
Jeffrey Mahn
Acoustics Research Group
Mechanical Engineering Department
University of Canterbury
Private Bag 4800
Christchurch 8140
New Zealand
jma251@student.canterbury.ac.nz
+64 3 364 2987 ext. 7090
Abstract

The standard, EN12354-1 describes a simplified statistical energy analysis (SEA) model to predict the apparent sound reduction index between two rooms inclusive of the contributions of the flanking paths. There is interest worldwide in applying the EN12354 model to lightweight building elements. However, lightweight elements typically do not meet the requirements of an SEA subsystem and therefore applying the EN12354 model to these elements may result in inaccurate predictions.

The purpose of this investigation was to systematically evaluate the application of the EN12354 model to lightweight building constructions. The evaluation included the determination of the probability density functions and the propagated uncertainty of the calculations. Knowledge of the probability density functions resulted in alternative calculations of the structure-borne sound transmitted through the constructions. The uncertainty analysis revealed that the uncertainty of the predictions is directly affected by the variance of the vibratory field measured on the elements. The vibratory fields of lightweight elements typically show large variances and therefore the propagated uncertainty of the EN12354 predictions for these elements can be significant.

The investigation included measurements both in the laboratory and in the field. The results of the laboratory measurements were compared to both predictions using the EN12354 methods and ESEA models which included higher order flanking paths and non-resonant transmission paths. The field measurements included in this investigation were unique because the flanking intensity sound reduction indices of the elements in the source room were measured. The measurements allowed for the EN12354 predictions for each flanking element to be assessed instead of just the apparent sound reduction index between the rooms.

The study resulted in proposed correction factors for when reciprocity does not hold and proposed changes to ISO10848 to improve the accuracy of the predictions when the EN12354 method was applied to lightweight building elements. However, neither the proposed correction factors nor the proposed changes to ISO10848-1 could correct for the potentially large differences between the predicted and the measured results.

Lightweight constructions may not be categorized as ideal SEA subsystems due to the lack of diffuseness of the vibratory field. Furthermore, in order for EN12354 to be applied to lightweight constructions, a reliable method of calculating the resonant component of the sound reduction index of double-leaf elements is required. Therefore, statistical methods including the EN12354 method may be unsuitable for use for the prediction of flanking noise for lightweight building constructions.

Based on the findings of this study, the use of the current EN12354-1 standard for the calculation of the apparent sound reduction index of lightweight elements is not endorsed.
1. Introduction

1.1. Noise and Annoyance in Buildings

Noise and annoyance in buildings has become an important subject as multi-tenancy buildings have become more common [1]. The number and the power of noise sources such as home appliances, home theatres and heating units have increased at the same time that people are becoming more aware of noise problems [2]. For example, noise complaint statistics from the Christchurch City Council for the year ending 30 June 2008 show that a total of 10,566 noise complaints were received by the council [3]. A study in the Netherlands showed 1/3 of all households experienced annoyance due to noise from neighbors [4]. In one Swedish study 82% ranked good sound insulation as their top priority among desired improvements [5]. A study in Germany reported that noise was a particularly important criterion when people chose a new residence or when they decided to change residences [6].

Beyond being just an annoyance, noise in buildings can influence the quality of life of those it affects. In a study by Grimwood [7], people reported that they had modified their behavior and their social lives due to poor sound insulation. Thirty-five percent of people said that both they themselves and visitors had to behave quietly and 18% said that they didn’t have visitors because of the noise they might make or might hear. Adults who indicated chronically severe annoyance by neighbor noise were found to have an increased health risk in the cardio-vascular system, the movement apparatus, as well as increased risk of depression and migraine headaches [8]. The effect of moderate annoyance to neighbor noise on children (0-17 years) is associated with elevated risks for respiratory symptoms and skin disease as a result of emotional stress [9]. Neighbor noise induced annoyance is therefore a highly underestimated risk factor for healthy housing [8]. Conversely, those who cause the noise may not understand why others are annoyed and may see those who complain as being unreasonable [10].

Van Dongen [4] found that the percentage experiencing annoyance and/or the degree of annoyance experienced in many cases clearly diminished in proportion to the quality of the sound insulation. Robert Frost’s quote, “good fences make good neighbors” could be rewritten in this context to “walls with excellent sound insulation make for better neighbors.”

