to a specific loudspeaker position in this thesis, Equation 11 was applied as specified in the ISO standard 15186-1 (2016).

$$TL_j = L_{p,j} - 6 - L_{In,j} \qquad \textit{(Eq. 11)}$$

where TL_j is the sound transmission loss calculated for the jth position of the outside loud speaker, $L_{p(j)}$ is the averaged outside sound pressure level measured at the jth speaker position and $L_{In,j}$ is the averaged of the sound intensity level for the interior surface of the specimen for the jth loudspeaker position.

According to the ASTM E966 (2010) measuring the sound pressure level in close proximity to the window's surface resulted in an increase of 5 dB in the measurements. Therefore, the 5 dB needed to be subtracted from the average sound pressure level measured on the source side of the window. This procedure is the same for each loudspeaker position. The final equation for calculating the sound transmission loss of the test windows was derived as Equation 12, with the aforementioned 5 dB correction into Equation 11.

$$TL_j = L_{p(j)} - L_{In,j} - 11 \qquad \textit{(Eq. 12)}$$

To calculate the sound transmission loss of the measured surface related for each window test, all the calculated sound transmission loss for the different positions of the load speaker will be averaged as in Equation 13. The sound transmission loss is then calculated from the average transmission loss for each loudspeaker position such that:

$$TL = \frac{1}{5}\sum_{j=1}^{5} TL_j \qquad \textit{(Eq. 13)}$$

The result yielded by Equation 13 denotes the sound transmission loss of the window test. Figure 24 depicted the final averaged sound transmission loss diagram for window test 5.

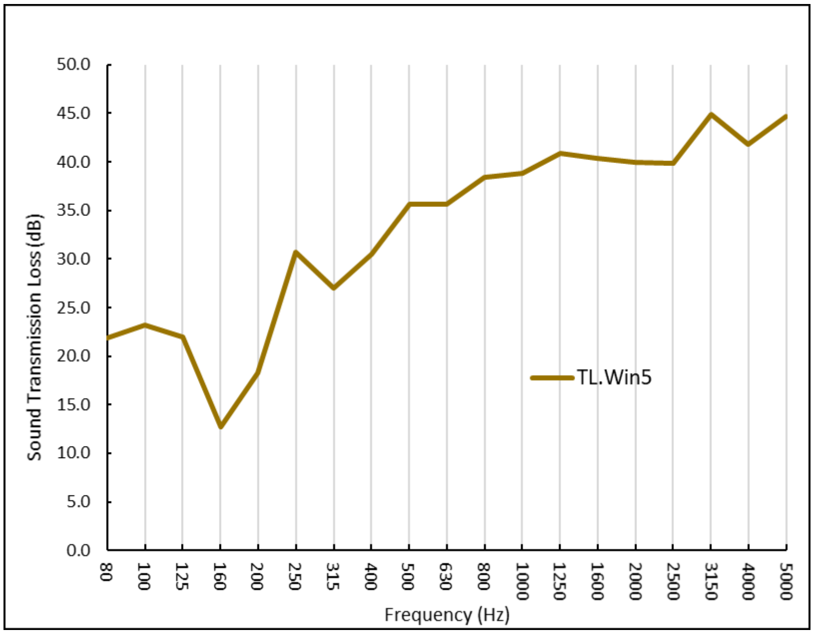


Figure 24. Calculated Sound Transmission Loss Using the BCIT Hybrid Test Method fjor window 5

4. Analysis and results

This section presents the results of an investigation aimed at evaluating the validity of the BCIT Hybrid Test Method in assessing the sound transmission loss of windows. The objective was to understand if this method can accurately identify alterations in the frame or the glazing system of the test windows.

Experimental measurements were conducted on sample windows donated by Centra Manufacturers, utilizing the BCIT Hybrid Test Method. All the windows used in this study were of the same type and size, double glazed with the same coating (LoE 270), the same gaskets, and the same spacer. The variables in the glazing systems of these windows included the thickness of glass panes, the width of the air space, and whether each of these glass panes was laminated or not.

The measurements were carried out in two phases. In the initial phase, windows from the Centra 2900 series were tested. The BCIT Hybrid Test Method's validity was evaluated by analyzing its accuracy with the existing theory. This involved investigating whether this test method could correctly depict the effects of variables such as glass pane thickness, air cavity depth, laminated glasses, and the effect of symmetrical glazing on mass-air-mass resonance frequency, critical frequency, and the depth of these dips in the sound transmission loss curves of the tested windows.

The measurement results of this phase were compared with the theoretical predictions related to two main frequencies in sound transmission loss curves of double-glazed windows: mass-air-mass resonance frequency and critical frequency. Equations from Quirt's studies (1982) on the double-glazing windows were employed for this comparison. The theory used in this study was checked by the results from the ASTM E90 test method for windows from the Centra 2900 series, which were of the same size and configuration as the window tests in the first phase of this study. These results provided a standard experimental basis for comparison and validation.

The insights gained from this phase were instrumental in shaping the second phase of the research, where the remaining test windows from Centra 2600 series with the same size and configuration from the window test of the first phase, underwent testing using the same methodology and procedure as the first phase. The objective was to compare the results of these windows to understand the effect of different glazing systems and also to investigate the effect of using foam insulated profiles on the sound transmission loss of the windows.

This section will present the findings of these investigations and discuss their implications for the field of architectural acoustics.

4.1. Phase one; validation of the BCIT Hybrid Test Method

For phase one, two casement windows from the 2900 series of Centra manufacturer were selected based on their sizes in comparison to the test wall. The dimension of both windows was 61.4 cm x 150.5 cm and the glass dimension was 49.2 cm x 138.1 cm. Both windows were double glazed and had the same coating; LoE 270, on one pane of glass, the same gaskets and spacers.

These two windows have the same frame and type, however, the glazing system of these windows was different. One of the windows was a double-glazing casement unit with a nominal interior glass thickness of 3.9 mm (1/8 inch) annealed glass, an interpane spacing of 9.8 mm (3/8 inch), and a nominal exterior glass thickness of 5.7 mm (1/4 inch) annealed glass. For ease of presentation in this thesis, this window is referred to as "BCIT

Annealed window" in the following figures and tables. The other window's glazing consisted of 6 mm (1/4 inch) interior laminated glass, an 8 mm (5/16 inch) air gap, and 5.7 (1/4 inch) mm annealed exterior glass, which is referred to as "BCIT Laminated window" in the subsequent tables and drawings. The sample windows used in phase one are described in Table 2.

Series No.	Frame Type	Interior Glass	Air Space	Exterior Glass	Window Dimension	Glass Dimension
2900	Casement Window	3.9 mm Annealed	9.8 mm	5.7 mm Annealed	614*1505 mm	492*1381 mm
2900	Casement Window	6 mm Laminated	8 mm	5.7 mm Annealed	614*1505 mm	492*1381 mm

Table 2. Sample Windows Used in phase one for the BCIT Hybrid Test Method

(BCIT first phase window tests)

4.1.1. The exterior measurements

The transmission loss measurements were divided into two main sections: the outside measurements and the inside measurements. For the outside measurements there were 5 different points for the microphone positions on the exterior surface of the window test. These points as was depicted in Figure 13 of section 3.1.2 are consisted of one point in the center of the window and 4 points in each corner of the window. These points were named in the figures as Center, UR (up right), UL (up left), DR (down right) and DL (down left). Also, in the outside measurements, there were 5 different points for the different loudspeaker positions. The exact placement of the speaker in related to the window position can find in Table 1 of section 3.1.1. These positions are referred as 15 d, 30 d, 45 d, 60 d and 75 d in relation to the center of the window test in the following figures, diagrams and tables of this study.

The measurement related to background noise was conducted immediately before measuring the outside sound pressure level for each window test. The sequence of the outside measurements followed these steps: first the background noise was measured. Then the loudspeaker was placed in position 15 d and the sound pressure level for each of 5 points on the exterior surface of the window test (Center, UR, UL, DR and DL) were measured. The results for all these 5 points on the window surface then were averaged by using Equation 9 in section 3.1.3. These steps were repeated for the rest of speaker positions (30 d 45 d, 60 d and 75 d). In Figures 25 and 26 the results for outside sound pressure level for each loudspeaker position and their difference with the outside background noise level can be seen for both windows.

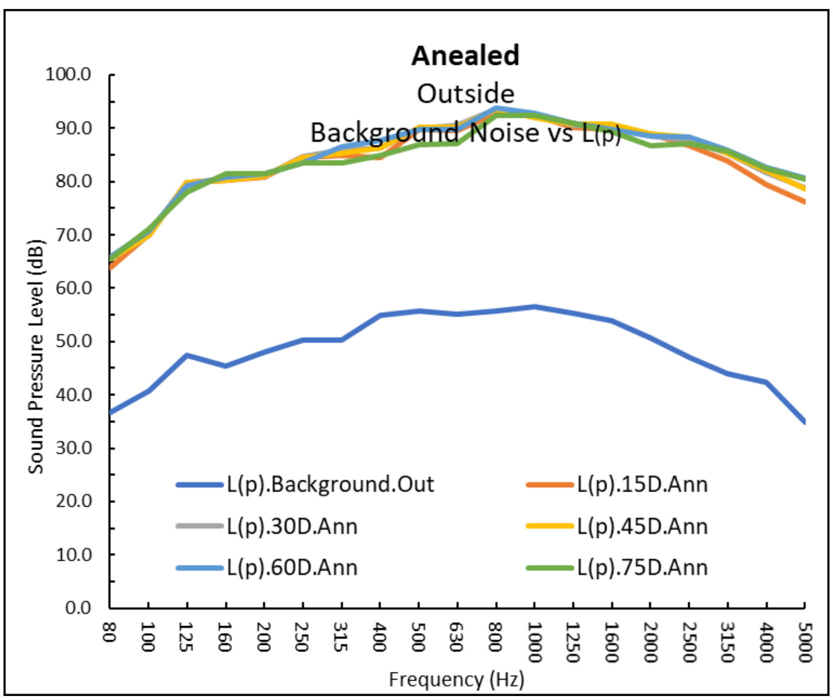


Figure 25. Exterior Sound Pressure Level and Outside Background Noise for the BCIT Annealed Window

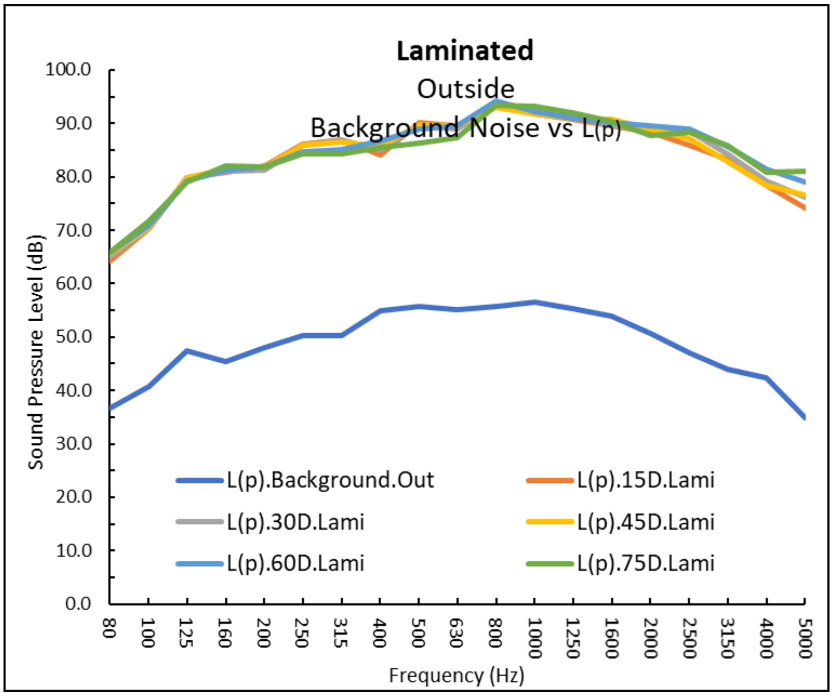


Figure 26. Exterior Sound Pressure Level and Outside Background Noise for BCIT Laminated Window

By analyzing the provided graphs (Figures 25 and 26), it is evident that the smallest disparity between the background noise level and the calculated sound pressure levels for each loudspeaker position and for each of test windows was approximately 27 decibels. This discrepancy significantly surpasses the required difference of 10 decibels according to the ASTM E966 Standard. This observation is noticeable in the following graphs (Figures 27 and 28).

