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THE IMPORTANCE OF MEASUREMENT UNCERTAINTY DURING TESTING

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1. INTRODUCTION

No measurement is ever exact - there is always an uncertainty associated with the result. It is surprising therefore that the topic of measurement uncertainties in many fields has been either totally neglected, or not considered in sufficient detail, until recent years.

This paper discusses the importance of measurement uncertainties, with particular reference to testing of sound level meters in the context of the new sound level meter standard IEC 1672 [1]. It also describes some background on techniques used in the estimation of uncertainties and discusses the methods of combination given in the ISO Publication 'Guide to the expression of uncertainty in measurement' [2].

2. TOLERANCES AND UNCERTAINTIES

IEC 1672 is a performance specification standard for sound level meters. As such it describes various facilities of the instrument and specifications that must be met for the instrument to conform to the standard. Each of the specifications includes a tolerance around the design goal or expected response to take account of the fact that no manufacturer, however worthy, can expect to meet all the specifications exactly. Some tolerance has to be permitted to allow for tolerances in components, difficulties of design etc., and the tolerances in the standard aim to make conformance realistically attainable if care is taken in these areas.

The tolerance should not be confused with the uncertainty of a measurement made on the sound level meter to verify whether it conforms to the standard. The uncertainty of a measurement result is a parameter that characterises the spread of values that could reasonably be attributed to the measurement. It states the range of values within which the measurement is estimated to lie, within a stated range of confidence.

Uncertainties of measurement fall into two main categories - those that can be described using a normal (Gaussian) distribution and those that can be modelled with a rectangular distribution, assigning equal probabilities to values between extreme limits. According to the ISO Guide, the former are termed Type A uncertainties and are generally those that can be evaluated by statistical methods, and the latter are termed Type B uncertainties and refer to uncertainty components that are generally evaluated by other than statistical means.

A Type A evaluation will usually be performed to obtain a value for the repeatability or randomness of particular measurements made on one particular occasion. In some cases the random component may be so small as to be insignificant in relation to other contributions of uncertainty, but if there is sufficient spread the mean value and standard deviation of the n values should be calculated from the following equation:

$$s = \sqrt{\frac{1}{n}\sum_{k=1}^{n}(x_k - \bar{x})^2}$$

where s is the standard deviation of the n values, x_k is the kth measured value of the quantity x and $\bar{x}$ is the mean value.

This can then be repeated for each sample of results taken. For large values of n the mean values approach a central limit of a distribution of all possible values. This is usually assumed to be a normal distribution. Often in practice, the results of a single sample of measurements are used to estimate the standard deviation of the whole population of possible values $s(x_k)$ as follows:

$$s(x_k) = \sqrt{\frac{1}{(n-1)}\sum_{k=1}^{n}(x_k - \bar{x})^2}$$

The Type A standard uncertainty is then calculated from $s(x_k) / \sqrt{n}$, and the benefit of performing several replications can be seen.

Type B components of uncertainty are more difficult to estimate. Usually due to the items of equipment used for any particular measurement, estimation of each component relies on previous data, experience and general knowledge of the measurement system. Each item must be considered separately to determine its contribution. For example, where a voltmeter and toneburst generator are used contributions must be estimated for both these instruments. These estimates may be from a formal calibration certificate where this is essential for traceability, or from the manufacturers specification, or in the case of the function generator, from an estimation of the effect on the measurement result if the number of cycles provided or the associated interval supplied are in error. Also to be considered are any contributions due to environmental effects, and those due to the instrument under test itself, for example in the reading of a sound level meter indication.

These contributions are usually considered to have rectangular distributions. If this rectangular distribution extends from $-a$ to $+a$ ie. a semi-range of a, the standard uncertainty is given by $a/\sqrt{3}$.

The exception is where an uncertainty is obtained from a calibration certificate for a particular instrument where the level of confidence or a coverage factor k has been quoted. This is treated as having a normal distribution and the standard uncertainty is given by

$$\frac{expanded\ uncertainty}{k}$$

A coverage factor $k = 2$ is usually recommended as it gives a level of confidence of approximately 95% (95.45%).