1.2. Current Regulation to Reduce Noise in Buildings

To reduce the problem of noise in buildings, the New Zealand Building Code Clause G6: “Airborne and Impact Sound” states minimum requirements for the sound transmission class of building elements of habitable spaces of household units including walls, floors and ceilings for new constructions in New Zealand [11]. However, it is often the case that building elements which were chosen based on laboratory testing according to ISO140 to meet the minimum requirements are found to have a lower sound reduction index once they are installed in the building, sometimes much lower [12, 13]. For example, in 1972, Lang [5] found that on average the weighted apparent sound reduction index in finished dwellings was 8 dB less than that which the partition itself should have provided according to laboratory measurement. Hongisto [14] found that the weighted sound reduction indices of walls
measured *in situ* could differ by up to 9dB from those measured in the laboratory due to the effects of flanking transmission.

Flanking transmission can strongly affect the sound insulation between rooms in a building. In buildings with heavy constructions of concrete or masonry, the flanking transmission may account for approximately fifty percent of the sound transmission between rooms with a common dividing partition [15]. Usually, each flanking path will be less important than the direct path but, since there are many such paths, flanking will often be important in the overall transmission of sound between two rooms [16]. If the source room and the receiver room have no common wall the entire sound transmission is through flanking paths [17].

In a study by Langdon [18] on noise in multi-tenant buildings, two-thirds of the people questioned heard noise from neighbors of one sort of another. What was striking about the response was that little noise was heard through the party walls but a great deal of noise was reported as coming from other parts of the building such as stairways, corridors and entrances and from outside. Langdon notes that the findings draw attention to the need to consider sound insulation not merely in terms of individual components such as party walls or floors between adjoining residences, but in terms of the building as a whole. Therefore, flanking transmission must be taken into consideration at the design stage when choices are being made concerning walls and floors and the junctions between them.

### 1.3. Controlling Flanking Transmission

Unfortunately, noise problems in buildings due to flanking transmission are often only discovered after the building has been constructed. At this point, efforts to meet the minimum requirements can be more costly and less efficient than if the building elements were properly specified in the design phase [19]. Very seldom has bad sound insulation been repaired. As a result, there are a large number of dwellings that do not comply with the minimum sound insulation requirements [5].

In conversations with acoustic consultants, many have confided that although they are aware of the problem of flanking transmission, the apparent sound reduction index is perceived as being too difficult to calculate and therefore flanking transmission is often ignored. This can lead to buildings that do not meet the building code or building elements which are overdesigned in an attempt to increase the apparent sound reduction index. Therefore, an accurate prediction method is needed that can be used to predict the apparent sound reduction index with confidence. Such a prediction method would not only aid Building Research to assess new building designs, but it would also help the building industry to mitigate costs by allowing less costly building elements which may not otherwise meet the minimum requirements for floor thickness, for example to be assessed.

### 1.4. Development of EN12354

In 1979 and 1986, Gerretsen of Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek (TNO) in Delft published studies which described expressions for first order flanking paths in terms of the sound reduction of the flanking elements and the velocity attenuation at the junction between the building elements in the
source and the receiver rooms [20, 21]. Gerretsen’s research became the basis for the European Committee for Standardization (CEN) standard, EN12354-1:2000: ”Estimation of acoustic performance of buildings from the performance of products” [22, 23]. The EN12354 method offers a standard method of predicting the apparent sound reduction index between rooms inclusive of the flanking paths. Inputs for the method include the velocity attenuation at the junctions between the building elements which may be calculated according to the recently released ISO10848-1:2006 [24]. This standard is an integral part of the calculations according to EN12354-1 and is included in the description of the EN12354 method in this study.

In the derivation of the EN12354 method, a number of assumptions were made about the building elements and the junctions between them. The assumptions had the benefit of simplifying the calculations to result in a standard method of calculating the apparent sound reduction index. For the assumptions to be satisfied, both the source and receiving elements must be homogeneous, isotropic and moderately damped. Heavy cast-in-place as well as masonry constructions usually satisfy these conditions well [25]. For buildings with mainly heavy, monolithic structures, the EN12354 method has been described as quite useful [26].

1.5. Lightweight Building Constructions

There is great interest globally in also applying the EN12354 method to lightweight building constructions. These constructions constitute a large percentage of the single and double family houses built in North America, Australia, New Zealand, Japan and Europe [27]. However, lightweight constructions are considerably more difficult to model than the heavy monolithic structures and considerable effort will be required to adapt the EN12354 method to lightweight constructions [28].

