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MEASUREMENT OF HAND-TOOL VIBRATION EMISSION AND WORKPLACE RISK

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1. BACKGROUND

The EU Machinery Directive [1] requires that suppliers of machinery must declare, amongst other information, the vibration emission of their equipment. The method of declaring vibration emission is to apply a standard test - usually written specifically for a class of equipment. The test is intended to provide a repeatable and reproducible method of estimating vibration emission. This investigation of the performance of CEN Standard test codes had the following aims:

- to reproduce (verify) manufacturers' declared vibration emission values,
- to assess the test codes for usability and repeatability,
- to compare vibration emission values determined by standardised tests with vibration magnitudes measured under real operating conditions,
- to explore the limitations of vibration emission data for indicating vibration exposure.

It was found that when comparing a selection of tools of similar type, the standard tests studied are only capable of producing a short list of tools likely to include those with the lowest emissions during normal use, but the absolute values quoted often fail to indicate the likely magnitude of the vibration hazard. The uncertainty in the measurement of vibration emission affects the ability to differentiate between tools - even those with widely different emission values. To comply with the vibration requirements of the Machinery Directive, manufacturers must not only reduce risks from vibration to the lowest level and report the vibration emission, but must give supplementary information, as necessary, providing for operator safety during foreseeable use and misuse of the tool.

2. METHOD

2.1 Test codes studied

The test codes investigated in detail to date have been written to determine the vibration emissions of chipping hammers [3], rock drills and rotary hammers [4], grinders [5], pavement breakers and pick hammers [6], and impact drills [7]. Work is continuing on the investigation of standards for sanders [8], and stoneworking tools and needle scalers [9].

2.2 Test procedure

The test procedure was to acquire a selection of new tools, test them in the laboratory according to the appropriate standard test code and then test them under conditions of normal use. The results were then examined to see the relationship, if any, between the manufacturer's declared emission and the measured emission during the study and also between the measured emission and the field vibration magnitude. The declaration and verification of vibration emission values is standardised under EN 12096:1997 [10].

3. RESULTS

3.1 Standard test codes

3.1.1 Comparisons of emission data

Analysis of variance of the results of the emission tests carried out during the study for all the test codes suggests, in general, that if two tools tested at the same laboratory have vibration emission values which have a ratio of 1.2 or less, then they are not significantly different at the 1% confidence level. So, for example, when comparing emission data, a tool with a declared emission of $10ms^{-2}$ may not in fact be of lower vibration than a tool declared at $12ms^{-2}$.

According to the standardised procedure for verification of manufacturer's emission data [10], the manufacturer's declared emission is verified if the subsequently measured ***a*** emission value is less than or equal to the manufacturer's declared emission, **a+K**, using either a declared or an assumed uncertainty value, ***K***. In most cases, the manufacturers had declared a single emission value, ***a***, so an assumed uncertainty value, ***K***, was calculated according to the guidance. In this study there were 63 tools tested with manufacturers declared emission values. 7 tools were declared at $<2.5ms^{-2}$, leaving 56 tools for which the comparison (study ***a*** vs. manufacturer's ***a+K***) was possible. In 41 of these cases (73%) the study verified the manufacturer's emission data.

Manufacturers' declared emission values and those measured for the study were also compared by rank to assess the usefulness of emission data in differentiating between tools.

Table 1. Rank correlation coefficients for comparison of declared vs reproduced emission data

Tool type	No. of tools tested	Range of emission values (ms^{-2})	Rank correlation coefficient	
			a vs ***a***	***a+K*** vs ***a+K***
Chipping hammers	12	1 -16	0.92	0.90
Rock drills	7	5 -17	0.85	0.82
Road breakers	10	3 -18	0.89	0.82
Pick hammers	5	6 -16	0.46	0.46
Impact drills	7	6 -12	0.40	0.17
Grinders	7	1 - 5	0.00	-

The best rank correlation coefficient was for measured and declared emission, ***a***, for chipping hammers where there was a correlation coefficient of 0.92. The comparison for grinders yielded a coefficient of 0.0 indicating that the tools were ranked in a completely different order. Table 1 shows that the better correlation coefficients are achieved when there are more tools and a greater spread of data. Manufacturers' data were indistinguishable for sanders and needle scalers, which lead to them all being equally ranked. The emission values measured for the study indicated some differences, but derivation of a rank correlation coefficient was not appropriate.