All the standard uncertainties of these input quantities, which are treated as independent, are then combined to give a single standard uncertainty of the output quantity by squaring, adding and taking the square root. This combined standard uncertainty is then multiplied by the coverage factor to give the expanded uncertainty of measurement - the quantity of interest for the purposes of reporting measurements. The measurement value will then be reported as x ± the expanded uncertainty. It should be accompanied by a statement giving the coverage factor used.

Only a simplified approach to uncertainties has been described in this paper to illustrate the general principles. Further details for more specific cases can be found in the ISO Guide.

3. WHY ARE UNCERTAINTIES IMPORTANT?

The importance of measurement uncertainties becomes clear when considering a test for conformance with a given standard by several different laboratories or test houses. Each test house is likely to have different uncertainties depending on the quality of their facilities, the equipment, the methods used and the personnel etc. Where an instrument is being tested for conformance to an International Standard a specification tolerance is given for each test. To conform the measured value must lie within the specification design goal and tolerance. But what about the measurement uncertainty? In the strictest sense using the purist approach, the measured value, extended by the uncertainty of measurement, should lie fully within the design goal plus the tolerance quoted. This ensures there are no 'grey' areas where the instrument may, or may not, conform.

The importance of the uncertainty of the measuring laboratory therefore becomes clear. If a laboratory has a small uncertainty and the measured value is nearing the edge of the tolerance, the instrument may still be found to conform with the standard. However if the same instrument is measured by a laboratory with much larger uncertainties, the instrument may fail to conform when the value is extended by the expanded uncertainty of measurement. The onus then, to some extent, is on the measurement laboratories to reduce their measurement uncertainties - manufacturers are more likely to employ test laboratories with smaller uncertainties where their instruments are most likely to pass a pattern evaluation or verification test!

Unfortunately, in the real world the approach to uncertainties is not quite so simple. For years specification standards have not even considered uncertainties of measurement and specification tolerances have not included any contribution for uncertainty. This is the case for the existing sound level meter standards IEC 651 and IEC 804. At the meeting of the IEC Committee responsible for specification standards for acoustical instruments (IEC TC29) last year it was decided that in future specification standards should include uncertainties of measurement. The ideal way to do this, and what should be the ultimate aim for IEC 1672, is for the standard to give the design goal specifications and the tolerances, and for those tolerances to incorporate both the tolerance for manufacturers and the uncertainty of the measuring laboratory. This leads to the situation that an instrument will only conform to the standard when the deviation from the design goal extended by the expanded uncertainty of measurement lies fully within the specification tolerance.

However during the 'transition period' this is not immediately possible, and various interim solutions have been considered for standards currently being written, such as IEC 1672.

4. UNCERTAINTIES OF MEASUREMENT AND IEC 1672

There are particular problems in applying the purist approach to uncertainties in new standards such as IEC 1672. Many of the tests are new so no information about testing uncertainties has been obtained. For tests that are similar to those in earlier standards the lack of consideration of uncertainties by IEC 651 [3] and IEC 804 [4] means that little data are available from measurement laboratories, particularly for pattern evaluation of new models of instrument. There is also little data on lower grade ie. class 2 meters, and some of the specifications have changed from those in IEC 651 and IEC 804 with the reduction in the number of accuracy classes to 2.

IEC 1672 1CDV therefore includes an interim, practical method of dealing with these uncertainties until further experience is gained with the test methods and more uncertainty data accumulated. Annex A of 1CDV in A.1.2 states 'Conformance to a specification of this International Standard is verified when the measurement of a deviation from a design goal plus the actual expanded uncertainty of measurement is equal to or less than the specified tolerance limit plus the actual expanded uncertainty of the measurement. Uncertainties of measurement shall be determined in accordance with the *Guide to the expression of uncertainty in measurement*. Expanded uncertainties shall be calculated by the testing laboratory with a coverage factor of 2.'