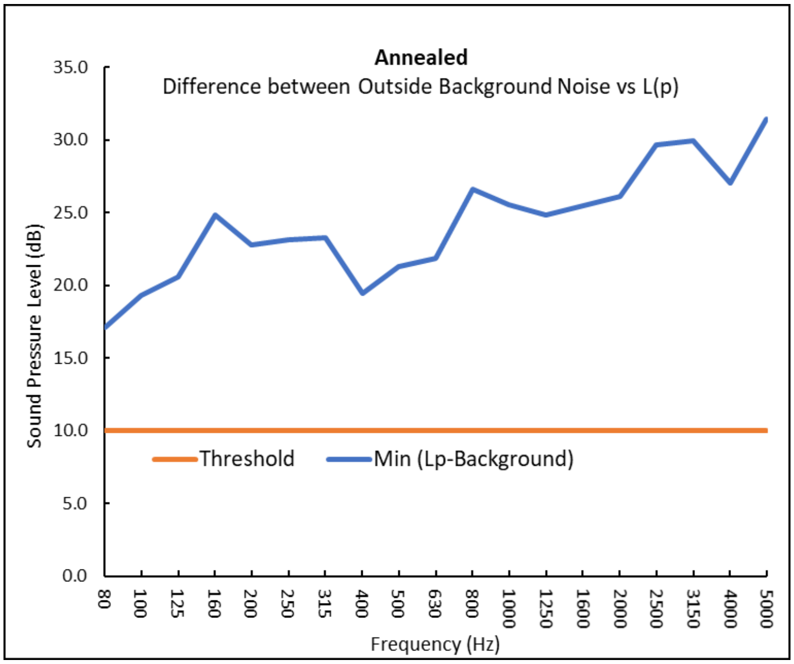


Figure 27. The minimum difference of Exterior Sound Pressure Level and Outside Background Noise for BCIT Annealed Window

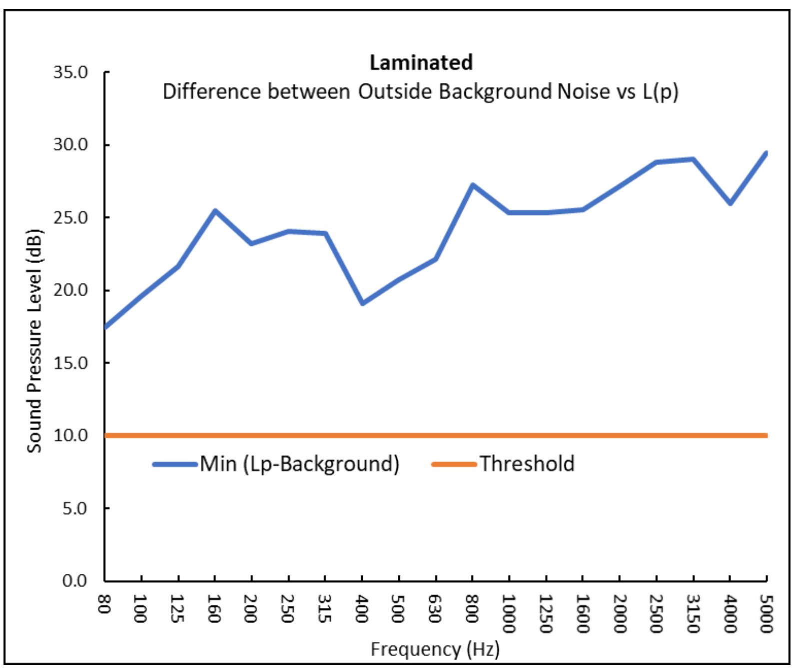


Figure 28. The minimum difference of Exterior Sound Pressure Level and Outside Background Noise for BCIT Laminated Window

Following the completion of these measurements, the standard deviation and the difference between the maximum and the minimum of the collected data related to the sound pressure level of all 5 points on the exterior surface of the window for each position of the outside loudspeaker and for each one-third octave band were computed. The outcomes of the assessment of standard deviation of mentioned measurements are displayed in Figures 29 and 30 and Figures 31 and 32 depicted the max and min differences for these measurements.

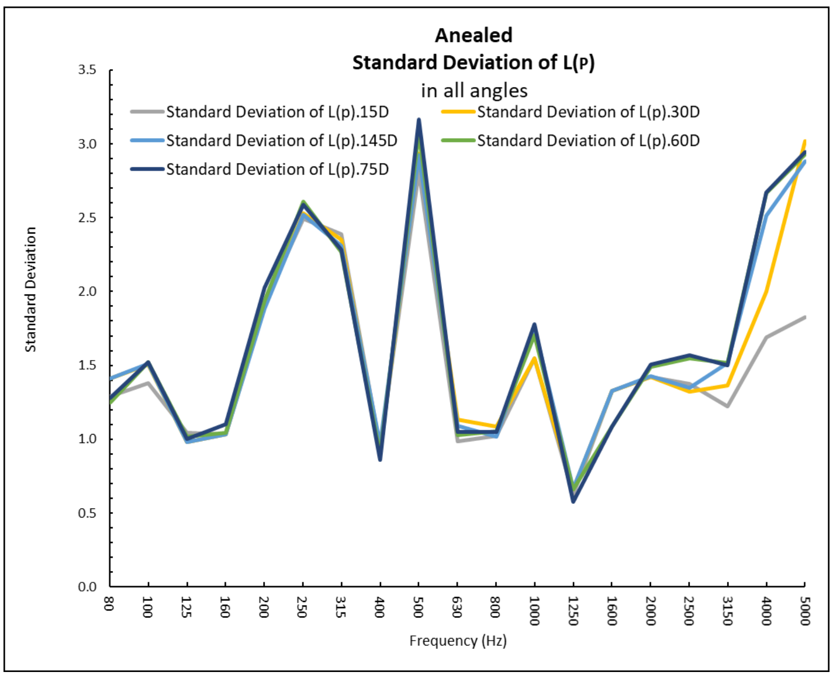


Figure 29. Standard Deviation of Sound Pressure Levels on Window Exterior surface for BCIT Annealed window

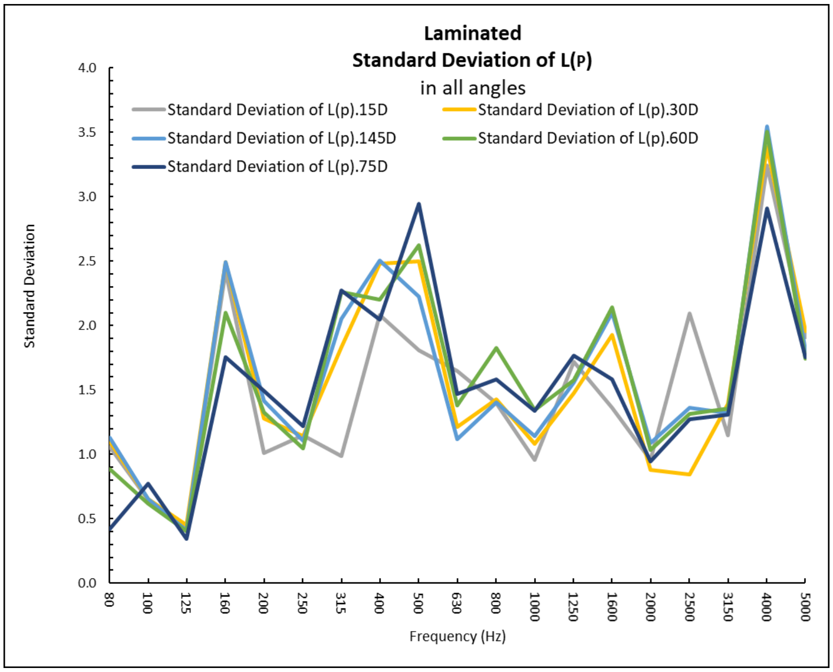


Figure 30. Standard Deviation of Sound Pressure Levels on Window Exterior surface for BCIT Laminated window

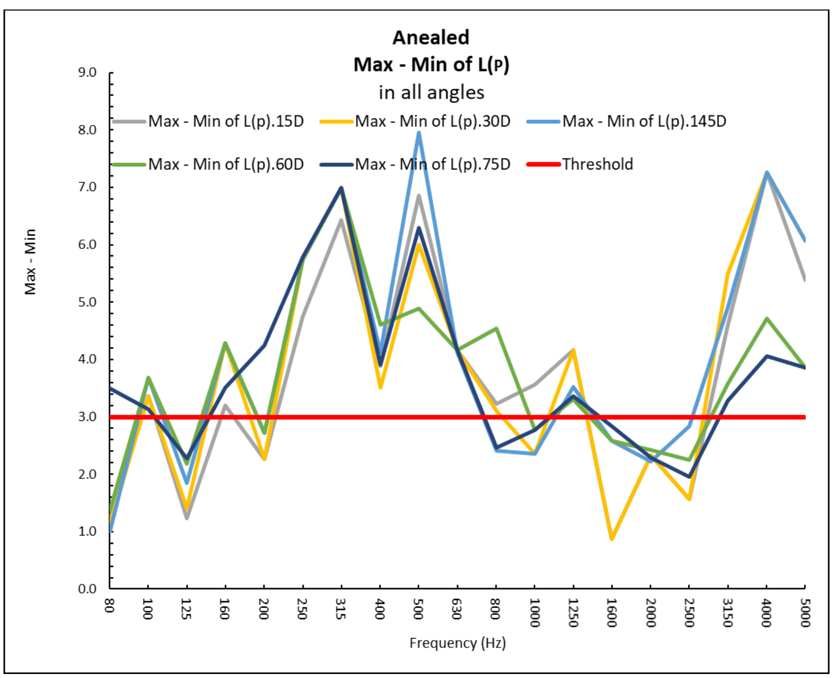


Figure 31. Max vs Min of Sound Pressure Levels on Window Exterior surface for BCIT Laminated window

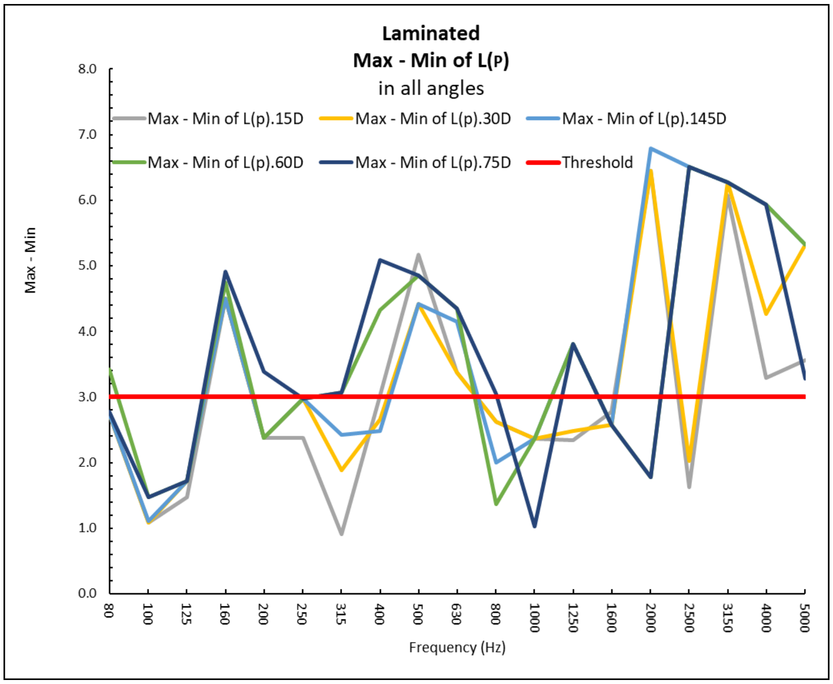


Figure 32. Max vs Min of Sound Pressure Levels on Window Exterior surface for BCIT Laminated window

In accordance with section 8-2-4 of the ASTM E966 standard, a preferred sound pressure variation of 3 dB across the window is recommended. However, the measurements conducted in this thesis did not achieve this desired quality specially when the difference between the maximum and minimum sound pressure level in each one-third octave band was calculated. In an attempt to improve the results, adjustments were made to the distance and direction of the loudspeaker with respect to the surface of the window test and the measurements were repeated. Unfortunately, these modifications did not yield satisfactory improvements in the results. Furthermore, the orientation of the loudspeaker was adjusted and verified using a point laser to ensure its precise alignment with the center of the window. Despite all the efforts, the obtained results still did not meet the requirements outlined in the E966 standard. It is worth noting that since the directivity of the loudspeaker was verified prior to the commencement of the tests, it can be deduced that this variation is primarily attributed to the test environment.

Additionally, it should be noted that the exterior measurements were conducted in an environment characterized by a significant overhang above and a fence located within a proximity of 30 cm from the right side of the window test. Furthermore, there is a storage area situated behind the fence. These factors can contribute to reflections and hinder the measurements from meeting the aforementioned requirement of the ASTM E966 standard.

4.1.2. The interior measurements

In relation to the measurements conducted on the interior section, an evaluation was carried out on three different factors to assess the test method and the interior environment. One of these factors focused on the surface pressure intensity index. In this regard, the sound intensity level was measured by scanning the entire surface of the window, while simultaneously measuring the sound pressure level. These measurements were done for each of window test and the results are illustrated in Figures 33 and 34. As evident from these graphs, the index for both windows consistently did not exceed 10 dB across all one-third octave bands, thereby satisfying the requirements outlined in the ISO 15186-1 (2016) standard.

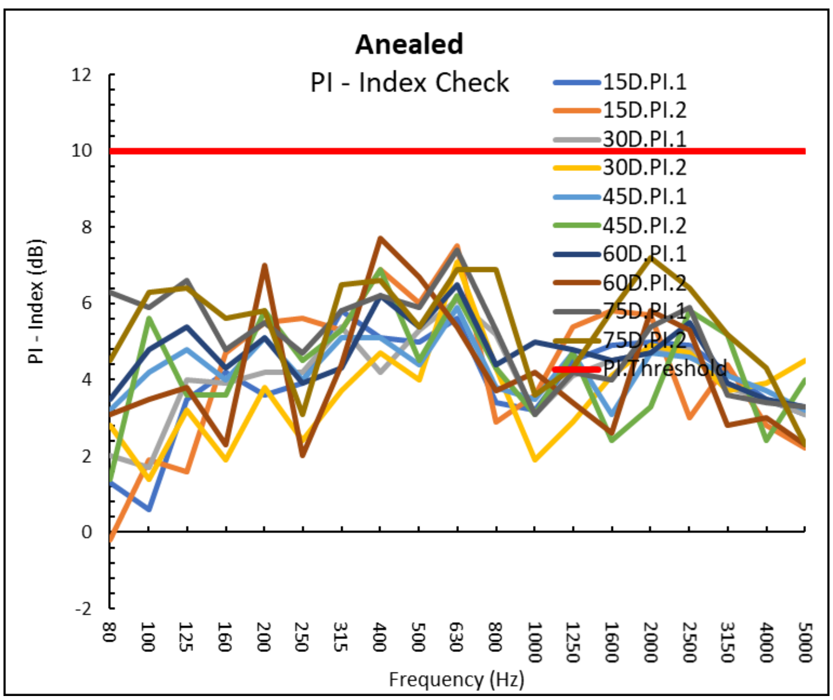


Figure 33. Qualification of the interior measurements for BCIT Laminated window by checking P-I index

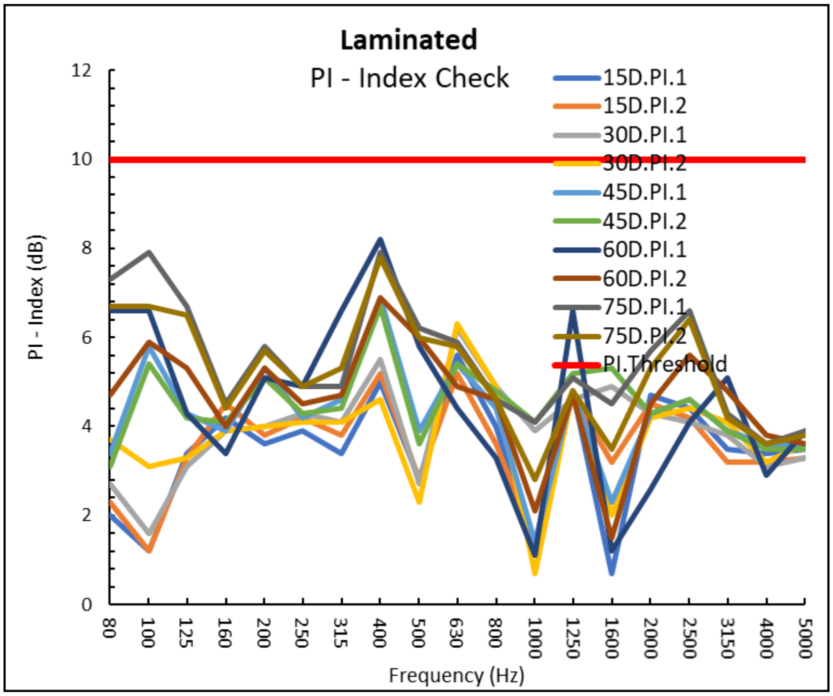


Figure 34. Qualification of the interior measurements for BCIT Laminated window by checking P-I index

Second factor for qualification of interior measurements was done by using different scanning patterns. A set of two scanning on the entire surface of the window was done with two different patterns. One path of scanning differed by 90 degrees from the other path. Figures 35 and 36 present the difference of this pair of measurements for each window test. As observed, the discrepancy between the two measurements for each measured frequency was no more than 1 dB, indicating compliance with the requirement specified in section 6-4-5 of the ISO 15186-1 (2016) standard. However, in certain frequencies, the difference approached or reached 1 dB.