3.1.2 Repeatability and reproducibility of standard test code results

For most of the standard test codes, results were repeatable and there was rarely any difficulty in achieving a coefficient of variation of 0.15 or less [2], but there were a few notable exceptions. Of the test codes studied, the one which created the greatest challenge in terms of achieving the required coefficient of variation was for stone working tools and needle scalers [9]. In this test vibration emission was greatly affected by the feed force. The recommended feed force (N) is the mass of the tool (kg) times 20 and unlike the similar test code for chipping hammers, there are no upper or lower limits specified. So for small tools, the feed force can be as little as 16 Newtons. For needle scalers, maintaining the tools in a vertical position during the test was particularly important. Poor results were obtained if the needles vibrated against the sides of the energy absorber.

Repeatability was problematic in the test for sanders [8]. The axis of highest vibration changed from operator to operator for two examples of the same model of palm sander. The test code for sanders does not define the direction for the measurement, so acceleration was monitored in two axes simultaneously and the highest axis was determined at the end of the test series. The possibility that the highest axis may vary from operator to operator and tool to tool is not addressed in any of the standard test codes.

The reproducibility of the test results was generally evaluated by comparing emission values measured in the study with those reported by manufacturers. Opportunities for comparisons with other laboratories arose during the testing of road breakers. Comparisons were made on three tools, two of which resulted in emission values within 10% of each other, for the third the emissions were within 25%. Also, four of the road breakers were loaned from a third laboratory, rather than from a manufacturer. These four tools had been tested previously at the other laboratory. Measured emission values for all these four tools were within 10% to 22% of each other.

Gillmeister and Schenk [11] have compared the results of a number of laboratories applying CEN Standard vibration test codes. They show a standard deviation of reproducibility of between 6% and 28% with the measurement uncertainty, ***K***, for any one machine ranging from 9% to 46%. Impulsive tools appeared to be responsible for the largest deviations.

3.1.3 Usability of test codes

Positioning of transducers - The test codes vary in their approach to the definition of the measurement location. In the grinders test code for example, the location is specified to the nearest few millimetres. In other test codes, the location is vague and results in variations in emission values [11]. The vibration emission can vary markedly along the length of a handle, etc. [12]. To measure at the hand position the mounted transducer usually interferes with the grip of the operator and this affects the amount of damping from the hand and consequently the vibration magnitude measured. Further variation may arise if the operators adopt different hand positions and postures to counter the presence of the transducers.

The standard test for palm sanders [8] recognises in its introduction that the specification to locate transducers at the palm position will affect an operator's normal hand position, but no guidance is given on how to get round the problem. Measurement at the palm position does not take account of the operators fingers which for palm sanders are in contact with the sides of the tool where the vibration magnitude is greater.

Test codes generally require that transducers are mounted in the middle of the handle. This is often not practical (particularly when using a block and cable tie or hose clip mounting system), because the location often interferes with the safe action of the throttle or switch. For laboratory testing this problem can be overcome by operating the tool from an additional electrical switch or air line valve. However, when measuring under conditions of normal use this is not practical or safe. The tests reported here required measurements at locations which could be used under conditions of normal use so measurement locations have varied slightly from those defined in the standard test codes. This may account for some of the variation between manufacturers' and the study's emission data.

Highest handle measurements - One major criticism of some standard test codes is that the defined measurement location often ignores the fact that there are two clear hand positions and often the specified transducer position is for the hand exposed to least vibration! The best example of this is for chipping hammers [3]. The measurement location is defined in the middle of the main handle, which is always the rear hand position on the tool. Much higher vibration magnitudes are likely to be measured at the front hand position and yet this is completely overlooked in the standard. If a standard test code is to have any chance of being able to predict the severity of risk to the user, then measurements have to be made which represent both hand positions or the higher hand position at the least.

Steel Ball Energy Absorbers - The project called for three different sizes of steel ball energy absorber. We found that certain parts of the energy absorber, most often the test bit itself, were prone to breaking. The test codes define the required hardness for the steel, but do not mention the need to subsequently temper the steel to avoid brittle failure during testing. The energy absorber is designed to provide absorption but to reflect a consistent 15 to 20% of the impact energy back to the tool. Strain gauge measurements of the amount of energy reflected on a single-piece test bit showed that on average 20% of the incident energy was reflected back along the test bit, although this ranged from 5 to 57% for individual impacts.

Achievement of nominal load speed for grinders - Vibration emission testing of electric grinders [13] requires that the tool should be tested at the nominal load speed, ie. the speed at which its rated power is reached during normal operation. The test code does not however give any guidance on how this should be achieved and this may well give rise to significant variations in emission test results between laboratories.