One of the leaders in the investigation of flanking noise in lightweight constructions has been the team at the National Research Council of Canada Institute for Research in Construction (NRC-IRC). The team at the NRC which includes Nightingale and Quirt, has published a series of guides which are available on its website as well as journal articles regarding the application of the EN12354 method to lightweight constructions. Crispin of the Belgian Building Research Institute has published a number of studies in regard to the vibration reduction index which is an input for the EN12354 method. Rindel formerly of the Technical University of Denmark has published journal and congress articles regarding flanking noise in lightweight constructions. There are also a number of other studies being conducted worldwide which are published in journals such as Building Acoustics, the Journal of Sound and Vibration and Applied Acoustics as well as the proceedings of several international acoustics congresses.

For example, Pedersen [29] and Metzen [30] have compared the weighted apparent sound reduction index calculated according to EN12354-1 and ISO717-1 [31] to measured values. Both studies evaluated a large number of lightweight building constructions (the study by Pedersen evaluated over 200 constructions). Pederson reported that the EN12354 method overestimated the flanking sound reduction index in some cases and under predicted in others. The difference between the calculated and the theoretical values was as high as 10 dB in some cases, but the overall average was 0 to 0.5 dB with a standard deviation of 3.1 dB for
walls and 3.2 dB for floors. The standard deviation for lightweight structures was higher than for monolithic structures which were also evaluated. Metzen reported that the EN12354 method under predicted the weighted apparent sound reduction index by 1.3 ± 1.1 dB.

However, neither study compared the calculated and the measured contributions from each flanking path. Furthermore, both of these studies only published the single number ratings. A separate study by Bradley [32] showed that comparing single number values for the apparent sound reduction index can show good agreement even when the 1/3 octave band data shows significant disagreement. Furthermore, the study by Pedersen used theoretical values for the vibration reduction index from the annex of EN12354-1. Pedersen notes that applying the value from the annex to lightweight constructions was probably less accurate than for monolithic elements. Other studies have shown that the value of the vibration reduction index calculated from the annex does not match the behavior of the vibration reduction index measured in the laboratory [33, 34]. Pedersen also used the sound reduction index of the lightweight building elements which included the non-resonant component which EN12354-1 states should not be included in the calculations. Therefore, although both of these studies were extensive evaluations of the EN12354 method, the input data which was used and the use of single number ratings for the evaluation does not allow for a true assessment of the errors of applying the method to lightweight constructions. What is needed to assess the accuracy of the EN12354 method is a systematic evaluation of the contribution of each flanking path to the apparent sound reduction index.

1.6. Current Research

The goal of the current research was to systematically evaluate the application of the EN12354 method to lightweight building constructions. The evaluation included the calculation of the uncertainty of the estimate based on the uncertainty of the inputs such as the resonant sound reduction index and the vibration reduction index. Predictions using the EN12354 method were compared to predictions using Statistical Energy Analysis and laboratory and field measurements. Changes to the EN12354 method were proposed to improve the accuracy of the predictions.

The outcome of this research was to be an understanding of some of the possible errors of applying the EN12354 method to lightweight building constructions so that it can be either used with caution or with confidence.
2. Limitations to the Application of the EN12354 Method

2.1. Introduction

An advantage of the EN12354 method is that it is straightforward to apply as compared to a full Statistical Energy Analysis (SEA) model. Even a path by path analysis of a full SEA model requires the calculation of the loss and coupling factors whereas the EN12354 method always uses the same equations and input data from a library of test data be put into the model. However, the relative simplicity of the EN12354 method was achieved by making assumptions about the elements and junctions of the system being evaluated. The simplifying assumptions limit the wall and junction systems to which the EN12354 method can be accurately applied. A summary of a number of the limitations to the application of the EN12354 method is presented in this chapter.

2.2. Restriction to First Order Flanking Paths

To make the EN12354 method manageable, it was assumed that contributions from higher order paths (paths which involve more than one junction) were insignificant compared to the first order paths and of the direct paths. Therefore, the EN12354 method only considers the flanking transmission between two elements and the junction between them [25]. However, Craik [35] has written that while the individual higher order flanking paths may be insignificant compared to the direct transmission, the sum of the contributions of the higher order paths may be significant. Craik estimated that the errors could be on the order of 5 - 10 dB. In a separate study, Galbrun [36] also found errors due to the exclusion of higher order flanking paths.

The exclusion of higher order flanking paths limits the application of the EN12354 method. For example, the EN13254 method can only be used to calculate the apparent sound reduction index between two adjacent rooms. Rooms that do not share a common element or junction would require the use of higher order flanking paths and a more complex SEA model would be required.

The exclusion of higher order paths also limits how problem elements, such as those with non-uniform energy density can be included in the analysis. It is possible to include a subsystem with non-uniform energy densities in a full SEA model by breaking up the subsystem into two or more subsystems with the appropriate coupling between them [25, 37]. However, the additional subsystems would require higher order flanking paths.

