# MEASUREMENT UNCERTAINTY IN HUMAN EXPOSURE TO VIBRATION

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## 1 INTRODUCTION

Instrumentation for measuring human vibration is used for assessing risk to personal health and safety from vibrating machines. It is clear the uncertainty in such measurement should be minimised so as to provide useful and just assessment. Quantifying this uncertainty has become the subject of considerable interest. Uncertainties associated with the process of field assessment of daily exposure to hand-transmitted vibration have been investigated in detail[1] and the DTI has established a program within the National Measurement System intended to provide "*definitive guidance regarding . .measurement uncertainties .. in the instrumentation of machines causing hand-arm vibration and whole-body vibration*"[2]. This paper describes experiments performed to demonstrate such measurement uncertainties.

The equipment used to instrument sources of human exposure to vibration should conform to the requirements of international standard ISO 8041[3]. Pitts[1] notes that the margin of error acceptable within the standard leaves a typical uncertainty of order ± 4% in a correctly calibrated system, rising to perhaps ± 10% at the extremes of the frequency range (where the standard's filter tolerances are wider). This source of uncertainty, whilst a factor of those results presented later in this paper, is not the object of the present work. Rather than the uncertainty native to the instrument, it is the uncertainty associated with its use "*in the instrumentation of machines*" which is of interest.

When field measurements of vibration exposure are conducted, a range of aspects totally unrelated to the instrumentation influence overall measurement uncertainty. These include temporal patterns of measurement and use, condition and operating load of the vibration source, etc.[1,4]. In laboratory testing of vibration emission[5] many of these uncertainties are removed by operating the source in a controlled environment. There remains, however, an important source of variation whenever human exposure is instrumented – the human!

Human participation as mechanical load for a source of vibration often introduces a source of variability capable of swamping all other factors. This observation motivated the design of a pair of experiments in which representative sources of human exposure to vibration were measured in realistic load conditions without the presence of a human operator or load. The uncertainties observed in these experiments would include factors associated with the instruments and their use alone.

It was intended that measurements should be made in each experiment which would return answers distributed according to uncertainties associated with:

1) repeated measurements with no replacement of the transducer or other disturbances
2) repeated measurements after removal / re-fitting of the transducer
3) measurements made with different instruments

To perform the tests, a range of measurement systems were assembled. Manufacturers represented were Bruel & Kjaer, 01 dB, Larson Davis, Svantek and Castle.

## 2 EXPERIMENT 1: HAND-ARM VIBRATION

The first experiment used an electric angle grinder as a source of hand-arm vibration. The grinder was operated in a standard test rig[6] in which the tool is run with an imbalanced wheel. Rather than the normal load speed specified in the standard, the tool was run at full (no load) speed, for simplicity. In normal use of the test rig a human operator holds the tool, applying a steady feed force. The details of the grip forces will change from one operator to the next and will change over time for a single operator, such that the tool experiences different boundary conditions. These changes in boundary conditions are sufficient to change the resulting vibration levels, particularly on those areas of the tool which have low mechanical source impedance (such as the support handle). To avoid these sources of uncertainty, a pair of "artificial hands" was constructed for the ISO 8662:4 rig.

These hands were designed with reference to measurements of the mechanical impedance of the hand-arm system[7]. Although this impedance is modelled with high-order analogues, the proposed hands used only two coupled masses suspended with reference to a frame by springs in each of three orthogonal directions. One of the masses (coupled to a "jubilee clip" holding one of the handles of the tool) participated in movement in all three directions, whilst the second mass was constrained to move only in the $X_h$ direction.

The mechanical parameters of the hands were designed to be:

| | $X_h$ *axis* | $Y_h$ *axis* | $Z_h$ *axis* |
|---|---|---|---|
| *m (kg)* | 0.105 + 0.035 | 0.035 | 0.035 |
| *K (N/m)* | 660 | 660 | 500 |
| *C (Ns/m)* | 60 | 68 | 150 |

which gave a good fit within the envelope of mechanical impedance magnitudes[7].

The practical embodiment of the artificial hands used identical springs on each axis and omitted the damping elements, for simplicity. The hands are shown holding an angle grinder in the test rig in plate 1. Transducers were mounted on the support and throttle handle of the grinder, using "cable ties". Tri-axial measurements allowed instrumentation of the weighted equivalent acceleration.

**Plate 1: Artificial Hands holding the Grinder**

# 3 EXPERIMENT 2: WHOLE-BODY VIBRATION

The whole-body experiment was motivated by the measurement of vibration transmission through a vehicle seat. Measures of seat transmission using a human subject would include inevitable variations associated with shifts of the occupant's position on the seat during and between measurement runs. Thus, the human subject was replaced by a 75 kg metal mass, which could be lowered onto the seat using a crane.