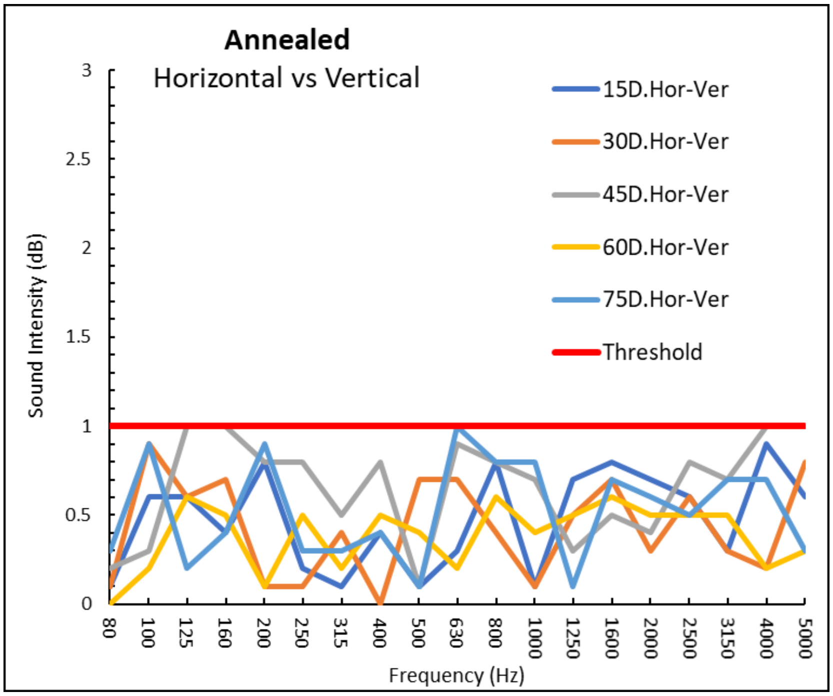


Figure 35. Qualification of the interior measurements for BCIT Annealed window by using different scanning pattern

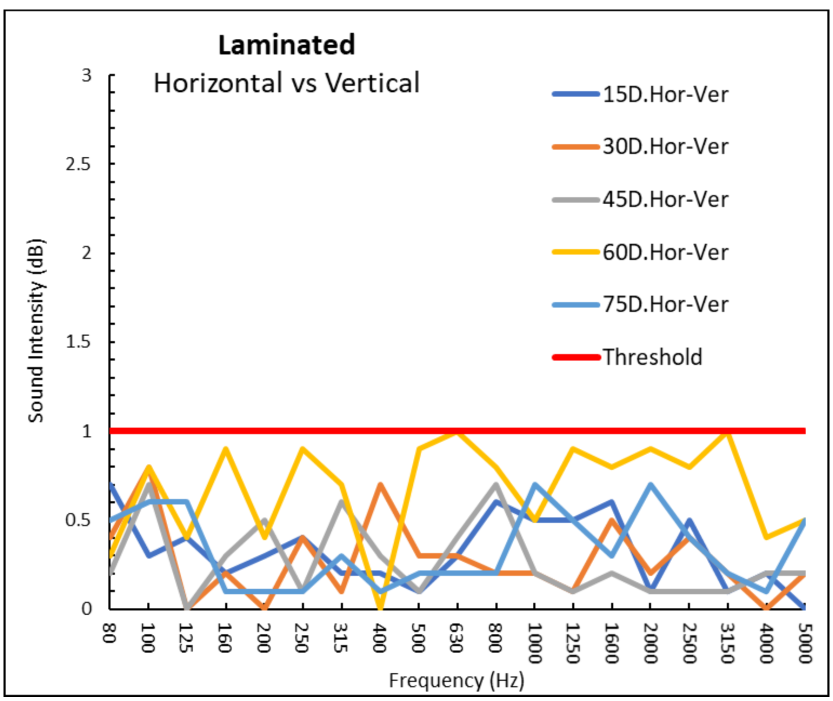


Figure 36. Qualification of the interior measurements for BCIT Laminated window by using different scanning patterns

To determine the sound intensity level for the interior side of the window, the previously mentioned measurements related to the two different patterns were arithmetically averaged. This average value was then utilized to calculate the sound transmission loss for the test windows for each position of the loudspeaker position. Multiple measurements conducted for interior sound intensity level revealed that in many instances, the data for an 80 Hz frequency did not meet the specified requirements. Therefore, it is advisable to exclude the data associated with this frequency from the relevant analysis.

The third step in the qualification process of interior measurements involves assessment of the background noise level. This assessment is essential to ensure accuracy and reliability of the measurements. In order to understand the impact of inside background noise on the interior measurements, the intensity and pressure levels of the interior background noise were carefully measured at the same time with the intensity probe. These measurements were then compared with the sound intensity and sound pressure levels recorded for the same surface when the loudspeaker was active (Figures 37 and 38). It was necessary to perform these comparisons for each of the five loudspeaker positions previously mentioned, as they represent different scenarios that can affect the accuracy of the measurements. These measurements were done for all one-third octave bands from 80 to 5000 Hz.

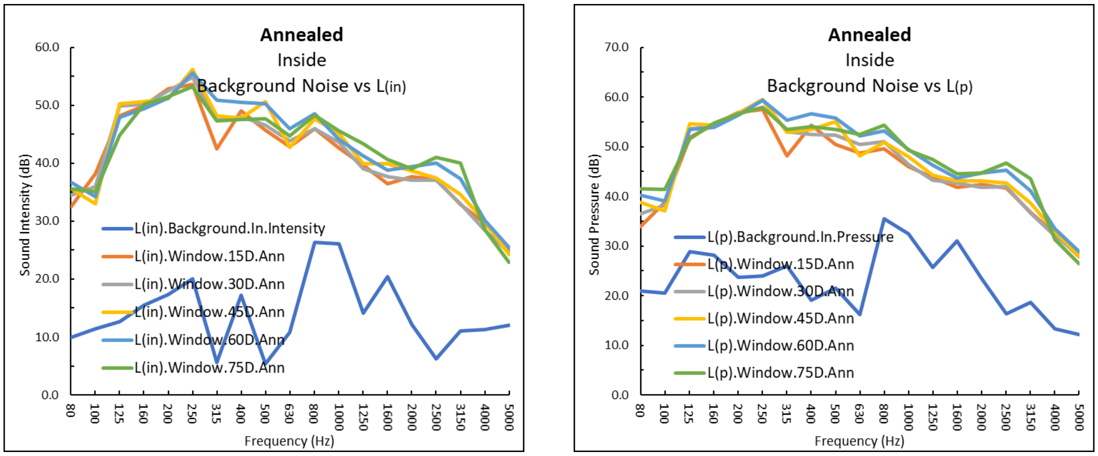


Figure 37. Interior background noise level vs the interior sound intensity and sound pressure level with outside loudspeaker on for BCIT Annealed window

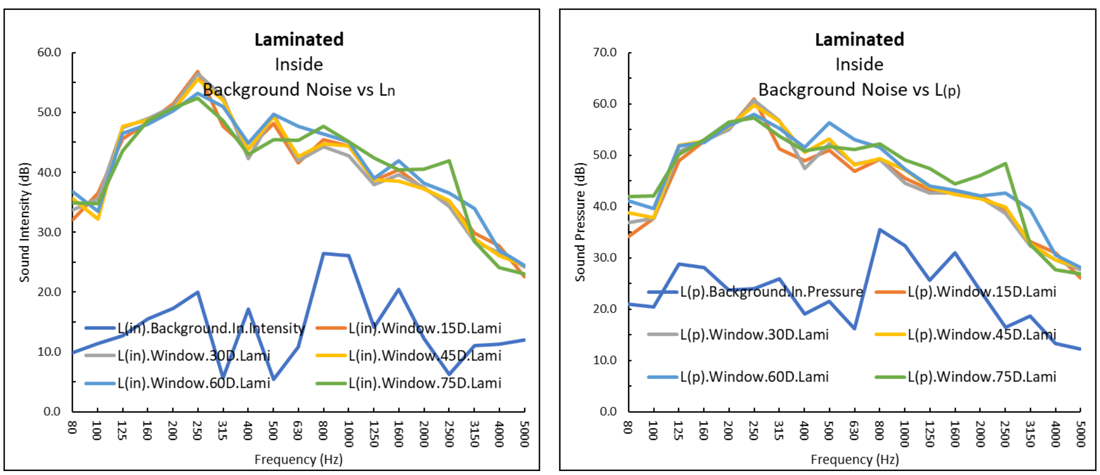


Figure 38. Interior background noise level vs the interior sound intensity and sound pressure level with outside loudspeaker on for BCIT Laminated window

In order to adhere to section 6.5 of the ISO 15186-1 standard, which provides guidelines for inside background noise levels, a minimum acceptable difference of 10 dB was considered between the measured sound intensity or sound pressure level and the background noise level. This threshold ensured that the desired measurements were distinguishable from the ambient noise, providing reliable and meaningful results.

To visually depict the minimum difference between the pressure or intensity level of the background noise and the interior sound pressure or intensity level, graphs (Figures 39 and 40) were created. These graphs allow for a clear comparison and assessment of the deviations between the background noise and the sound levels inside the room when the loudspeaker was active, considering all the different loudspeaker positions outside.

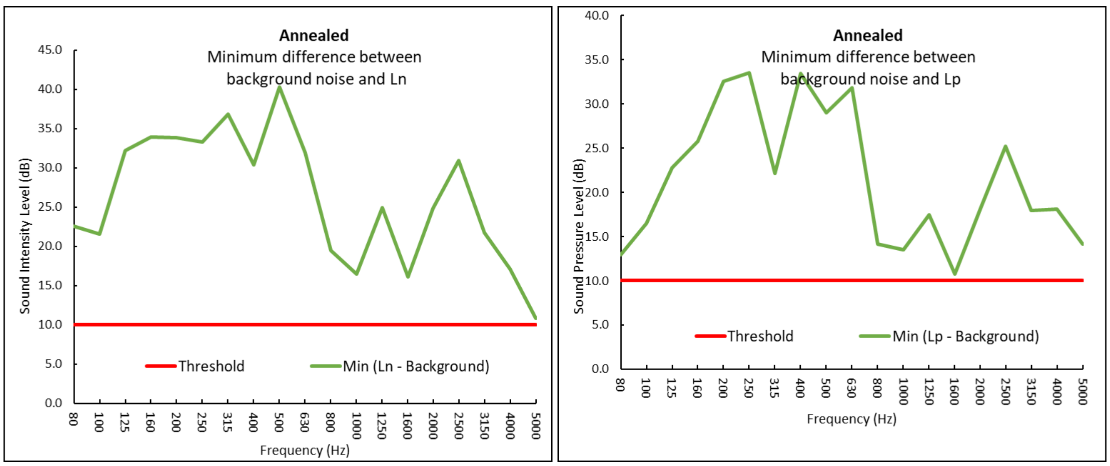


Figure 39. The minimum difference of interior Sound Pressure Level and inside Background Noise for BCIT Annealed Window

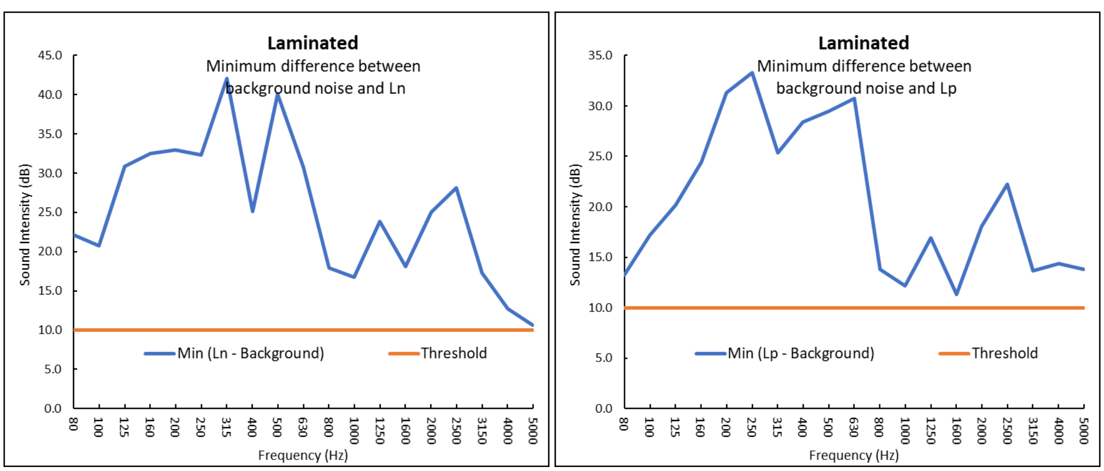


Figure 40. The minimum difference of interior Sound Pressure Level and inside Background Noise for BCIT Laminated Window

Upon analyzing these graphs, a notable observation is that the background sound pressure level was found to be particularly high at frequencies 800, 1000, and 1600. Consequently, the difference between the background sound pressure level and the interior sound pressure level when the loudspeaker was active approached the 10 dB threshold at the mentioned frequencies. This finding was consistent with multiple measurements of the interior background sound pressure level at these specific frequencies. Taking these results into consideration, it is concluded that the calculated sound intensity level for each window test conducted in this laboratory cannot be considered reliable for the aforementioned frequencies and all the mentioned steps should be taken for the measurements of interior side for all loudspeaker positions. The measurements should be checked and validated to achieve the acceptable data for the interior sound intensity level of test windows for each loudspeaker position. Only the acceptable data was used to calculate the sound transmission loss of window test.