Nightingale investigated the possibility of including higher order flanking paths by using an effective vibration reduction index [38]. The study showed that it is not possible to simply sum the values of the vibration reduction indices along a longer flanking path. Furthermore, the use of an effective vibration reduction index was limited to elements which satisfy the requirements for a SEA plate subsystem.

In this study, the exclusion of the higher order flanking paths was investigated by comparing the results of predictions using the EN12354 method to those from full ESEA models inclusive of higher order flanking paths. The exclusion of the higher order paths was found
to lead to differences between the measured and the predicted results as high as 13 dB for some of the elements tested in the laboratory. However, the predictions from the full ESEA models still differed from the measured values. Therefore, even a more complex SEA model could not accurately predict the flanking sound reduction index of the elements tested despite the inclusion of the higher order flanking paths. The results show that the use of SEA may be inappropriate for the lightweight elements tested in this study.

2.3. Elements as Ideal SEA Subsystems

Several authors [35, 38] including Gerretsen [39] have equated the EN12354 method to a first order approximation of a SEA model. Therefore, the elements and transmission paths to which the EN12354 method is applied are subject to the same requirements as those of an SEA subsystem [23]. The requirements include [23, 40]:

- The vibration response is controlled by resonant modes of vibration.
- The frequency band under evaluation must contain resonant modes.
- The elements must support a uniform energy density (diffuse vibratory fields).
- The elements must be moderately damped.
- The elements must be weakly coupled.
- The forces which act on each element must be statistically independent.

These requirements have been shown to be acceptable for heavy, monolithic constructions such as concrete, but not necessarily applicable for lightweight constructions such as double-leaf timber framed walls [26, 29] as discussed in the following sections.

2.3.1. Resonant Modes of Vibration

The calculation of the EN12354 estimate of the flanking sound reduction index includes as inputs the sound reduction indices of the elements in the source and receiving room. In compliance with the requirement of a SEA subsystem that the vibration response is controlled only by resonant modes of vibration, the sound reduction index used in the calculations must only be the resonant component of the total sound reduction index. Although the non-resonant component of the sound reduction index may be larger than the resonant component below the critical frequency, it must not be included in the EN12354 calculations or else the EN12354 method may underestimate the value of the flanking sound reduction index [23].

The requirement that only the resonant component of the sound reduction index be used in the calculation of the flanking sound reduction index presents a significant difficulty in applying the EN12354 method to lightweight constructions which may have a critical frequency in or above the frequency range of interest. For these materials, the sound reduction index measured according to ISO140 [41] or ISO15816 [42] may include a significant contribution from the non-resonant component and therefore may not be used in the EN12354 calculations.

EN12354-1:2000 does not offer guidance for the calculation of the resonant component of the sound reduction index. Several methods of determining the resonant component of the sound
reduction index from measured data or from theoretical calculations have been proposed in the literature and these methods were evaluated as part of this study by comparing the predictions according to EN12354 to measured data. None of the EN12354 predictions using the various methods of predicting the resonant component of the sound reduction index accurately fit the measured flanking sound reduction index. The lack of accuracy is due in part to the theoretical models which are based on single-leaf elements rather than double-leaf elements as well as uncertainty in the measurement of the sound reduction index.

If EN12354 is to be applied to lightweight double-leaf structures, then a reliable theory for calculating the resonant component of the sound reduction index of double-leaf constructions is needed. Otherwise, the apparent lack of accuracy of the calculations for single-leaf constructions when applied to double-leaf constructions may limit the application of EN12354 to constructions with critical frequencies below the frequency range of interest.

The results of the investigation of the separation of the resonant component of the sound reduction index were presented at Inter-Noise 2007 [43] and published in the journal, *Building Acoustics* in June, 2008 [44, 45].

2.3.2. Sufficient Modal Overlap
The fundamental element of the SEA model is a group of energy storage modes. These modes are usually of the same type (flexural, torsional, acoustical) that exist in the subsystem. The power transmitted between the subsystems depends on the difference in modal energy of the subsystems and the strength of the coupling between them. Energy storage in each subsystem is determined by the number of available modes for each subsystem in each frequency band [46]. If SEA is to be used to predict structure-borne sound transmission, then it is necessary for the response of the structure to be controlled by resonant modes. This requirement can therefore put a limit on the frequency range over which SEA can be applied since there may be few modes present to store energy at the lower frequencies [47]. Hopkins [48] notes that it is still possible to apply SEA in the 1/3 octave bands where there are few modes present, but with errors in the predictions of unknown magnitudes.