The seat, intended for use on an agricultural vehicle, was mounted on a flat steel plate atop a vertical hydraulic shaker. The shaker was driven by a pink noise source, resulting in significant accelerations of the mounting plate from 5 Hz to 500 Hz. The acceleration was continuously monitored by a reference transducer on the steel plate. The acceleration of the top of the seat, loaded by the metal mass, was instrumented by accelerometers in "whoopee cushions".

The whole-body experiment is shown in plate 2.

**Plate 2: The Whole-body Experimental Rig**

# 4 RESULTS

In each experiment, groups of ten repeated measurements were made with a range of commercial instrumentation systems all claiming conformance to the relevant standard[3]. Six measuring systems were used in the hand-arm experiment whilst another six systems were investigated in the whole-body work. Absolute calibration and frequency response of the appropriate weighting filters was checked for all instruments.

## 4.1 Repeat Measurement With No Repositioning

The results of repeating measurements with no disturbance of the transducer or the experimental rig are shown below. The results are presented as ratio of standard deviation to mean for each data set of ten measurements. The data sets in Figure 1 were collected from only four instruments in the hand-arm experiment and five instruments in the whole body work. Data sets 2 and 3 were gathered from the same instrument.

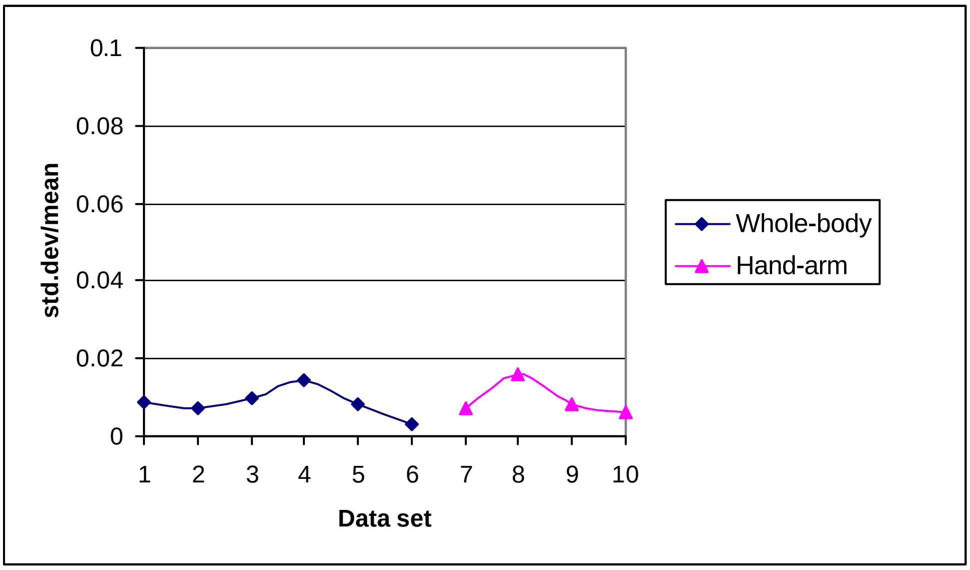


**Figure 1 Distributions of results with no transducer re-positioning**

It is seen that the distributions of results for repeat measurements of whole-body or hand-arm vibration exposure are distributed with ratio s/µ < 2%.

## 4.2 Repeat Measurements With Transducer Re-Positioning

The results of repeating measurements with removal and replacement of the transducer system are shown below, for each instrumentation system. The results are presented as ratio of standard deviation to mean for each data set of ten measurements.