Thus the actual measured value must lie within the specification tolerance, but to demonstrate conformance the actual uncertainty of the laboratory is taken into account. To ensure that laboratories do not have/quote a very large uncertainty enabling them to pass virtually any instrument a further paragraph in Annex A was added. A.1.4 states 'The maximum expanded uncertainties of measurement given in this annex are the maximum values permitted for demonstration of conformance under this annex to the specifications of this International Standard. Tests to demonstrate conformance to the specifications of this International Standard shall not be performed if actual values of expanded uncertainties of measurement exceed the maximum permitted values'. Equivalent statements are included in Annex B on periodic tests under B.1.2 and B.1.4. This approach begs the question of why the tolerance limits in the main text are not purely broadened by the maximum permitted expanded uncertainties and a single value quoted. There are two main reasons for not using this approach at this time:

- IEC 1672 is a new standard - manufacturers need to know the extent of the tolerance available for design

and

- very little data on measurement uncertainties exists for the tests prescribed by the standard. Quoting the maximum permitted uncertainties separately in the Annexes will allow measurement laboratories to report whether the values are realistic, and ease any necessary modification.

When experience with the testing methods has been gained and uncertainty data collected, it will be possible to combine the tolerances and uncertainties of measurement into the main document. However it is clear this is not possible now, and so the above solution was agreed as a temporary measure to speed up the progress of IEC 1672.

The maximum permitted expanded uncertainty values in IEC 1672 are based on the little data available from some metrology laboratories, and some of the values may well be changed as a result of the comments received from National Committees on the 1CDV. However there seems to be a tendency to underestimate uncertainties of measurement, particularly when apparently large values result. Any laboratory that wishes to change the suggested values in 1CDV must ensure that their uncertainty calculations follow the requirements of the ISO Guide, and that uncertainties have been included for all the elements of the measurement chain as well as in reading the indications from the device under test.

IEC 1672 principally uses two approaches to the maximum permitted uncertainties: either a dB value is quoted or a percentage of the appropriate tolerance is quoted. For example in the tests of steady level linearity, A.6.5.6 gives a maximum permitted expanded uncertainty of measurement of ± 0.2 dB for tests at 1 kHz and ± 0.4 dB for tests at other frequencies, whereas for the test of directional response the maximum permitted expanded uncertainties given in A.6.3.6 are ± 30% of a class 1 tolerance limit. For these percentages the class 1 tolerance limit referred to is the smaller-in-magnitude limit rounded up to the next tenth of a decibel. Separate maximum uncertainties are quoted for each test, and there are some differences between the values quoted in Annex A and Annex B.

Consider an example of a test of tone burst response with F time-weighting. Annex A requires an initial measurement to be made with a continuous signal and then various length single tonebursts to be applied. Take a 200 ms toneburst: compared to the indication for the continuous level the maximum indication in response to the burst should be -1 dB, with a tolerance of ± 0.5 dB for a class 1 instrument. The maximum permitted expanded uncertainty of measurement is ± 0.2 dB. According to IEC 1672 the deviation from the expected response plus the actual expanded uncertainty of measurement must be equal to or less than the specified tolerance limit plus the actual expanded uncertainty of measurement. So in the case of the maximum permitted uncertainties given in A.6.6.6, (the deviation ± 0.2 dB) must be equal to or less than (± 0.5 dB ± 0.2 dB) which is interpreted as ± 0.7 dB. However if the actual measurement uncertainty of the testing laboratory is less than the maximum permitted, for example ± 0.1 dB, then the deviation from the expected response extended by the actual expanded uncertainty must be within ± 0.6 dB etc.

In a laboratory without good calibrated equipment, the length of the burst may be grossly in error and the correctly calculated uncertainties may amount to 0.5 dB. Under the maximum permitted expanded uncertainty criteria in IEC 1672 this laboratory would not be able to perform the test to this standard. This is a reasonable restriction as the error in the burst length may be such that a meter which would fail to comply with the correct burst length, is actually passing due to the incorrect number of cycles in the burst. Equally an instrument which may conform when the correct burst length is applied may fail as a result of the burst having an incorrect number of cycles.