Therefore, in order to apply the EN12354 method with confidence, the values of the modal overlap factor and the number of modes of the elements should be calculated in each 1/3 octave band to determine the validity of the calculations. However, EN12354-1 currently does not include guidance for calculating these values or limits on the frequency range to which the predictions can be applied. The omission of limits can lead to false confidence in the results of the predictions and as this study showed, errors in the predictions at the low frequencies in excess of 20 dB.

2.3.3. Uniform Energy Density and Moderate Damping
The ideal SEA subsystem and therefore the EN12354 element is required to support a uniform energy density. It is therefore also assumed that the surface velocity is uniform when the element is excited along the elements edge with the junction [25] as would be the case for flanking transmission in buildings. For these conditions to be satisfied, the elements are assumed to be homogeneous, isotropic and moderately damped [49].
Nightingale has reported that the vibration response of lightweight wood frame constructions is typical of a periodic plate/beam structure and therefore should not be considered as homogeneous and isotropic [49]. The vibration field in framed wooden structures can exhibit a strong gradient that will be different in directions parallel and perpendicular to the joints [50]. Therefore, these elements do not meet the basic requirements for simplified prediction models such as the EN12354 method [49]. Villot adds that since lightweight elements are often highly damped, the vibrational fields are no longer reverberant and existing standards often lose relevance [51].

The lightweight elements tested as part of this study all failed to support diffused vibratory fields as defined by ISO10848-1. Therefore, more complex elements typical of lightweight constructions in New Zealand are also expected to fail to support diffused vibratory fields. It is possible to include a subsystem with non-uniform energy densities in a full SEA model by breaking up the subsystem into two or more subsystems with the appropriate coupling between them [25, 37]. However, the EN12354 method does not allow for an arbitrary number of subsystems due to the exclusion of higher order flanking paths.

As part of this study, an alternative calculation of the average velocity level and the average velocity level difference of the elements was proposed based on the probability density function of the non-diffuse vibratory field of lightweight elements. Failure to account for the correct probability density function of the mean square velocity measured on the elements can lead to errors of several dB in the flanking sound reduction index predicted by EN12354. However, the proposed estimates were not sufficient to correct the errors due to the use of the statistical methods on systems which do not support diffuse fields and therefore fall outside the scope of the methods.

2.3.4. Weak Coupling
Under the condition of weak coupling there is a power flow difference between two systems with the restriction that the external forces applied to the individual subsystems are statistically independent [52]. The assumption that the external forces are statistically independent is only ensured by “rain on the roof” excitation and not by a single point force or acoustic field excitation [53]. A related assumption which is central to SEA is that the modal vibrations of coupled sets are uncorrelated. This assumption is necessary to justify the linear dependence on modal energies of power flow expressions [52]. Craik [54] notes that fortunately in most real building structures the conditions of strong coupling will not often occur.

However, it is possible to have strong coupling in laboratory experiments where the subsystems are not connected to a number of other walls or floors as they would be in a real building. ISO10848-1, section 4.3.3 addresses the requirement of weak coupling during the measurement of the vibration reduction index in the laboratory by limiting the range of values over which the measurements are valid. If the limit is not met, then ISO10848 recommends adding damping material to the edges of the elements or connecting the elements to other structures. The additional damping affects the loss factor of the system under test, but in the case of heavy, monolithic structures, EN12354 makes use of the reverberation time measured
in the laboratory and in the field to make the vibration reduction index invariant. There is no such provision for lightweight constructions.

Furthermore, the requirement that the external forces are statistically independent by satisfying “rain on the roof” excitation is not addressed since ISO10848 states that using an electromagnetic shaker to excite the elements is the preferred excitation technique for the measurements.

2.4. Reciprocity

If the SEA and EN12354 equations are to hold for a given system then the coupling loss factors must satisfy the reciprocity relation [55]. If reciprocity does not hold then the coupling loss factors can be negative and power can flow from a subsystem with low energy to one with high energy which is against the spirit of SEA [56]. Craik [57] found that many of the random errors due to low modal overlap or due to system simplifications cancel out when reciprocity holds but that the standard deviation of the energy levels is higher when reciprocity does not hold.

In the derivation of the EN12354 method, Gerretsen assumed that the transmission of structure-borne sound through the system was independent of the transmission direction. The assumption had the benefit of canceling the often unknown radiation efficiency terms from the equations for the flanking transmission factor. However, Gerretsen [39] notes that in practice the flanking sound reduction index has been found to be different in each transmission direction.