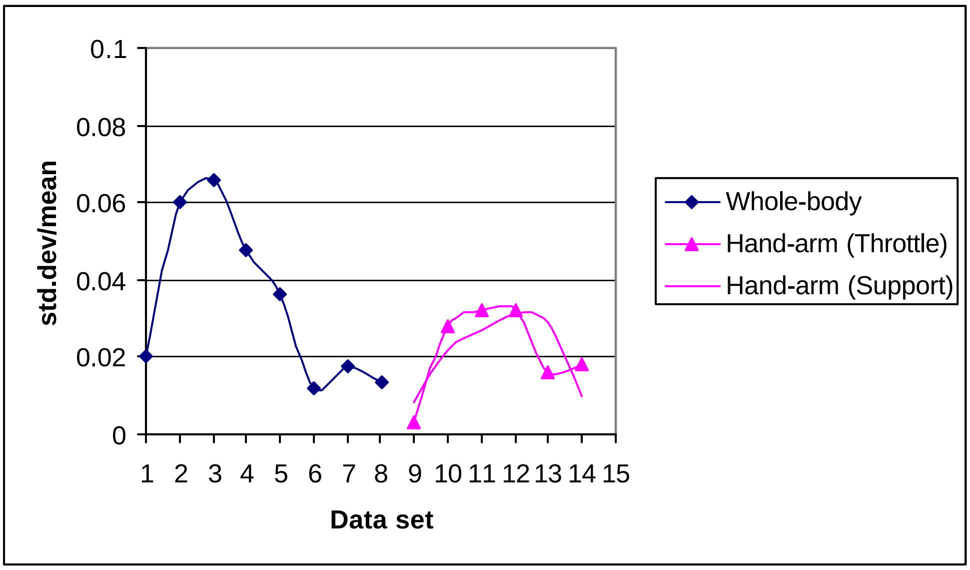


**Figure 2 Distributions of results with transducer re-positioning**

Data sets 2 and 3 were gathered from one instrument and data sets 5 and 6 from another. It is seen that the whole-body results generally are more widely distributed than the hand-arm results. For the whole-body experiment, s/µ < 7%, whilst s/µ < 4% for the hand-arm results.

## 4.3 Variations Between Instruments

The means of ten measurements of weighted acceleration are compared in the figures below.

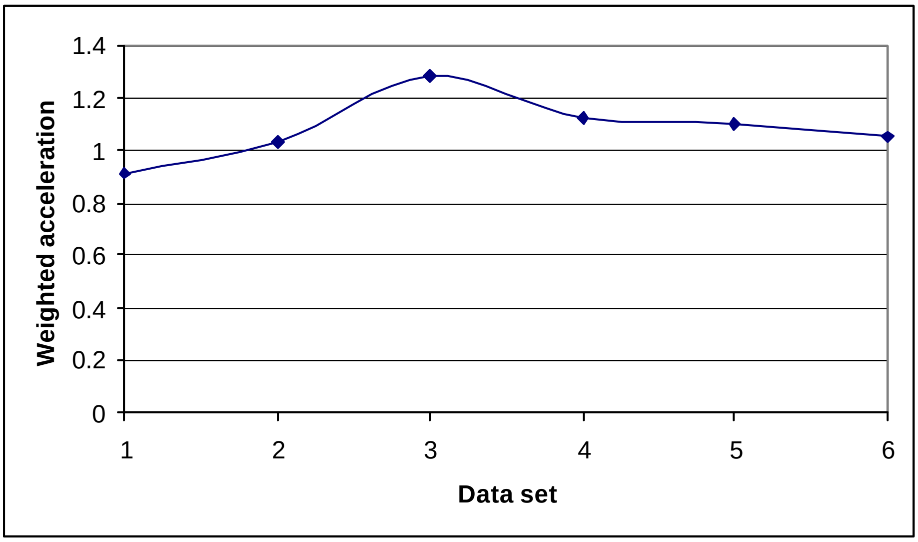


**Figure 3 Mean Whole-body $W_k$ weighted accelerations in $ms^{-2}$**

Only five of the available instruments were used to gather the data in Figure 3. Data sets 3 and 4 were collected from the same instrument used in different configurations (see discussion, below),

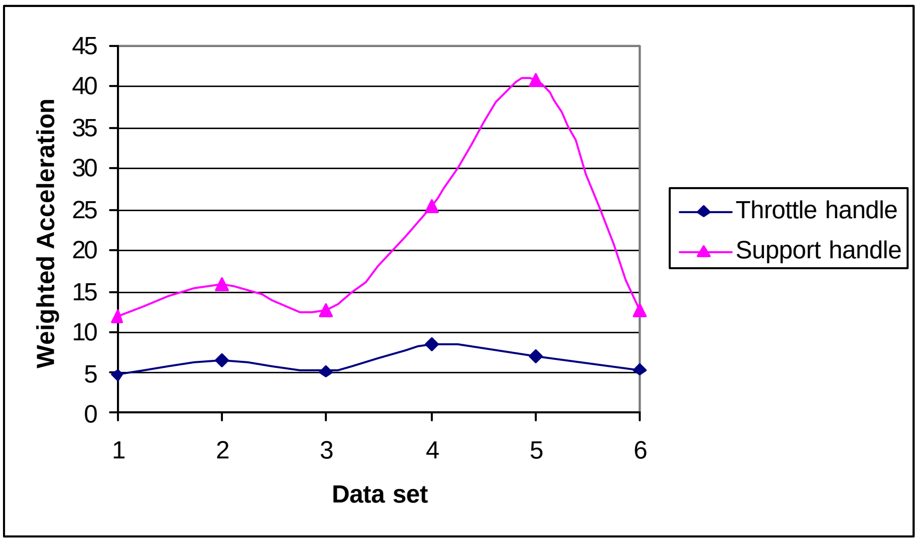


**Figure 4 Mean Hand-arm weighted accelerations in $ms^{-2}$**

Whilst the different systems in the whole-body experiment and the throttle handle returned reasonably consistent results, the data for the support handle shows alarming variations.