4.1.3. The experimental sound transmission loss measured with the BCIT Hybrid Test Method

Based on the analysis of the sound pressure level on the exterior surface of the window test and the sound intensity level on the interior side, the sound transmission loss of each window was computed using Equation 12 outlined from section 3.2.1 of this thesis. This calculation was performed for each loudspeaker position. For each window test, the sound transmission loss was calculated as the last step of the BCIT Hybrid Test Method by averaging the sound transmission loss achieved for each loudspeaker position, using Equation 13 of section 3.2.1 (Figures 41 and 42).

$$TL_j = L_{p(j)} - L_{In,j} - 11 \qquad \textit{(Eq. 12)}$$

$$TL = \frac{1}{5}\sum_{j=1}^{5} TL_j \qquad \textit{(Eq. 13)}$$

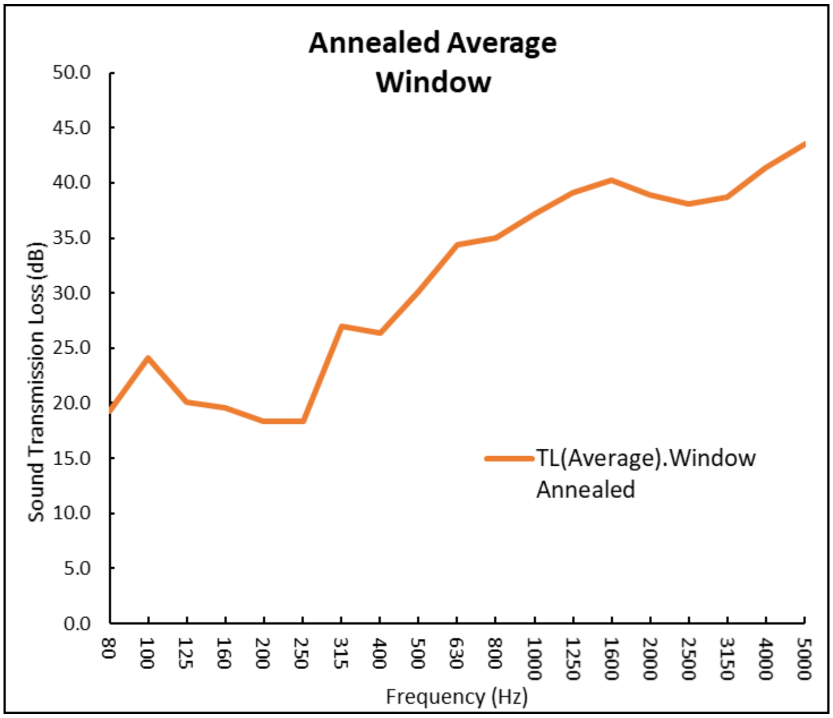


Figure 41. Average sound transmission loss from the BCIT Hybrid Test Method for Annealed window

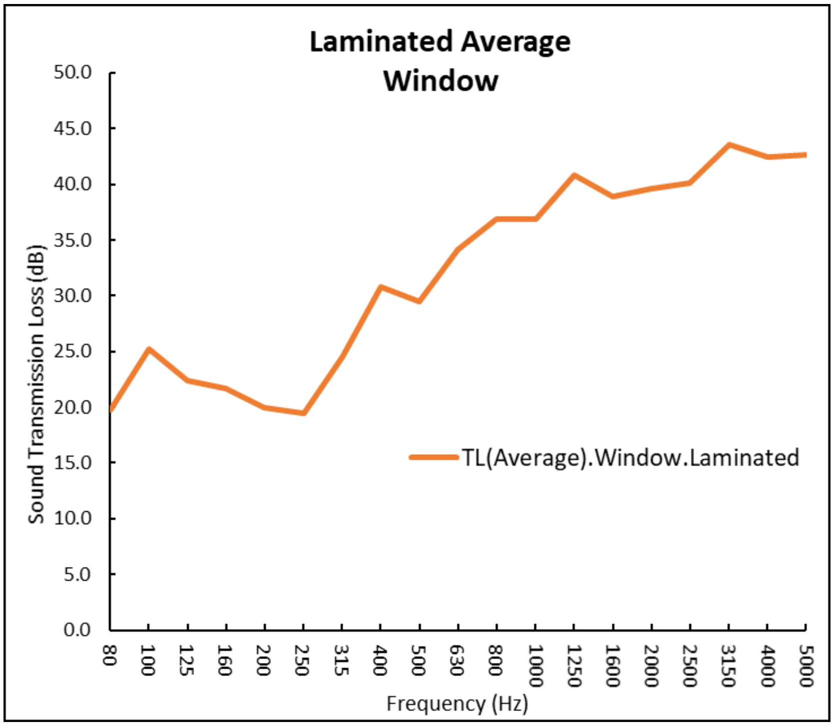


Figure 42. Average sound transmission loss from the BCIT Hybrid Test Method for Laminated window

In the pursuit of achieving greater accuracy in the results obtained from measurements using the BCIT Hybrid Test Method, it is imperative to acknowledge that certain aspects require further examination and analysis. This acknowledgment serves as a reminder of the complexities involved in such measurements and the continuous efforts needed to refine the process. The inside background noise which was in frequencies 800, 1000 and 1600 Hz meet the threshold defined in standard the ISO 15186-1 (2016). This caused the measured sound intensity level of the inside surface of the test windows not being reliable for calculating the sound transmission loss of the window in the frequencies reported. Alternatively, the outside sound pressure deviation across the exterior surface of the test windows did not meet the requirements of the ASTM E966 (2011) standard. This was a departure from the standard as well. Also, in the ISO 15186-1 (2016) standard, an approximately diffuse sound field is produced in the source room. However, in the BCIT

Hybrid Test Method, by averaging the measurements of different loudspeaker position and consequently causing different sound incidence angles, it was tried to reach to an acceptable approximation of the diffuse field (the ASTM E966, 2011). This alternative approach can cause inaccuracies in the sound transmission loss of a window measured with this method. The exact effect of this discrepancy warrants further investigation.

It’s important to note that in theASTM E966 and BCIT Hybrid Test Method, the exterior surface of the test windows is exposed to the outside environment. As a result, factors such as outside temperature, moisture levels, and wind conditions could not be controlled or kept constant for different measurements. These variations could potentially impact the results obtained. While understanding the precise effect of these variables on the measurements was beyond the scope of this thesis, further investigation is required to determine the impact of changes in temperature, moisture levels, and wind on the results of the BCIT Hybrid Test Method.

4.2. Validation of Theoretical Framework Using E90 test Windows

In this section, the theoretical predictions was validated by comparing it with the experimental outcomes derived from the E90 test measurements. The E90 test measurements served as the standard experimental basis in the first phase of this study. Table 3 provided data on the thickness of the glass and air gap for two windows, that have been previously evaluated using the ASTM E90 standard test method by an independent laboratory.

One of these windows, a double-glazing casement window from the Centra 2900 series, had a nominal interior glass thickness of 4 mm (1/8 inch) annealed glass, an interpane spacing of 11 mm (7/16 inch), and a nominal exterior glass thickness of 5.7 mm (1/4 inch) annealed glass. For the purpose of clarity in this thesis, this window is referred to as the “E90 Annealed window” in the subsequent figures and tables.

The other window is from the same series (Centra 2900 series) and had the same configuration and size as the E90 Annealed window. It had a glazing consisting of 6 mm (1/4 inch) interior Laminated glass, a 13 mm (1/2 inch) air gap, and 5.7 mm (1/4 inch) exterior annealed glass. This window is referred to as the “E90 Laminated window” in the following tables and drawings. Figure 43 illustrates the sound transmission loss results obtained through the E90 test method for E90 window test .

In instances where the interpane spacing varied within the range of 11 to 13 millimeters, the theoretical predictions anticipated nearly identical mass-air-mass resonance frequencies. The predictions were in good agreement with the experimental results obtained from measurements according to the ASTM E90 standard.

Turning to the critical frequency, Table 3 reveals that the E90 Laminated window exhibited a higher mass per unit area in comparison to the E90 Annealed window. The corresponding transmission loss curves, depicted in Figure 43, indicated a lower critical frequency for the E90 Laminated window as opposed to the E90 Annealed window.

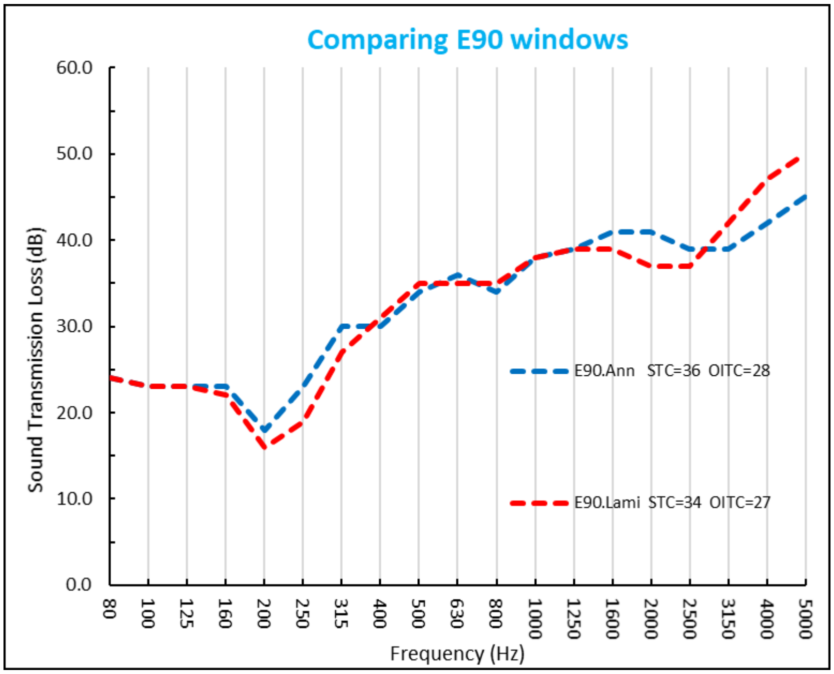


Figure 43. Comparing the sound transmission loss of the E90 window tests

(The E90 data are courtesy of Intertek Group plc)

Identification	Series No.	Frame Type	Interior Glass	Air Space	Exterior Glass	Area
E90 Annealed	2900	Casement Window	4mm, Annealed	11 mm	6mm, Annealed	0.93 m^2
E90 Laminated	2900	Casement Window	6mm, Laminated	13 mm	6mm, Annealed	0.93 m^2

Table 3. Data of the E90 window tests

4.2.1. Comparing the theoretical prediction and measurement results for mass-air-mass resonance frequency

In section 2.3.2 of the literature review, Equation 7 was introduced for calculating the mass-air-mass frequency for double-glazed windows from Quirt (1982) and the dependency of this resonance frequency was discussed in that section.

$$f_{mam} = \frac{1}{2\pi}(\rho_o c^2)^{1/2}\left(\frac{m_1+m_2}{m_1 m_2 d}\right)^{1/2} \qquad \textit{(Eq. 7)}$$

In this stage, to validate the selected equations for these frequencies the results from the ASTM E90 test method for two windows from the Centra 2900 series, which had the same size and configuration as the BCIT phase one test windows were used. The results from the ASTM E90 test method provided a standard experimental basis for comparing and validating the theory used in this thesis.

Figure 44 and 45 show predicted mass-air-mass resonance frequency and critical frequency related to the phase one E90 windows (E90 Annealed window and E90 Laminated window) as vertical lines and the measured transmission loss of these windows.