If the system includes elements with critical frequencies in or above the frequency range of interest, then the response of the elements may include a significant non-resonant component. It is a SEA subsystem requirement that the response of the elements only be resonant. Since the non-resonant component should not be included in the calculation of the flanking sound reduction index its inclusion can cause the assumption of reciprocity to fail. Therefore, the assumption of reciprocity is only valid for heavy walls with sufficiently low critical frequency so that only resonant transmission is considered [15]. Furthermore, the assumption of reciprocity is only valid if the direct transmission path is the only transmission path. However, in an actual building there may be multiple flanking paths including higher order flanking paths and therefore assumptions based only on the direct transmission can be responsible for errors [36].

The use of statistical methods showed that the assumption of reciprocity failed for even the simple constructions tested in the laboratory as part of this study. A correction factor was proposed based on the best estimate of a log-normal distribution for the flanking transmission loss. However, the correction factor included the radiation efficiencies of the elements which limited the usefulness of the correction factor.

While the proposed correction can be used to correct for the error due to the assumption of reciprocity, the correction does not address the validity of the method when the assumption of reciprocity does not hold. It has been shown [35, 37, 38] that the equations of EN12354-1 may be equated to a first order Statistical Energy Analysis (SEA) model where there is only
one junction and only bending waves are considered. Therefore, the method of EN12354-1 is subject to the same restrictions as SEA [25]. If reciprocity does not hold then the coupling loss factors can be negative and power can flow from a subsystem with low energy to one with high energy which is against the spirit of SEA [56]. Therefore, the validity of using EN12354-1 may be in question for lightweight constructions.

The results of the investigation of the validity of the assumption of reciprocity and the proposed correction factor were presented at the Acoustics ‘08 conference [58].

2.5. Gaussian Probability Density Functions

The EN12354 method appears to assume that all of the terms described by the method have Gaussian probability density functions (PDF’s). For example, the spatial average of the mean square velocity is calculated as the mean of the measurements. The best estimate for repeat observations from a Gaussian distribution is the mean of the measurements [59] which implies the mean square velocity was assumed to have a Gaussian PDF. While the assumption that the time and spatially averaged mean square velocity has a Gaussian PDF may be acceptable for elements which have a low variance, observations of the response of lightweight elements may not be diffuse and therefore may not be described by a Gaussian distribution.

Furthermore, if the propagated uncertainty of the EN12354 method or acoustic methods in general is to be determined, the PDF’s described by the methods must be known. The topic of the PDF’s of acoustic terms attracted great interest at the conference, Acoustics ‘08 where there was a session dedicated to “measuring methods and uncertainty in building acoustics.” One of the achievements of this study was that the PDF’s of all of the terms in EN12354 and ISO10848 as well as the terms from several related standards were identified through the analysis of measured data and Monte Carlo simulations. The results of the study were presented at Inter-Noise 2008 [60] as well as a paper published in the journal, Building Acoustics in December, 2008 [61].

2.6. Uncertainty

In general, no measurement is perfect and the imperfections give rise to errors in the results. Consequently, the result of a measurement or of a calculation based on measured data is only an estimate of the true value of the measurand and it is only complete when accompanied by a statement of the uncertainty of the estimate [62]. Currently, neither EN12354-1 [22] nor ISO10848-1 [24] give guidance for calculating the uncertainty of the terms the standards describe. Before the EN12354 method can be used with confidence, an estimate of the uncertainty of the prediction method is needed.

The uncertainty of the prediction method depends on several factors including the accuracy of applying the method to the structure in question, the type of elements and junctions involved in the construction, the effect of workmanship and the uncertainty of the input data [22]. The scope of this study was to determine the uncertainty of the predictions based on the uncertainty of the input data which has been propagated through the calculations. In addition
to leading to an understanding of the accuracy of the predictions, an estimate of the propagated uncertainty will allow the sources of the propagated uncertainty to be determined.

The ISO Guide 98 Part 3, The Guide to the Expression of Uncertainty in Measurement (GUM) [63] has become the de facto standard for the evaluation of measurement uncertainty in metrology [64] and served as the guideline for calculating the propagated uncertainty in this study. Monte Carlo simulations (MCS) according to ISO Guide 98-3/Supplement 1 [65] were used to validate the uncertainty equations.

As part of the study, it was found that the definition of the direction averaged velocity level difference according to ISO10848 led to large errors in the prediction of the uncertainty using the GUM method. An alternative definition of the direction averaged velocity level difference was proposed that was validated by MCS.