3.2 Measurements of vibration during normal use

Following completion of the standard tests, the tools were taken to various work locations where they were tested under conditions of normal use. Field measurements were made at foundries, construction sites, shipyards, stonemasons' yards, and train and vehicle maintenance depots. Experienced operators performed tasks which were representative of normal working. For tools having a variety of different applications, the variety was reflected in the work sites and processes selected. Triaxial vibration measurements were made at the measurement locations and using the same transducer mounting techniques as used for the standard tests to enable direct comparison of emission and field data. The data were compared in terms of absolute values and also comparisons were made of the rank order of the tools according to the emission and field data.

3.3 Relationship between Standard test codes and normal use

Overall results from all of the tool types studied show that in over 60% of cases the mean field vibration was higher than the reproduced emission value, ***a***. The tests for impact drills and rock drills gave the best relationship between emission and field data. When the data for the impact drills and rock drills are excluded from the overall results, because these tests are based on actual drilling operations, the number of cases where mean field vibration exceeds emission data is closer to 80%.

Table 2 below shows comparisons of standard laboratory test results versus field data using rank correlation and regression analysis. For each tool type the correlation coefficient of the rank order of highest to lowest laboratory and field measurements was calculated. The results given are measured emission, ***a***, versus mean field vibration magnitude. Results for chipping hammers, road breakers and especially rock drills show good correlation.

For the regression analysis [14], the results for rock drills and chipping hammers show significant correlation at the 5% level or better, but for both of these tool types the measurement location was not usually that of the hand which is likely to experience the highest vibration. Although the results of emission tests may rank tools in a similar order, the standardised laboratory tests do not produce vibration emission magnitudes representative of field vibration magnitudes.

Table 2. Comparisons of a emission versus mean field data.

Tool type	No. of tools tested	Rank correlation coefficient	Regression analysis coefficient, R^2
Chipping hammers	12	0.89	0.51
Rock drills	7	0.96	0.93
Grinders	10	0.50	-
Road breakers	10	0.86	0.35
Pick hammers	5	0.20	0.12
Impact drills	7	0.71	0.49
Sanders	6	0.31	-
Needlescalers	6	0.71	-

4. DISCUSSION

4.1 Sources of Variability

4.1.1 Operating conditions of pneumatic tools

During the laboratory tests, tools were operated according to the manufacturers' instructions. When on site however, certain obstacles to this were encountered. Site compressors were found to vary in operating pressure anywhere from around 80psi up to 200psi, and there was rarely any means of measuring the supply pressure for pneumatic tools, let alone altering it to that specified by the manufacturer. For some tools such as stone working tools, the technique of the skilled stonemason was to use the supply valve to vary the operating pressure depending on the task in hand. Unfortunately these variations could not be monitored during the field measurements.

4.1.2 Operating techniques and applications

During testing of some tools, particularly small chipping hammers, stone working tools and needle scalers, variations in operating forces were seen to influence the emission values measured. These influences would also affect the results of the field measurements and yet to attempt to control these influences would interfere with the realism of the field measurements.

An example of the potential of the operator to influence the field measurement results was seen when testing palm sanders at a train maintenance depot. Under the same measurement conditions the mean field vibration magnitude for an experienced operator was $9.6ms^{-2}$ compared with $2.4ms^{-2}$ for an inexperienced operator, a difference of 400%. This example highlights the potential for variation in vibration measurements and emphasises the fact that single figure emission values can, at best, only indicate the likelihood of workplace risk.

Of the test codes investigated to date, none take account of periods when the tool might be running off load, idling, or running up to, or down from normal operating speed and yet all of these conditions can affect the vibration magnitude produced, as can variations in the way in which the operator uses the tool, different bit types and different work surfaces.

4.1.3 Anti-vibration handles and reduced vibration tools

A number of the tools tested during the course of the project were reduced vibration tools. Such tools are often designed to be used at much lower feed forces than standard tools and consequently some vibration reduction features do not operate efficiently when the feed force conditions of the standard test are applied. Some vibration reduction mechanisms for impulsive tools seem to reduce vibration in the main axis of operation of the tool at the expense of increased vibration in the orthogonal axes. Consequently when the total vibration value is considered, the advantages of the vibration reduced tools can be minimal.

Operators with no previous experience of vibration reduced tools generally disliked them despite their lower vibration, because they were generally thought to be less effective. This may have been because the tools were not being used in the intended way and this highlights the need for training in use of reduced vibration tools as directed by the tool manufacturer if they are to be accepted.

A number of road breakers with suspended handles were tested for this study and these gave relatively low emission values, but the suspended handles could be completely compromised when the operator pulled the tool out of the work surface with the power still on. The suspended handles are only designed to work with the correct amount of feed force applied to them and if the feed force is too great or applied in the other direction the measured vibration magnitudes can be much higher.