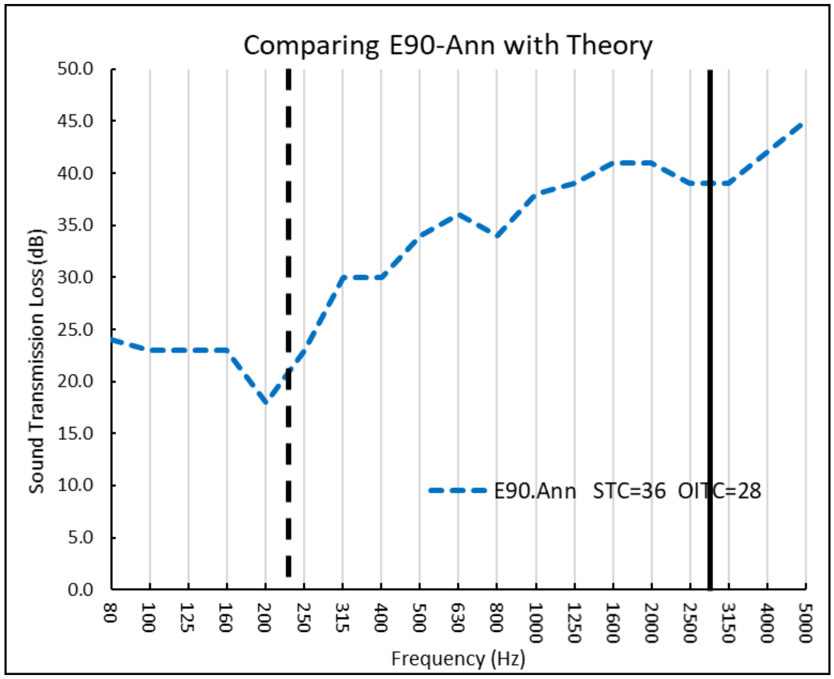


Figure 44. Comparing the predicted versus measured mass-air-mass resonance frequency and critical frequency of E90 Annealed window

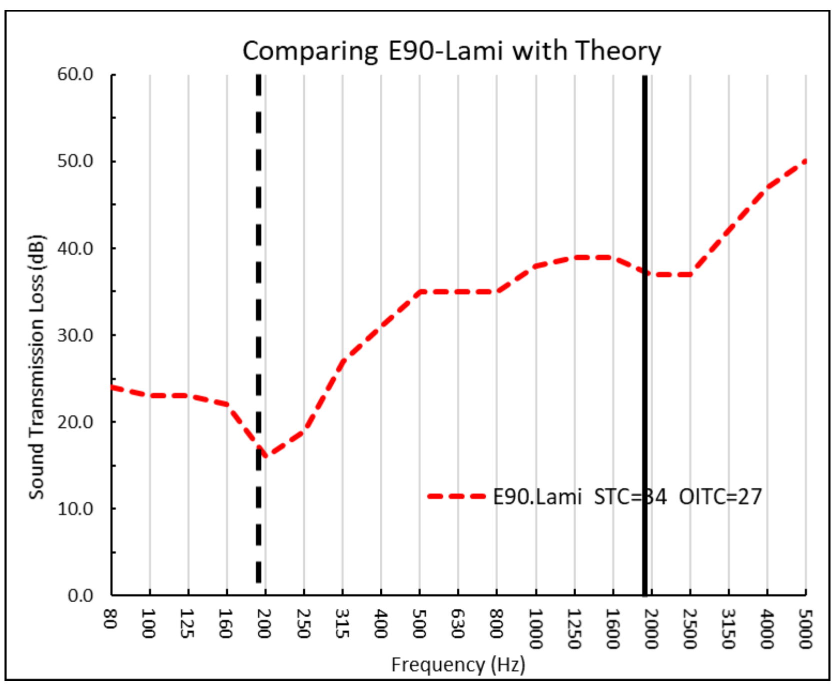


Figure 45. Comparing the predicted versus measured mass-air-mass resonance frequency and critical frequency of E90 Laminated window

As was depicted in Figures 44 and 45, in the ASTM E90 test results the mass-air-mass resonance frequency for both E90 Annealed window and E90 Laminated window were around 200 Hz. Table 4 shows the predicted and the measured mass-air-mass resonance frequency for the two windows with the ASTM E90 results. The predicted mass-air-mass resonance frequency for E90 Annealed window was 238 Hz and for E90 Laminated window was 192 Hz. The comparison between the predicted and measured values revealed a satisfactory agreement, indicating the validity of the theoretical approach in depicting the mass-air-mass resonance frequency and the critical frequency resonance behavior of the windows.

Parameter	d	T1	T2	D	m_1	m_2	*Predicted* f_{mam}	*Measured* f_{mam}
Description	Interpane spacing (d)	Glass 1 thickness	Glass 2 thickness	Glass Density	Mass per unit area of glass 1	Mass per unit area of glass 2	$f_{mam} = 60\left(\frac{m_1 + m_2}{m_1 m_2 d}\right)^{1/2}$	Central frequency of the corresponding 1/3 octave band with E90 test method
Dimentions	mm	mm	mm	g/cm³	Kg/m²	Kg/m²	Hz	Hz
E90 Annealed	11	4	6	2.4	9.6	14.4	238	200
E90 Laminated	13	6	6	2.5	15	15	192	200

Table 4. Predicted and measured mass-air-mass resonance frequency for E90 window tests

4.2.2. Comparing the theoretical prediction and measurement results for critical frequency

The measured critical frequency of windows with the ASTM E90 test results was compared with the theoretically predicted critical frequency using Equation 6 from the literature review. Since the specific information regarding the glass used in these measurements was not available, general glass data was utilized for the related calculations (Saji et al, 2018). The critical frequency achieved with both theoretical and measured the ASTM E90 methods presented in Figures 44 and 45. The comparison between the predicted and measured values for both E90 annealed window test and E90 Laminated window test, revealed a satisfactory agreement, indicating the validity of the theoretical approach in depicting the critical frequency for the window test in this study. Table 5 provide the data used in calculating the critical frequency. It also presented the critical frequency obtained from the ASTM E90 test measurements in the last column.

$$f_c = \frac{c^2}{2\pi m}\left(\frac{12\rho^{3(1-\sigma^2)}}{E}\right)^{1/2} \qquad \textit{(Eq. 6)}$$

Parameter	C	E	σ	ρ	m	Predicted f_c	Measured f_c
Description	Speed of sound	Young's modulus of elasticity	Poasson's ratio	Density of the panel	mass per unit area	$f_c = \frac{c^2}{2\pi m}\left(\frac{12\rho^{3(1-\sigma^2)}}{E}\right)^{1/2}$	Central frequency of the corresponding 1/3 octave band with E90 test method
Dimentions	m/s	N/m^2	-	kg/m^3	kg/m^2	Hz	Hz
E90 Annealed	343	70	0.23	2400	9.6	2924	(2500-3150)
E90 Laminated	343	70	0.23	2500	15	1989	(2000-2500)

Table 5. Predicted and measured Critical frequency of the E90 test windows

As shown in Table 5, the measured critical frequency for the annealed window is higher than the Laminated window. As previously discussed in the literature review and demonstrated in Equation 6, which pertains to the prediction of the critical frequency, a decrease in the mass per unit area of glass leads to an increase in the critical frequency. The range of the critical frequency calculated by using Equation 6, is near the critical frequency achieved by measurements with the ASTM E90 standard method.

4.3. Comparing the theoretical prediction and the experimental results of the BCIT Hybrid Test Method

Having qualitatively established the validity of the existing theory via comparison with the E90 test results in Sections 4.2, in this section, a comparison was conducted between the experimental outcomes from the BCIT Hybrid Test Method measurements and the theoretical predictions that were previously discussed in the literature review. Table 6 alongside Figure 46, respectively presents the data related to the specification of the windows and the final results of the sound transmission loss measured using the BCIT Hybrid Test Method for Annealed window and Laminated window of the fisrt phase of this study.

The effect of interpane spacing on the mass-air-mass resonance frequency of the two windows was examined in the theory and the BCIT Hybrid Test Method. Despite a difference in interpane spacing of less than 2 millimeters, the windows were predicted to have nearly identical mass-air-mass resonance frequencies based on the theoretical predictions. The experimental results showed the same results.

As for the critical frequency, it was observed in Table 6 that the Laminated window had a higher mass per unit area compared to the Annealed window. The transmission loss curves of these windows, as depicted in Figure 46, showed that the Laminated window had a lower critical frequency compared to the Annealed window. These results were consistent with the theoretical predictions.

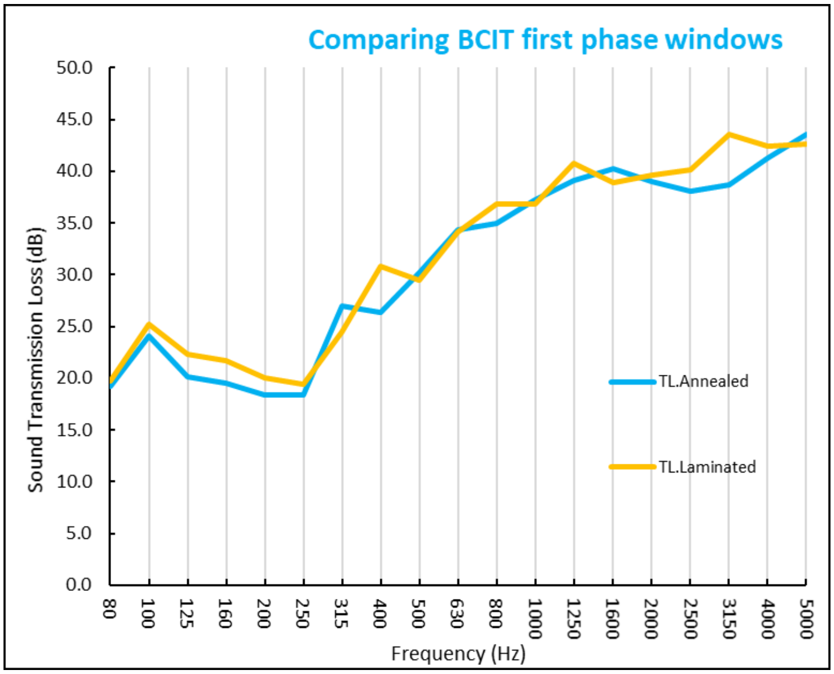


Figure 46. Comparing the sound transmission loss of the test windows used in the BCIT Hybrid Test Method with theoretical prediction

Identification	Series No.	Frame Type	Interior Glass	Air Space	Exterior Glass	Area
BCIT Annealed	2900	Casement Window	3.9 mm Annealed	9.8 mm	5.7 mm Annealed	0.93 m^2
BCIT Laminated	2900	Casement Window	5.7 mm Laminated	8 mm	6 mm Annealed	0.93 m^2
E90 Annealed	2900	Casement Window	4mm, Annealed	11 mm	6mm, Annealed	0.93 m^2
E90 Laminated	2900	Casement Window	6mm, Laminated	13 mm	6mm, Annealed	0.93 m^2

Table 6. Data of test windows used in first phase of this study

4.4. Phase One Conclusion

The validation process emphasized the effectiveness of the BCIT Hybrid Test Method in assessing the sound transmission loss of windows. The insights gained from this first phase are expected to guide future investigations in this field. This conclusion serves as a closure to the first phase of the study, setting the stage for the second phase where more windows were studied using the same BCIT Hybrid Test Method.

4.5. Phase two; parametric study of window tests using BCIT Hybrid Test Method

In the second phase of this study, five windows (Window 2 to Window 6) underwent testing. The same procedure and methodology used for the test windows in the first phase of this study were applied. The test windows in phase one, referred to as BCIT Annealed and BCIT Laminated windows and both were Window 1 in this study. Phase two test windows were from 2600 Centra series with the same size and configuration as the first phase test windows. These windows were supplied and donated by Centra Manufacturers to be tested and used in this study. The naming of these windows has been done based on the labels on them. A list of these test windows can be found in Table 7.

Identification	Series No.	Frame Type	Interior Glass	Air Space	Exterior Glass	Area
Win 2	2600	Casement Window	5.7 mm Annealed	8 mm	5.7 mm Annealed	0.93 m^2
Win 3	2600	Casement Window	6 mm Laminated	8 mm	5.7 mm Annealed	0.93 m^2
Win 4 Foam	2600	Casement Window	6 mm Laminated	21 mm	6 mm Laminated	0.93 m^2
Win 5	2600	Casement Window	6 mm Laminated	21 mm	6 mm Laminated	0.93 m^2
Win 6	2600	Casement Window	6 mm Laminated	8 mm	5.7 mm Annealed	0.93 m^2

Table 7. Sample Windows Used in phase Two for the BCIT Hybrid Test Method

In the second phase of this study, the windows under investigation had the following veriables: These windows had two different interpane spacing of 8 mm and 21 mm. The windows also featured a variety of glass pane configurations, including both panes being annealed glass, one with annealed glass and the other with laminated glass or both glass panes being laminated. Only one window (W4), had a foam-insulated frame.

4.5.1. Window test No. 2

Window 2 is a symmetric double-glazed casement window from Centra 2600 series. Both glass panes in this window were annealed glasses with an air cavity of 8 mm in between. Table 7 indicates that Window 2 is the only sample in phase two of this study without any pane of glass being laminated, the same as the BCIT Annealed window of first phase. However, the BCIT Annealed window in phase one was asymmetric window versus Window 2 that was symmetric. In Figure 47 the sound transmission loss achieved for Window 2 is presented. Also, the theoretical prediction of mass-air-mass resonance frequency and critical frequency related to this window is depicted in this figure. The figure exhibited the same mass-air-mass resonance frequency for both Window 2 and theory. Regarding the critical frequency, there is a slight difference between the measurements and the theory.

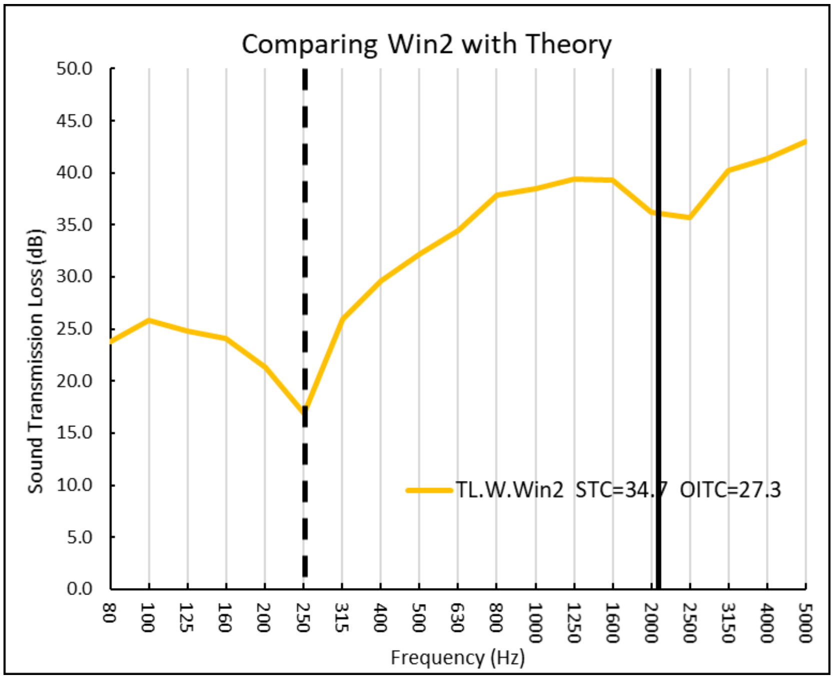


Figure 47. Comparing the predicted mass-air-mass resonance frequency and critical frequency with the experimental results of Window 2 based on the BCIT Hybrid Test Method

Table 8 revealed that the interpane space of window 2 is approximately 2 mm less than Annealed Window. This difference is negligible and could lead to the same mass-air-mass resonance frequency for window 2 in compare with Annealed window. The same trend for the mass-air-mass frequencies of these two windows was observed in Figure 48 which compare the transmission loss curves of Window 2 and Annealed window; the mass-air-mass resonance frequency of Window 2 is around 250 and the same as the mass-air-mass resonance frequency of Annealed E Window. The predicted and the measured mass-air-mass resonance frequency for these two windows summarized in Table 9 and as it was discussed the predicted data is in good agreement with the measured data for mass-air-mass resonance frequency for Window 2 and Annealed window.