To illustrate further the large number of contributions that often form the combined standard uncertainty, consider a more complex case, such as the acoustical measurement of the frequency weightings described in subclause A.6.4 of IEC 1672. Measurements are performed in a free-field facility and the deviation from the design-goal frequency weighting is determined as the indication on the sound level meter display device minus the frequency-weighted free-field sound pressure level. The free-field sound pressure level is measured by an appropriately calibrated laboratory standard microphone. Assuming the insert voltage method is used to establish the level measured by the microphone, then uncertainty components due to the following will contribute to the expanded uncertainty:

- measurement of insert voltage to standard microphone
- measurement of associated attenuation
- polarizing voltage to standard microphone
- resetting drive signal of sound source to the same level for both meter and microphone
- reading indication on sound level meter
- atmospheric pressure correction to standard microphone sensitivity
- ambient temperature correction to standard microphone sensitivity
- rounding of final result

- pressure sensitivity of standard microphone
- free-field correction applied to pressure sensitivity
- calibration of the attenuator
- calibration of the voltmeter
- type A contribution.

The first eight contributions listed above are likely to be estimated in terms of semi-range, whereas the uncertainties in the calibration of the microphone, voltmeter and attenuator are likely to be already quoted for a coverage factor of 2.

The above list does not include any uncertainties in the environmental coefficients of the meter if the result has to be corrected to reference environmental conditions, or any uncertainty in corrections for level linearity if measurements are not made at the same level at each frequency.

Many of these contributions are frequency dependent, and a separate calculation would be required at each frequency. It is clear that the effort to initially assign values to all these contributions and to calculate the expanded uncertainty is not inconsiderable, but has the benefit that once performed, assuming the method stays fixed, only small changes will be required.

These calculations show it would be unreasonable and unfair to reputable manufacturers, and to the end user, to allow laboratories to perform evaluation and verification tests to this standard if their associated uncertainties of measurement are not reasonably small, carefully estimated and well-defined. It must be clear which models of meter conform to the standard, and it is important that uniform results on conformance are obtained in different countries around the world, when all are testing the same instrument. A further benefit of the interim approach to uncertainties used in IEC 1672 is that the manufacturer does not need to know in advance the actual measurement uncertainty of a particular laboratory for each test - indeed it may be impossible for the laboratory to calculate these in advance of making the measurements.

Subclauses A.8 and B.6 of IEC 1672 refer to the test reports that shall be supplied by the testing laboratory following either full conformance testing or periodic tests. These test reports are required to include certain items such as the test configurations, test conditions and the actual test results which must be accompanied by a statement of the corresponding uncertainties of measurement. Each user will therefore be supplied with the test results and information on the uncertainty of measurement from the testing laboratory that was applied when verifying conformance of the sound level meter with the standard.

5. THE RÔLE OF ACCREDITATION

This paper has stressed the importance of uncertainties of measurement during testing to

IEC 1672, and the need for a testing laboratory to ensure all relevant components have been considered and combined according to the ISO Guide. However this relies on full understanding of the uncertainties involved and the estimation of realistic values for each contribution. Whilst this will present little problem for many laboratories, how can the manufacturer in the case of full testing described in Annex A, or the individual user of a sound level meter submitted for verification to Annex B, be sure that the uncertainties have been properly considered?

This is an area where formal accreditation of laboratories has a important rôle. Many countries around the world now have assessment bodies - in the UK this function is performed by the United Kingdom Accreditation Service (UKAS). Formal accreditation for testing or calibration not only considers the procedures used, traceability of instrumentation, record keeping etc., but also makes an independent assessment of the uncertainties of measurement that a laboratory proposes to report. This independent assessment gives the user of the instrument confidence in the methods and procedures used during testing or calibration, and also in the uncertainties of measurement quoted.

6. CONCLUSIONS

A thorough investigation of contributions to the uncertainty and calculation of an expanded uncertainty of measurement is vital for the consistent application of an international specification standard such as IEC 1672, when determining whether an instrument conforms to the specifications.

The inclusion of maximum permitted uncertainties of measurement in IEC 1672 is a major change from the existing standards IEC 651 and IEC 804. It ensures that the manufacturer has to meet the design goals within the specification tolerances, whilst testing laboratories with large uncertainties of measurement will not be able to confuse the market by producing inconsistent judgements on conformance.

7. REFERENCES

1. IEC 1672 1 CDV (April 1997), Sound level meters.

2. ISO Publication, ISBN 92-67-10188-9:1995, Guide to the expression of uncertainty in measurement. (Published in the UK by BSI as PD 6461: Part 3 :1995).

3. IEC 651:1979, Sound level meters.

4. IEC 804:1985, Integrating-averaging sound level meters.