4.1.4 Resilient coatings.

Each test code contains a statement regarding measurements where the tool has a resilient coating. The options for dealing with resilient coatings are:

- remove the resilient coating,
- clamp the accelerometer tightly to minimise the effect of the resilient coating,
- use an adaptor.

For the tests reported here the mounting assembly was secured as tight as possible, to try to eliminate the effects of resilient coatings. Mounting techniques can influence the measured results and if the option to use an adaptor is to be included, then there should be a full definition of its characteristics.

4.1.5 Highest axis measurements

A complication with the comparison of emission and field data during this project was the fact that for some tools such as impact drills, the highest axis measured under conditions of normal use did not coincide with the axis measured for the emission test. A number of test codes such as those for chipping hammers, stone working tools and needle scalers ignore the front hand position and yet for these tools, it is invariably the front hand which is exposed to the highest magnitudes of vibration. If emission test data are to be expected to reflect the risk presented to the operator by the tool then they need to include measurement of the highest hand highest axis vibration magnitude.

4.1.6 Simulation and Reality

Field tests raised doubts about the success of artificial tests in representing the main source(s) of vibration. For example, the grinder test code assumes that imbalance of the wheel is the main contributor to the vibration experienced on the handle of any grinder, but this study found no evidence to corroborate this.

4.2 Vibration Emission and Workplace Risk

4.2.1 The EU Machinery Directive

The EU Machinery Directive sets out a hierarchy for reducing risks to health and safety: inherently safe machinery design and construction; taking necessary protection measures in relation to risks that cannot be eliminated; and informing users of any residual risks. The ultimate requirement of the Machinery Directive is that machinery must be useable without risks to health or safety.

The primary requirement of the Machinery Directive concerning vibration is to reduce risks resulting from vibration to the lowest level. There is also a specific requirement to report the vibration emission in terms of frequency weighted root mean square acceleration when it exceeds a threshold of 2.5 m/s². The performance of the standards studied in assisting compliance with these requirements is summarised in Table 3.

Table 3: Performance of Standards in relation to the EU Machinery Directive

Tool	Repeatability and Reproducibility	Verification of manufacturer's emission data according to EN12096	Ranking of emissions in the order found in the workplace	Representation likely workplace magnitude	Verification of risks from vibration reduced to lowest level
Chipping hammers [3]	Satisfactory	9 out of 12	Satisfactory	Requires development	Satisfactory
Rock drills [4]	Satisfactory	7 out of 7	Satisfactory	Variable	Satisfactory
Grinders [5]	Satisfactory	9 our of 13	Requires development	Requires development	Requires development
Pavement breakers & pick hammers [6]	Satisfactory	13 out of 17	Satisfactory	Requires development	Requires development
Impact drills [7]	Variable	8 out of 9	Satisfactory	Requires development	Variable
Sanders [8]	Variable	1 out of 3	Satisfactory	Requires development	Variable
Stoneworking tools & needle scalers [9]	Variable	3 out of 6	Requires development	Requires development	Requires development

Key: **Satisfactory** - the standard is generally **capable** of performing the function
Variable - the standard is **generally satisfactory** but anomalies have been noted
Requires development - the standard is generally **incapable** of performing the **function**

4.2.2 Complying with the vibration requirements of the Machinery Directive

Vibration emission data has a role to play in verifying that the risks resulting from vibration are reduced to the lowest level. The standards investigated are generally repeatable and reproducible and the majority of examples produce data that indicates the relative risk within broad margins. Manufacturers' data could not be verified for about 1 in 4 cases within margins of up to 50%. The almost universal failure of Standards to give an accurate indication of workplace vibration hazard leaves the manufacturers with a requirement to explain the vibration risk that is not evident from the data and prevents sensible comparison of data across different classes of tool.

Not only must manufacturers provide information alerting the purchaser to means of controlling the vibration hazard during foreseeable use and misuse of the tool by, for example, providing instructions in the correct usage and limitations of vibration reduction features, but they must also explain deficiencies in the data they have provided in accordance with CEN vibration test codes.

6. FURTHER WORK

This study has identified many limitations in the current battery of standardised hand-arm vibration emission tests. In some cases marked differences were noted in the efficiency of tools in performing their intended task, though no account was given to this in the test procedure.

Further work is being considered to prepare proposals for revisions to existing standards to make them better able to indicate risk, while providing for realistic comparisons between equipment.

7. REFERENCES

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