Name	Series name	Frame type	Glass 1 width	Air space	Glass 2 width
BCIT Annealed	2900	Casement Window	3.9 mm Annealed	9.8 mm	5.7 mm Annealed
Win 2	2600	Casement Window	5.7 mm Annealed	8 mm	5.7 mm Annealed

Table 8. Comparing Window 2 versus Annealed window

Parameter	d	T1	T2	D	m_1	m_2	*Predicted* f_{mam}	*Measured* f_{mam}
Description	Interpane spacing (d)	Glass 1 thickness	Glass 2 thickness	Glass Density	Mass per unit area of glass 1	Mass per unit area of glass 2	$f_{mam} = 60\left(\frac{m_1 + m_2}{m_1 m_2 d}\right)^{1/2}$	Central frequency of the corresponding 1/3 octave band
Dimentions	mm	mm	mm	g/cm³	Kg/m²	Kg/m²	Hz	Hz
BCIT Annealed	9.8	3.9	5.7	2.4	9.36	13.68	257	250
W2	8	5.7	5.7	2.4	13.68	13.68	256	250

Table 9. Predicted and measured mass-air-mass resonance frequency for W2 and Annealed window

In Table 10, the predicted critical frequency for Window 2 and Annealed window is calculated by using Equation 6 of section 2.2. The measured critical frequency for both windows also are depicted in this table. For Annealed window, both predicted and measured critical frequency are in good agreement with each other. However, for Window 2, there was a slight deviation in the critical frequency achieved by measurements from the predicted data. One potential hypothesis here could be the effect of the high variation of the sound pressure level on the exterior surface of the window. This might have been caused inaccurate data for calculating the sound transmission loss correctly within this frequency.

By looking at the sound transmission loss graphs for both windows in Figure 47, it is evident that these two windows exhibit clear differences in their critical frequencies. The critical frequency of Annealed Window is higher than that of Window 2 due to the more mass per unit area in Window 2. This trend is the same in the predicted data.

Parameter	C	E	σ	ρ	m	Predicted f_c	Measured f_c
Description	Speed of sound	Young's modulus of elasticity	Poasson's ratio	Density of the panel	mass per unit area	$f_c = \frac{c^2}{2\pi m}\left(\frac{12\rho^{3(1-\sigma^2)}}{E}\right)^{1/2}$	Central frequency of the corresponding 1/3 octave band
Dimentions	m/s	N/m^2	-	kg/m^3	kg/m^2	Hz	Hz
BCIT Annealed	343	70	0.23	2400	9.36	2999	2500
W2	343	70	0.23	2400	13.68	2052	2500

Table 10. Predicted and measured critical frequency for W2 and Annealed window

4.5.2. Window test No. 3

Window 3 is an asymmetric double-glazed casement window from Centra 2600 series and had one pane of laminated glass on the interior side with thickness of 6 mm and another pane of annealed glass with thickness of 5.7 mm with an interpane space of 8 mm. By comparing Window 2 and Window 3, it is evident that the main difference between these two windows is that one of the glass panes in Window 3 is laminated. The sound transmission loss of these two windows showed in Figure 48. These windows have the same mass-air-mass resonance frequency and the same critical frequency. However, graph of Window 2 showed a deeper dip in its critical frequency and a slightly deeper dip in its mass-air-mass resonance frequency compare with Window 3. Theoretically speaking, as in Window 2 both of glass panes had the same mass per unit area and thickness, this may cause a deeper dip in the transmission loss graph for both mass-air-mass resonance frequency and critical frequency. Also having one pane of laminated glass instead of annealed glass in Window 3, may improve the acoustic performance of this window specifically in the vicinity of the two dips due to higher damping. This trend is in line with the results of measurements as well.

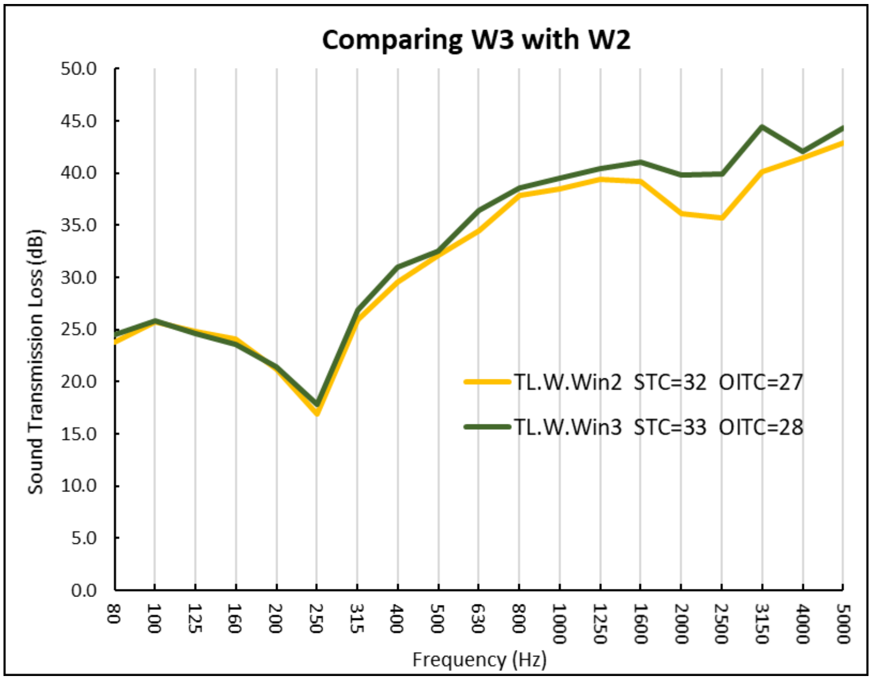


Figure 48. Sound Transmission loss curves for window 2 and window 3

The theoretical prediction and measured data related to the mass-air-mass resonance frequency and for critical frequency for Window 3 are showed in Figure 49. The figure showed that the measurements with the BCIT Hybrid Test Method are in good agreement with the theoretical prediction for both mass-air-mass resonance frequency and critical frequency.

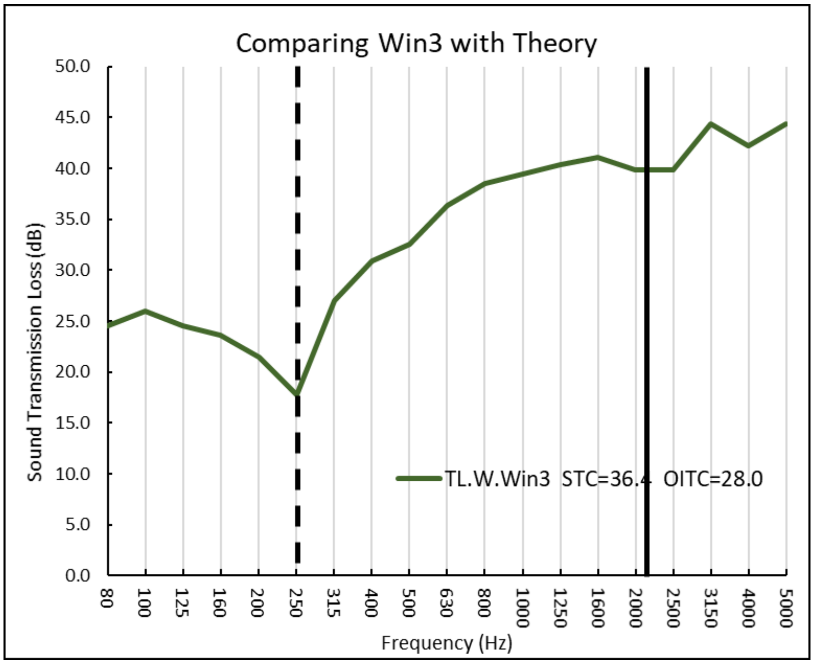


Figure 49. Comparing the predicted mass-air-mass resonance frequency and critical frequency with the experimental results of Window 3 based on the BCIT Hybrid Test Method

To compare Window 3 with Laminated window of the first phase of this study, it can be said that both windows had the same interpane glass space. The interpane space in Window 3 and Laminated window were 8 mm. As it was mentioned in the literature review, this may lead to same mass-air-mass resonance frequency for both windows. By observing Table 11, the theoretically predicted mass-air-mass resonance frequency based on Equation 6 of this study and the measured mass-air-mass resonance frequency based on the BCIT Hybrid Test Method for both windows were almost the same and was around 250 Hz. Also, as Window 3 and Laminated window have the same mass per unit area for their both glass panes, the same critical frequency is predicted for both these windows theoretically. Table 12 presented the calculated and the measured critical frequency of these two windows. It can be seen that the critical frequency of these two windows was around 2000 in both mentioned method.

Parameter	C	E	σ	ρ	m	Predicted f_c	Measured f_c
Description	Speed of sound	Young's modulus of elasticity	Poasson's ratio	Density of the panel	mass per unit area	$f_c = \frac{c^2}{2\pi m}\left(\frac{12\rho^{3(1-\sigma^2)}}{E}\right)^{1/2}$	Central frequency of the corresponding 1/3 octave band
Dimentions	m/s	N/m^2	-	kg/m^3	kg/m^2	Hz	Hz
BCIT Laminated	343	70	0.23	2500	14.25	2094	1600-2000
W3	343	70	0.23	2500	14.25	2094	(2000-2500)

Table 11. Predicted and measured mass-air-mass resonance frequency for W3 and Laminated window

Parameter	d	T1	T2	D	m_1	m_2	Predicted f_{mam}	Measured f_{mam}
Description	Interpane spacing (d)	Glass 1 thickness	Glass 2 thickness	Glass Density	Mass per unit area of glass 1	Mass per unit area of glass 2	$f_{mam} = 60\left(\frac{m_1 + m_2}{m_1 m_2 d}\right)^{1/2}$	Central frequency of the corresponding 1/3 octave band
Dimentions	mm	mm	mm	g/cm^3	Kg/m^2	Kg/m^2	Hz	Hz
BCIT Laminated	8	6	5.7	2.5	15	14.25	248	250
W3	8	6	5.7	2.5	15	14.25	248	250

Table 12. Predicted and measured critical frequency for W3 and Laminated window

4.5.3. Window test No. 4

Window 4 was the only window in this study with the foam insulated frame. It was a 2600 casement window with two laminated glass panes with the interpane space of 21 mm. As it had the same glazing system as Window 5, the sound transmission loss graph of this window was compared with Window 5 in the following figure (Figure 50). This figure revealed that when using the BCIT Hybrid Test Method, the insolated foam frame in Window 4 did not result in significant changes in the overall window's sound transmission loss, the mass-air-mass resonance frequency, the critical frequency and their deeps compared to Window 5.

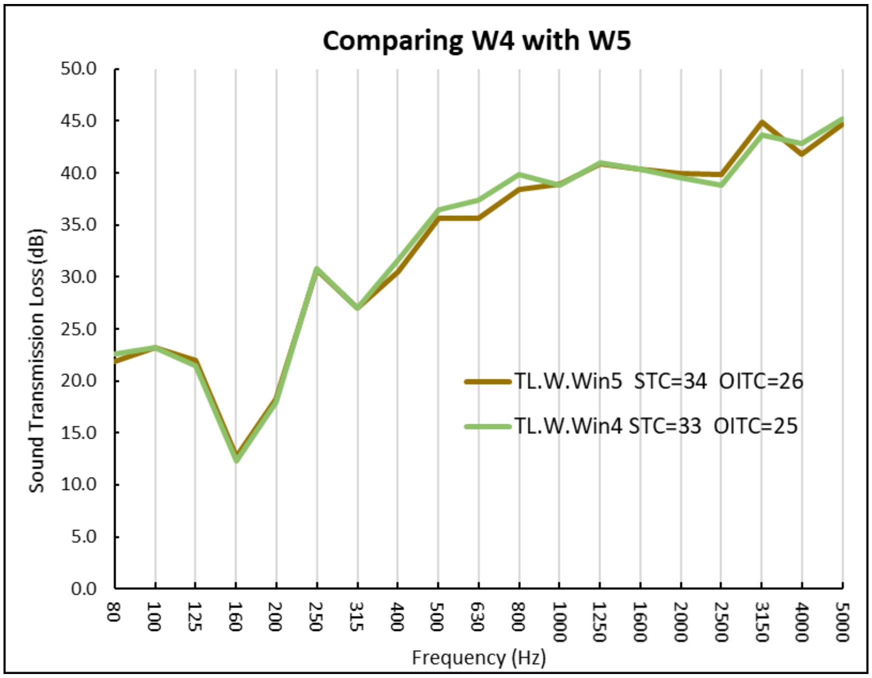


Figure 50. Sound Transmission loss curves for window 4 and window 5

4.5.4. Window test No. 5

Window 5 is a symmetric double-glazed casement window from 2600 series. It has two laminated glass panes with thickness of 6mm and an air cavity of 21 mm. Figure 51 presented Window 5 measured sound transmission loss based on the BCIT Hybrid Test Method and the predicted values related to the mass-air-mass resonance frequency and critical frequency of this window. As it can be observed in the following figure, the experimental results of the mass-air-mass resonance frequency and the critical frequency of Window 5 were in good agreement with the predicted values.