# 5 DISCUSSION

Figure 1 confirms that commercial human vibration meters, conforming to international standard[3] and correctly calibrated, are capable of producing reasonably consistent measures of the weighted accelerations which constitute human exposure to vibration. The results, obtained in stable and representative experimental conditions, are distributed about a mean, with $s/\mu < 2\%$. When, however, the transducer is removed and re-positioned, the distribution of results broadens, as shown in Figure 2.

The act of removing and re-positioning the transducer can introduce a placement error in re-positioning the transducer. In the case of both the whole-body and the hand-arm experiments, transducer re-positioning was estimated to be accurate to better than ±2 mm.

In the case of the hand-arm experiment, re-positioning the transducer involved re-fitting the "cable tie" strap which held the accelerometer mounting block to the angle grinder handle. Experience revealed the tension of this strap to be critical and satisfactory performance could not be guaranteed without the use of a cable tie tool to tighten the strap. The superior performance seen in Figure 2, measurement set-up 9, is in part due to the use of the "Kabelrap" system, a product of HellermannTyton. Conventional reusable "ratcheting" cable ties were used in all other Hand-arm measurement set-ups. These re-usable ties showed signs of significant aging after 15-20 uses and fresh ties were used for every set of ten measurements.

Re-positioning the "whoopee cushion" in the Whole-body experiments necessitated removal of the mass from the seat and re-fitting. Although the mass could be accurately positioned with reference to stitched seams on the uncompressed seat cushion, deformation of the seat under the weight of the mass meant that repositioning of the mass in the equilibrium could be the subject of significant error, partially explaining the poorer repeatability seen in the Whole-body data of Figure 2.

Five of the measurement systems used to instrument the Whole-body experiment returned a range of mean weighted (vertical) accelerations, as reported in Figure 3. Data sets 3 & 4 of Figure 3 are associated with one instrument, although in set-up 3 the whoopee cushion was inverted. The 14 % difference between the mean accelerations with the same accelerometer in these two orientations appeared to reflect a stable and repeatable error. The ratio of largest to smallest mean weighted acceleration was 1.40 (1.26 if measurement set-up 3 is excluded).

The six measurement systems used to instrument the Hand-arm experiment returned a range of mean weighted equivalent accelerations as reported in Figure 4. The results for the throttle handle were most consistent, with a ratio of largest to smallest mean weighted acceleration of 1.855. However, the range of mean accelerations reported for the support handle were very widely distributed, with of largest to smallest mean weighted acceleration of 3.449. Neither of these ratios is acceptable when considered against ordinary expectations of the validity of measurement of hand-arm vibration (*e.g. the ISO test [6] accepts a test sequence to be valid when ratio of maxima to minima is less than 1.4*). If data sets 4 & 5 are rejected, the ratio of largest to smallest mean weighted accelerations is 1.42 for the throttle handle and 1.34 for the support handle.

The high values of mean acceleration indicated by data sets 4 & 5 are conspicuous in Figure 4 and both these data sets were derived from instruments which used transducers with common features. They both used high-mass accelerometers, when the other measurement set-ups included lighter and smaller accelerometers. They also shared an accelerometer mounting block which was significantly larger than the other set-ups. The exaggerated readings in data sets 4 & 5, particularly on the support handle, may be due to mass loading effects. More probably, the longer accelerometer mounting block moves the accelerometers further from the point of contact with the handle, making the transducers more sensitive to rotational motion.

## 6 CONCLUDING OBSERVATIONS

Experimentation has revealed that, whilst individual instruments are capable of producing repeatable measures of vibration, the mean weighted accelerations reported by different instruments in the same environment differ considerably.

The instruments all claimed conformance to international standard, were all correctly calibrated and used within their intended operating envelope. The experiments placed the instruments in controlled, stable environments in which the greater number of the factors imposing uncertainty on practical assessment of human exposure to vibration had been removed or minimised.

It would appear that *the instrumentation of machines causing hand-arm vibration and whole-body vibration* is subject to considerable uncertainty, in which commercially available contemporary instrumentation systems can return results differing by 30%.

## ACKNOWLEDGEMENTS

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