The propagated uncertainty of the flanking sound reduction index was found to depend on the standard deviation of reproducibility of the sound reduction index according to ISO140-2, the uncertainty of the average velocity level measured on the elements according to ISO10848, the uncertainty of the areas of the elements and the uncertainty of the correction terms. The results of the uncertainty study have been accepted for the proceedings of Inter-Noise 2009 and have been submitted for consideration for publication in the journal, Building Acoustics.

It is suggested that future versions of the ISO10848 and EN12354 series include guidance for the calculation and the declaration of the uncertainty of the input terms and the calculated terms described in the standards.
3. Conclusions and Recommendations

3.1. Conclusions

As part of this study, the probability density functions of the terms described by the EN12354 method were determined. Knowledge of the PDF’s of the terms was necessary for the calculation of the propagated uncertainty of EN12354-1 and ISO10848-1 according to the method of GUM. GUM was also shown to be applicable to terms which had a log-normal distribution, but were converted into logarithmic values for the EN12354 predictions. The uncertainty of the EN12354 method was found to depend on the standard deviation of reproducibility of the sound reduction index according to ISO140-2, the uncertainty of the average velocity levels measured on the elements according to ISO10848 and the uncertainty of the dimensions and the structural reverberation times of the elements. Input data with small variances and small Type B uncertainty would lead to low uncertainty in the EN12354 predictions. The uncertainty calculations will be a valuable tool to those employing the EN12354 since the uncertainty calculations will help to quantify the accuracy of the predictions, something which has been sorely lacking until this study.

Furthermore, knowledge of the PDF’s led to alternative calculations of the average velocity level in cases where the PDF can not be approximated as a Gaussian distribution. Errors due to the approximation of a Gaussian distribution were shown to propagate directly into the prediction of the flanking sound reduction index.

Changes to ISO10848-1 were proposed to improve the predictions for lightweight construction and to result in an accurate statement of the uncertainty. Also proposed was a correction factor to correct for errors due to the assumption of reciprocity between the flanking sound reduction index in each transmission direction. The use of the correction factor is limited by the inclusion of the radiation efficiency terms.

The requirement that only the resonant component of the sound reduction index be used in the EN12354 calculations was shown to be a real challenge to the application of EN12354 as well as full SEA models to lightweight constructions. A review of different methods of calculating the resonant component of the sound reduction index either from data measured according to international standards or from theory showed that the different methods result in a wide range of values. Directly calculating the resonant component using the theory of Lee or Leppington was shown to be the best method of determining the resonant component of the sound reduction index. However, these theories were based on homogeneous, single panels and were shown to give inaccurate results if they were applied to the double-leaf constructions which are typical of lightweight elements. If the EN12354 method is to be applied to lightweight, double-leaf constructions, a new theoretical model to calculate the resonant component of the sound reduction index for double-leaf panels is needed.

The experimental evaluation of the application of the EN12354 method to lightweight building constructions presented in this study included laboratory and field testing. The testing was unique compared to prior studies in that intensity measurements allowed for the measurement of the flanking sound reduction index of each of the flanking paths.
The use of the L-panels in the laboratory had the advantage over field testing in that possible errors such as mismatching of velocity level difference data or the effect of workmanship were mitigated. The evaluation of the single-leaf MDF L-shaped panel showed the prediction by the EN12354 method differed from the measured value by up to 14 dB. The results of the EN12354 predictions for the double-leaf L-shaped panels differed from the measurements by as much as 29 dB. Better accuracy can not be expected for more complex elements in buildings. Furthermore, the full ESEA model also failed to accurately predict the flanking sound reduction index for the double-leaf L-panels indicating that the use of SEA may not be appropriate for this type of building element.

The field measurements included the measurement of the flanking sound reduction index of each flanking path in addition to the measurement of the apparent sound reduction index between the source and the receiving rooms. The path by path analysis showed errors between the measured and the predicted flanking sound reduction indices in excess of 10 dB in some of the 1/3 octave bands. However, due to the dominance of the direct path, the difference between the measured and the predicted weighted apparent sound reduction index was only 1 dB. Evaluations including only single number ratings or only the evaluation of the apparent sound reduction index were concluded to be inaccurate assessments of the accuracy of the EN12354 method if the direct transmission was the dominant path.

Reasons for the potentially large differences between the measured and the predicted values include the limitations of the simplified calculations according to EN12354 such as the inclusion of only first order flanking paths. Furthermore, the elements evaluated in this study failed to meet the requirements of an ideal SEA subsystem. For example, many of the elements had modal overlap factors less than one at the low frequencies in violation of the requirements of a SEA subsystem and limiting the accuracy of the predictions in these frequency bands.