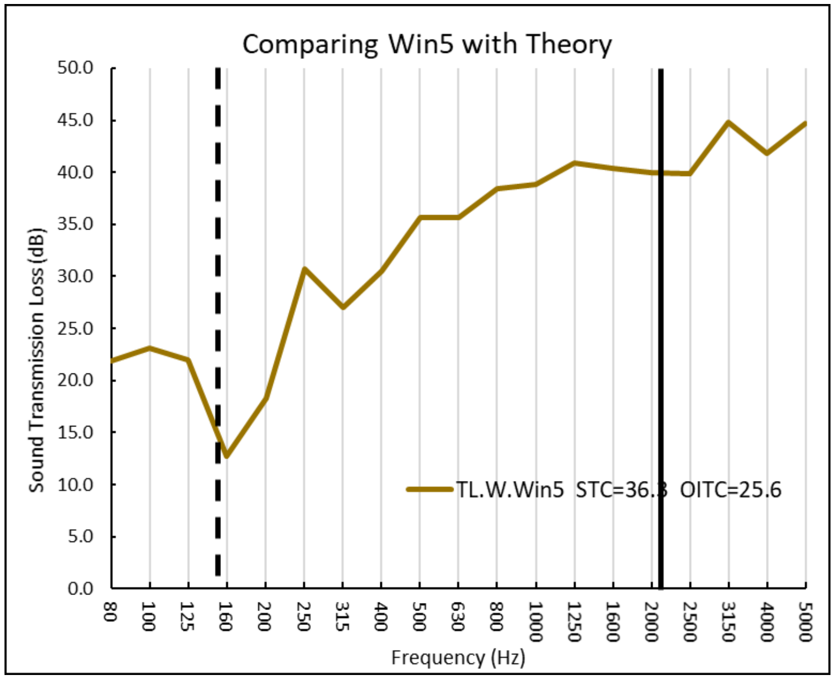


Figure 51. Comparing the predicted mass-air-mass resonance frequency and critical frequency with the experimental results of Window 5 based on the BCIT Hybrid Test Method

The measured mass-air-mass resonance frequency of Window 5 based on the BCIT Hybrid Test Method as presented in Table 13 was 160 Hz in compare with the predicted values of 148. For the critical frequency of Window 5, the experimental result was around 2000 to 2500 Hz as the measured sound transmission loss for these two frequencies were almost equal. The predicted value for critical frequency of this window was 2029. These results revealed an acceptable similarity between the theory and measurements for critical frequency of Window 5 as presented in Table 14.

Parameter	**d**	**T1**	**T2**	**D**	m_1	m_2	***Predicted*** f_{mam}	***Measured*** f_{mam}
Description	Interpane spacing (d)	Glass 1 thickness	Glass 2 thickness	Glass Density	Mass per unit area of glass 1	Mass per unit area of glass 2	$f_{mam} = 60\left(\frac{m_1 + m_2}{m_1 m_2 d}\right)^{1/2}$	Central frequency of the corresponding 1/3 octave band
Dimentions	mm	mm	mm	g/cm³	Kg/m²	Kg/m²	Hz	Hz
W5	21	6	6	2.6	15.6	15.6	148	160

Table 13. Predicted and measured mass-air-mass resonance frequency for W5

Parameter	C	E	σ	ρ	m	Predicted f_c	Measured f_c
Description	Speed of sound	Young's modulus of elasticity	Poasson's ratio	Density of the panel	mass per unit area	$f_c = \frac{c^2}{2\pi m}\left(\frac{12\rho^{3(1-\sigma^2)}}{E}\right)^{1/2}$	Central frequency of the corresponding 1/3 octave band
Dimentions	m/s	N/m^2	-	kg/m^3	kg/m^2	Hz	Hz
W5	343	70	0.23	2600	15.6	2029	2500

Table 14. Predicted and measured critical frequency for W5

Figure 52 displayed the sound transmission loss related to Window 5 and Window 2 based on the BCIT Hybrid Test Method. These two windows are both symmetric windows, first with both panes of glasses laminated and the latter with two annealed glasses. Therefore, comparing these two windows could help to investigate more about the BCIT Hybrid Test Method in distinguishing laminated and annealed glass. As it can be observed in Figure 52, Window 5 exhibits a lower mass-air-mass resonance frequency compared to Window 2 due to its larger air cavity. However, concerning the critical frequency, the difference in glass thickness between these windows is minimal, resulting in both windows having a measured critical frequency of approximately 2500 Hz."

Remarkably, Window 5, with both glass panes being laminated, shows a significant reduction in its critical frequency dip when compared to Window 2, which possessed two annealed glasses. This observation indicates that the inclusion of laminated glasses in Window 5 has a positive effect on mitigating the critical frequency dip which is in good agreement with the literature review.

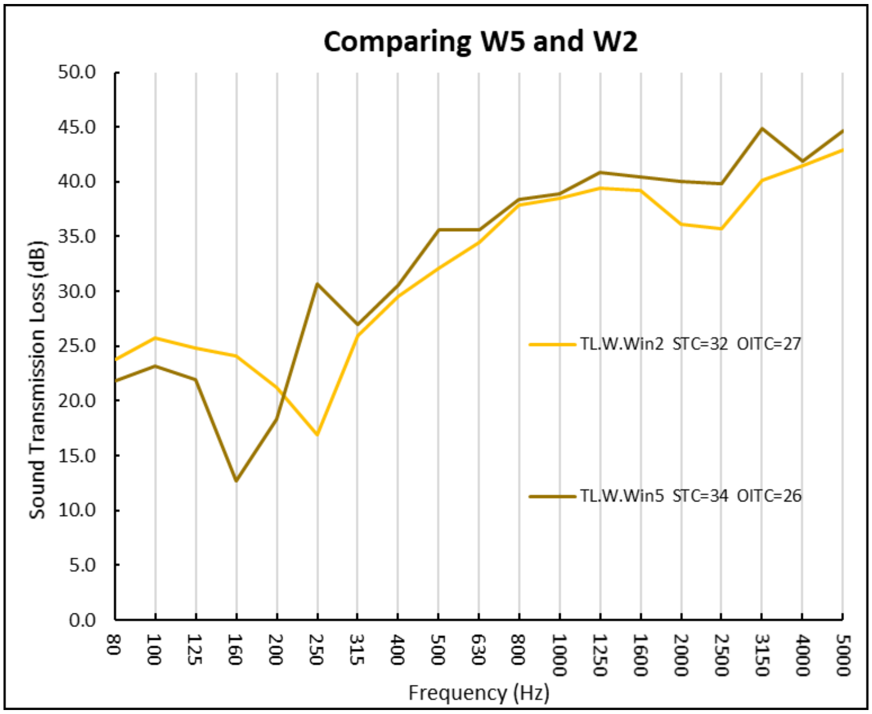


Figure 52. Sound Transmission loss curves for window 5 and window 2

Window 3 and Window 5 exhibit several notable differences. Firstly, their interpane spacing varies, with Window 5 having a larger distance between the glass panes (21 mm) compared to Window 3 (8 mm). Theoretical predictions suggest that this difference leads to a lower mass-air-mass resonance frequency for Window 5 compared to Window 3, and the measurements (Figure 53) align well with this theory.

Another significant distinction between these two windows lies in their glass thickness. Window 5 features symmetric glasses, with both glass panes measuring 6 mm and being laminated. In contrast, Window 3 displays a slight difference in glass thickness, with one pane measuring 5.7 mm and the other 6 mm. In theory, this difference may result in a slight improved dip in the critical frequency of Window 3 compared to Window 5. However, it is important to note that only the interior glass in Window 3 is laminated. This difference may contribute to a deeper dip in the critical frequency for Window 3 compared to Window

5, which benefits from the presence of laminated glass in both panes and potentially experiences increased damping in its critical frequency. Consequently, when comparing the measured sound transmission loss graphs for these two windows, both windows exhibit an equal coincidence dip (Figure 53). One hypothesis is that the effect of damping in Window 5 could be diminished by the negative impact of its symmetric glasses in this window.

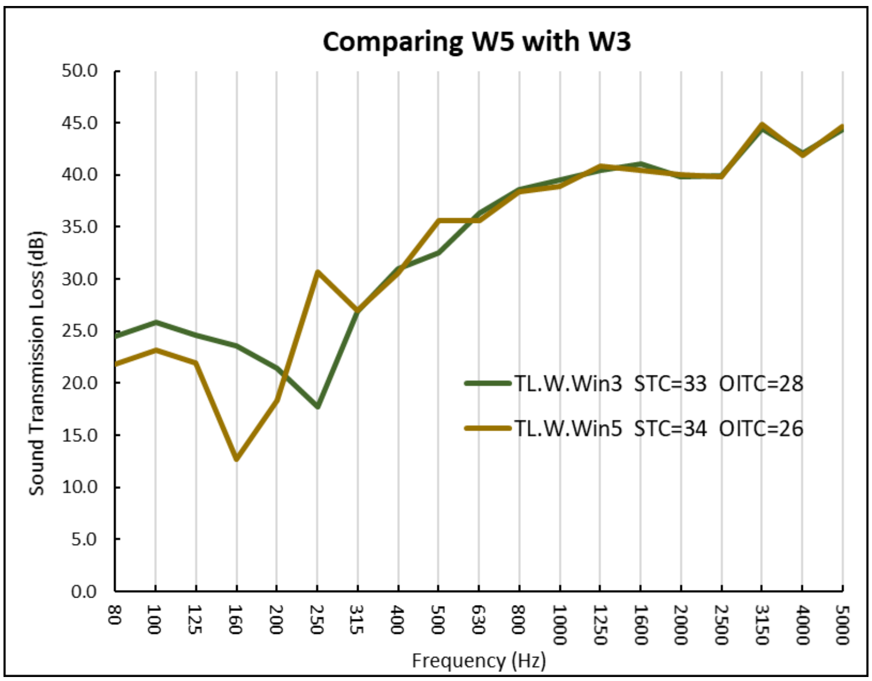
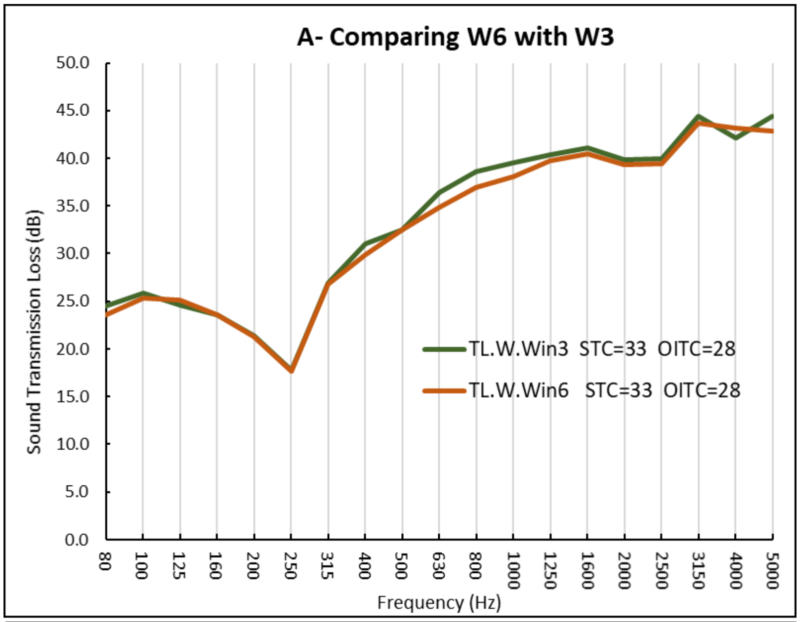


Figure 53. Sound Transmission loss curves for window 5 and window 3

4.5.5. Window test No. 6

Window 6 is an asymmetric double-glazed casement window, comprising a laminated 6 mm glass for the interior pane and an annealed 5.7 mm glass for its exterior pane. It belonged to the 2600 series. A comparison between Window 6 and Window 3 reveals striking similarities between the two windows. Window 6 was utilized in this thesis to assess the repeatability of the BCIT Hybrid Test Method, ensuring that the measurement results obtained with this method were acceptably consistent and repeatable.

Both windows exhibited identical mass-air-mass resonance frequencies and critical frequencies. However, there is a slight difference of less than 2 dB in the measured sound transmission loss between the two windows at frequencies 800 and 1000 Hz. This deviation can be attributed to the elevated level of inside background noise at these specific frequencies for Window 3 and 6 as can be observed in Figure 54. The presence of high background noise could influence the measured sound transmission loss in these frequency ranges.



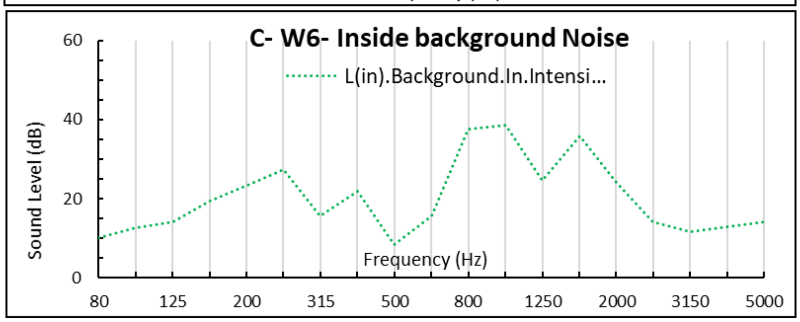


Figure 54. A- Sound Transmission loss curves for window 6 and window 3
C- Inside background noise for Window 6

5. Discussion

The main objectives of this study were to propose and validate the BCIT Hybrid Test Method in assessing the sound transmission loss of windows, and to investigate whether this method could accurately detect changes in the frame or the glazing system of the test windows. To discuss the validity of the BCIT Hybrid Test Method, the conducted tests were analyzed from different aspects. First, the experimental results by the BCIT Hybrid Test Method were compared with the findings of previous studies in this field, which are summarized in the literature review. Second, the theory concerning the two main frequencies in sound transmission loss of double-glazed windows (mass-air-mass resonance and critical frequencies) was compared and validated by the sound transmission loss measurements according to the ASTM E90 standard. Finally, the results of BCIT Hybrid Test Method were compared to the predicted values for mass-air-mass resonance frequency and critical frequency. The results demonstrated the validity of the BCIT Hybrid Test Method in measuring the sound transmission loss of windows, indicating its potential for use in early-stage window research. The study showed that the BCIT Hybrid Test Method could accurately depict the effects of variables such as the thickness of the glass panes, the depth of the air cavity, the use of laminated glasses, and symmetrical glazing on the sound transmission loss curves of double-glazed windows.

5.1. Consistency with the previous studies and researches

In this thesis the effect of following variables on the sound transmission loss of window tests were analyzed: glass thickness, interpane spacing, Laminated glass and symmetrical glazing. As previously discussed the BCIT Hybrid Test Method could distinguish the increase in the glass thickness of a window. The sound transmission loss graphs obtained from the BCIT Hybrid Test Method showed a decrease in the critical frequency by increasing the thickness of the glass. Also, except for the frequencies around the mass-air-mass resonance frequency and the critical frequency, there was an increase in the sound transmission loss of the test windows by increasing the thickness of the glass, which is in compliance with the mass law. This can be observed in Figure 55 which compared the sound transmission loss graphs of Window 2 and Annealed window. Window 2 had two annealed glass with the same thickness of 5.7 mm and Annealed window had two annealed glass, one with a width of 3.9 mm and the other with a width of 5.7 mm. In the vicinity of the mass-air-mass resonance frequency and critical frequency, Window 2 had less sound transmission loss although it had thicker glass panes. One important reason for the decrease in the sound transmission loss of Window 2 comparing with BCIT Annealed window, is related to the effect of symmetrical glazing on the amount of drops occurs in the two dips in the transmission loss graphs; mass-air-mass resonance frequency and critical frequency. For other frequencies, the graph related to Window 2 showed greater values for the sound transmission loss curves which is in agreement with the mass law.

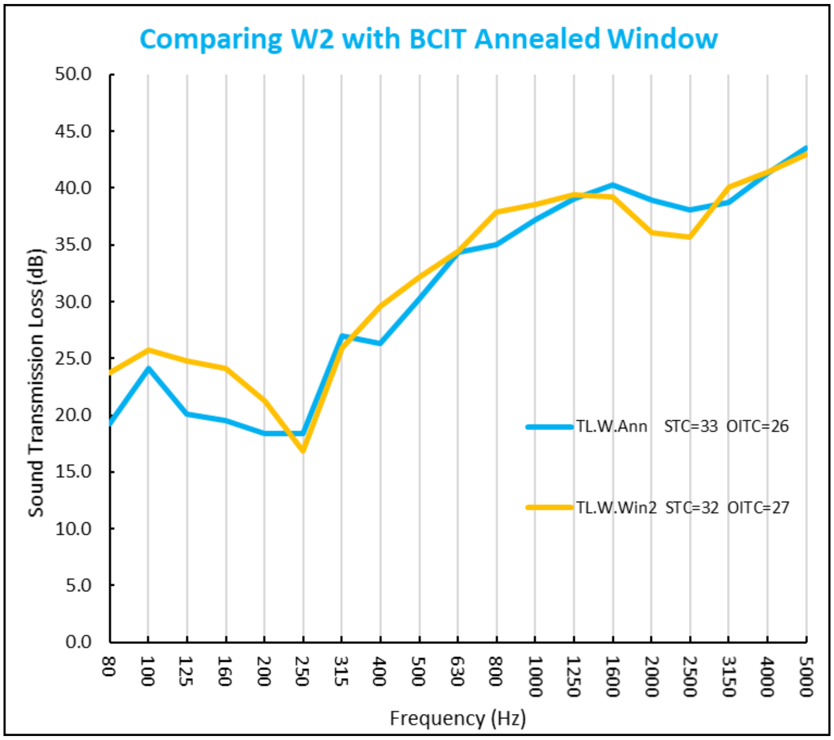


Figure 55. Sound Transmission loss curves for window 2 and BCIT Annealed window

The measurement results in this study indicated that the BCIT Hybrid Test Method effectively captured the impact of varying interpane spaces in the sound transmission loss graphs of windows. Increasing the width of the gap between the glass panes resulted in a decrease in the mass-air-mass resonance frequency. However, within this series of test windows in this study, enlarging the air gap coincided with using symmetrical glass panes. This combination led to a deeper mass-air-mass resonance dip. Consequently, the positive effect of increasing the interpane space was counteracted by the negative effect of using symmetrical glass panes.

The BCIT Hybrid Test Method in this study, effectively highlighted the impact of glass lamination on sound transmission loss. Windows with laminated glass showed reduced critical frequency dips compared to those with annealed glass, aligning with previous findings as mentioned in literature review, and indicating improved acoustic performance due to laminated glass. However, the BCIT Hybrid Test Method indicated that the inclusion of laminated glass in both panes with the same thicknesses as explained before had negative impact on the acoustic performance of the test windows. This phenomenon was also observed in two series of the ASTM E90 test results when in the double-glazed window, one glass was annealed and one was laminated but the thickness of these two glasses was almost the same.

5.2. Consistency with Theoretical Predictions

The results obtained through the BCIT Hybrid Test Method demonstrate a consistent trend with theoretical predictions introduced in the literature review regarding the mass-air-mass resonance frequency. In the BCIT Hybrid Test Method measurements, an increase in interpane spacing is accompanied by a decrease in mass-air-mass resonance frequency, aligning with theoretical expectations and confirming the method's ability to represent the effect of interpane spacing on window acoustic behavior. The close agreement between the measured data and the theoretical predictions further validates the reliability and validity of the BCIT Hybrid Test Method. In Table 15, the results of both measured and theoretical prediction of mass-air-mass resonance frequency of all windows employed in this study can be observed.

Parameter	d	T1	T2	D	m_1	m_2	*Predicted* f_{mam}	*Measured* f_{mam}
Description	Interpane spacing (d)	Glass 1 thickness	Glass 2 thickness	Glass Density	Mass per unit area of glass 1	Mass per unit area of glass 2	$f_{mam} = 60\left(\frac{m_1 + m_2}{m_1 m_2 d}\right)^{1/2}$	Central frequency of the corresponding 1/3 octave band
Dimentions	mm	mm	mm	g/cm³	Kg/m²	Kg/m²	Hz	Hz
BCIT Annealed	9.8	3.9	5.7	2.4	9.36	13.68	257	250
E90 Annealed	11	4	6	2.4	9.6	14.4	238	200
BCIT Laminated	8	6	5.7	2.5	15	14.25	248	250
E90 Laminated	13	6	6	2.5	15	15	192	200
W2	8	5.7	5.7	2.4	13.68	13.68	256	250
W3	8	6	5.7	2.5	15	14.25	248	250
W4 Foam	21	6	6	2.6	15.6	15.6	148	160
W5	21	6	6	2.6	15.6	15.6	148	160
W6	8	6	5.7	2.5	15	14.25	248	250

Table 15. Predicted and measured mass-air-mass resonance frequency for windows phase one and two of this study

Similarly, the BCIT Hybrid Test Method demonstrated consistent results with theoretical predictions when examining the impact of glass thickness on the critical frequency. Thicker glass panes in windows led to lower critical frequencies, aligning with the expected trend. However, a slight difference was observed between the measured data and theoretical predictions. Further investigation and tests are needed to better understand the reasons behind these deviations. Table 16 displays the critical frequency results for all windows used in this study, both the measured values and the theoretical predictions.

Parameter	C	E	σ	ρ	m	Predicted f_c	Measured f_c
Description	Speed of sound	Young's modulus of elasticity	Poisson's ratio	Density of the panel	mass per unit area	$f_c = \frac{c^2}{2\pi m}\left(\frac{12\rho^{3(1-\sigma^2)}}{E}\right)^{1/2}$	Central frequency of the corresponding 1/3 octave band
Dimentions	m/s	N/m^2	-	kg/m^3	kg/m^2	Hz	Hz
BCIT Annealed	343	70	0.23	2400	9.36	2999	2500
E90 Annealed	343	70	0.23	2400	9.6	2924	(2500-3150)
BCIT Laminated	343	70	0.23	2500	14.25	2094	1600-2000
E90 Laminated	343	70	0.23	2500	15	1989	(2000-2500)
W2	343	70	0.23	2400	13.68	2052	2500
W3	343	70	0.23	2500	14.25	2094	(2000-2500)
W4 Foam	343	70	0.23	2600	15.6	2029	2500
W5	343	70	0.23	2600	15.6	2029	2500
W6	343	70	0.23	2500	14.25	2094	(2000-2500)

Table 16. Predicted and measured critical frequency for windows phase one and two

5.3. Departure from the referenced standards

This section discusses a number of departures from the referenced standards. The BCIT Hybrid Test Method, which integrates components from the ASTM E966 (2011) and the ISO 15186-1 (2016) standards, is designed to assess the acoustic performance of windows in a manner that is both more accessible and cost-effective. Some of these departures are inherent to the methodology employed by this method. These departures, therefore, contribute to the innovative nature of the BCIT Hybrid Test Method and its potential to advance the field of window acoustic performance evaluation. These departures were deliberately incorporated into this method, making it more suitable for small laboratories with limited resources and providing an economical alternative to standards such as ASTM E90, ASTM E966, ASTM E2249, ISO 15186-1, and ISO 140. Other departures related to the available measurement equipment and also the available lab infrastructure.

As it was explained, this study adhered to the ASTM E966 (2011) for source side measurements and the ISO 15186-1 (2016) for receiver side measurements. This amalgamation of the two standards was intended for the primary objective of assessing the compatibility and effectiveness of this combined approach in evaluating window acoustic performance.

The second departure pertains to the sound pressure level measurements for the window's exterior surface. The five measurements of the exterior surface of the test windows that was explained in the section 3.1.2 of this study, were conducted sequentially in this study as was depicted in Figure 13, diverging from the ASTM E966 (2011) standard, which prescribes simultaneous measurements at different specimen points. This departure, coupled with exposure to the outside environment, could introduce variations in exterior measurements, leading to imprecise results.

For the exterior measurements in accordance with section 8.2.4 of the ASTM E966 (2011) standard, a preferred sound pressure variation of 3 dB across the exterior surface of test specimen is recommended. In this study, despite efforts to adjust the loudspeaker's position and direction to achieve uniform sound pressure levels on the test windows' exterior side, In most frequencies, this value was above the acceptable limit in the exterior measurements. This variation may be attributed to external factors such as fences and the big overhang in the place of the exterior measurements as can be observed in Figure 56. Further investigation is needed to comprehend the impact of varying external noise pressure levels on the results.

Figure 56. Outdoor space for external testing

Another point of departure was that the exterior and interior measurements were not conducted simultaneously, due to the instrument availability in the lab. This departure could lead to less precise results for the calculated sound transmission loss in test windows, especially considering that the test methodology indicated the exterior measurements being taken in the outdoor environment. In such cases, the lack of simultaneous measurements may introduce additional variability due to inevitable fluctuations in the exterior sound pressure level.

Another departure was that the exterior and interior measurements were not done at the same time due to the instrument that was available in the lab. This departure could potentially lead to imprecise results for the calculated sound transmission loss for the test windows, especially considering that the tests were conducted in an uncontrolled exterior environment.

Lastly, this study departure from the ASTM E966 (2011) by employing a microphone windscreen with an approximate width of 1.5 mm for the flush method as can be seen in Figure 57. The standard suggests a modified foam windscreen that is partly cut away to permit placement of the microphone close to the surface. This equipment variation should be considered within the context of measurement methodology. However, the distance of the microphone from the exterior surface of the test windows during the measurements were all the time within the acceptable range with this thin windscreen.

Figure 57. Outdoor space for external testing

In summary, this section has outlined several departures from referenced standards, including the sequential nature of exterior measurements, challenges in achieving uniform sound pressure levels on the test windows' exterior side, discrepancies in interior background noise levels, and equipment variations such as microphone windscreen. These insights provide valuable considerations for potential areas of improvement and opportunities for further research. By recognizing these limitations and their potential implications, future research and improvements in measurement techniques may lead to enhanced precision and repeatability of the BCIT Hybrid Test Method.

5.4. Limitations of this study

One significant limitation was the manual nature of measurements in this thesis, which introduced a degree of subjectivity as the accuracy of results depended on the individual conducting the tests' skill level. Implementing a mechanical base method of measurements, specifically in the scanning method with the intensity probe, could reduce errors related to individual discrepancies. Particularly in this thesis's methodology, where scanning was done on an imaginary surface, maintaining a constant speed of movement of the intensity probe and adhering to the imaginary surface of measurements can affect results.

Conducting exterior measurements in an outdoor environment exposed the tests to uncontrolled factors such as wind, moisture, and temperature variations. Each of these factors could potentially influence test results. However, understanding each factor's precise impact on test outcomes is complex and necessitates further investigation and in this stage not being aware of the exact effect of these factors can be considered as the limitation of this method.

Another critical issue was related to the specimens used in the first phase. These windows were not completely matched to each other. Having identical samples tested with two different methods and comparing them could yield more accurate results. It would be beneficial to have exact windows tested with these two methods of measurement. Given that the E90 windows had different interpane spacing compared to the BCIT first phase windows, this thesis was limited to analyzing the mass air mass resonance and critical frequencies for indirect comparison of the two test methods. Furthermore, the effects of laminated glazing and symmetrical glazing were examined on a comparative basis.

Lastly, the study utilized a sound analyzer software, Samurai, to perform measurement and analysis functions. This software processed the data recorded by the microphone and intensity probe. However, the software functioned as a black box, with its internal calculations and applied methodologies remaining unclear. Greater transparency about the software's inner workings could significantly aid in analyzing the measurement results. These limitations provide valuable insights into our study's constraints and highlight areas where further research or alternative methodologies may be beneficial.

6. Conclusions

This study has explored the BCIT Hybrid Test Method's effectiveness, a hybrid approach that combines elements of the ASTM E966 (2011) and the ISO 15186-1 (2016) standards, in evaluating the acoustic performance of double-glazed windows. The results have demonstrated a consistent trend with theoretical predictions and previous studies, validating the method's reliability in terms of detecting the effects of changing mass per unit area of glass panes, changing the depth of the interpane space, having laminated glazing compared to annealed glazing and having symmetrical glazing.

However, several departures from the referenced standards were observed, primarily due to the manual nature of measurements and the outdoor environment's uncontrolled factors. These departures, coupled with equipment variations such as microphone windscreen, highlight areas for potential improvement and further research.

The study also identified limitations related to the specimens used and the sound analyzer software, Samurai. Despite these limitations, the BCIT Hybrid Test Method potentially can be an accessible and cost-effective alternative for assessing window acoustic performance in the early stages of research and development in a comparative base.

Future research should focus on addressing the aforementioned limitations to enhance the precision and repeatability of the BCIT Hybrid Test Method. This includes implementing a mechanical base method of measurements, understanding each environmental factor's precise impact on test outcomes, using identical samples for different methods, and gaining more transparency about the software's inner workings.

In conclusion, the BCIT Hybrid Test Method, despite its limitations, provides a valuable foundation for future research in this field. With further refinement and investigation, this method could greatly facilitate the evaluation of window acoustic performance in their preliminary stages. This would not only benefit window manufacturers in their product development process but also contribute to mitigating noise pollution in urban areas.

7. References

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