The requirement of a SEA subsystem that the elements support a diffuse vibratory field can be problematic for lightweight elements. Attempts to reduce the non-diffuse vibratory fields in this study by breaking up walls into smaller elements was found to improve the predictions at the higher frequencies, but at the cost of less accurate predictions at the lower frequencies. Therefore, the overall effect of the smaller elements on the accuracy of the predictions in this study was negligible. However, the ability to break up walls into smaller elements is limited due to the exclusion of higher order paths.

Based on the systems tested as part of this study, the current version of the standard, EN12354 can not be endorsed as a reliable means of predicting the apparent sound reduction index for lightweight constructions. If EN12354 is used in its current form as an estimate of the apparent sound reduction index in buildings which include lightweight elements, it should only be with the understanding that the predictions can potentially include significant errors.
3.2. Recommended Changes to EN12354 and ISO10848

Recommended changes to future versions of EN12354-1 include the addition of:

- A section explaining the calculation of the modal overlap factor and the modal density and the potential effect on the accuracy of the EN12354 method when the modal overlap factor is less than one. The section will be of great assistance to people who are not familiar with SEA, but use EN12354 without understanding the possible frequency limitations of the calculations.

- A section about the uncertainty of the predictions. The section should include an explanation of how to calculate the uncertainty and the expanded uncertainty from the uncertainty of the input data as was shown as part of this study. Other sources of uncertainty such as workmanship should also be discussed with sources listed if estimates are given. The addition of the uncertainty analysis will greatly improve the confidence in the predictions. Furthermore, a person calculating the flanking sound reduction index according to the EN12354 method would be able to determine how the quality of the input data affected the uncertainty of the EN12354 predictions.

- A requirement that measurements of the velocity level difference, the structural reverberation time, the sound reduction index and other inputs into the EN12354 method include an expression of the uncertainty of the measurements. The uncertainty of the measurements is a necessary part of any measurement which is lacking from many acoustics standards. The determination of uncertainty is an important topic which needs to be addressed by the ISO and CEN standard committees when revisions of standards such as ISO140, ISO10848 and EN12354 are published in the future.

- More equations to account for higher order flanking paths to the EN12354 calculations to make it more applicable to lightweight, double-leaf constructions. Instead of treating double-leaf walls as homogeneous elements, the EN12354 method should address the multiple elements in the wall. The inclusion of more flanking paths which use experimental data to define the coupling loss factors will increase the complexity of the EN12354 calculations, but with the benefit of more accurate predictions.

- A statement regarding how the resonant component of the sound reduction index is to be calculated. Failure to specify which calculation to use can result in a wide range of predicted values when different calculation methods are used.

Most importantly, if the EN12354 method is to be applicable to lightweight elements, a reliable theory for calculating the resonant sound reduction index of double-leaf constructions is needed. Until such a theory is published, the use of the EN12354 method should be restricted to elements with critical frequencies below the frequency range of interest.

It is recommended that future versions of ISO10848-1 include:

- The proposed estimate for the direction averaged velocity level difference. The error in the ISO10848 estimate is propagated into the calculation of the apparent sound reduction index. The proposed estimate was shown in some cases to improve the prediction of the apparent sound reduction index by several dB.
• Definite limits on the validity of the assumption of a diffuse vibratory field. The limits should include a statement that if the limit is exceeded then the EN12354 method should not be used.

• A section about the uncertainty of the predictions as described in this thesis.

3.3. Proposed Future Work

Future work to evaluate the flanking transmission through double-leaf constructions with metal studs should include building and testing L-shaped panels identical to the gypsum board on metal studs L-shaped panel evaluated in this study, but with wood studs. The measurements from the new L-shaped panel will allow for the evaluation of the hypothesis that metal studs allow for greater flanking transmission in double-leaf constructions than wood studs.

Additional field testing with additional measurements to allow for a full ESEA model may allow for greater insight into the differences between the predicted and measured flanking sound reduction indices. The future measurements should include the flanking intensity sound reduction index of the elements in the receiving room since the use of intensity measurements proved to be insightful in this study to distinguish between the dominant paths and the difference between the flanking and the direct transmission.

This study resulted in equations to describe the propagation of uncertainty in the EN12354 predictions due to the uncertainty of the inputs. Other sources of uncertainty such as workmanship also need to be quantified. There have been other studies made and numbers for the uncertainty due to workmanship are often mentioned at conferences. However, without reference to a large scale study of multiple field measurement sites, a true indication of the uncertainty due to workmanship can not be known.

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References


