Proceedings of the Institute of Acoustics

EFFECTS OF LOW FREQUENCY WHOLE-BODY SINUSOIDAL VIBRATION ON SPEECH

Michael R. Taylor

Smiths Industries Aerospace and Defence Systems - currently seconded to the UK National Physical Laboratory (Division of Radiation Science and Acoustics)

INTRODUCTION

Fixed wing aircraft have fairly broad band vibration characteristics concentrated below 10Hz, whilst rotary-wing aircraft have discrete often intense vibration frequencies between 15-25Hz. Unfortunately major body resonances affecting speech production also occur within these frequency ranges [1].

Research results published by Nixon [2] and Nixon and Sommer [3] [4] have shown whole-body sinusoidal vertical (Gz) vibration at 6, 8 and 10Hz, can contribute to a reduction in speech intelligibility. Low frequency whole-body sinusoidal vibration has also been observed by Leeks [5] to cause a reduction in automatic speech recognition accuracy, particularly when speakers are subjected to 10Hz or 20Hz Gz vibration at acceleration levels of 0.25g (rms).

This paper describes data acquisition and analysis experiments designed to contribute towards the understanding of speech variability as a function of whole-body Gz sinusoidal vibration.

THE BODY AS A MECHANICAL SYSTEM

At frequencies below 100Hz the body acts as a lumped parameter system and resonances occur due to interaction of tissue masses with purely elastic structures [6]; below 2Hz the body appears to move as a simple mass with practically no relative internal motion [7]. Resonant frequencies for transverse Gx vibration have been identified to occur only at frequencies below 3Hz. Vertical Gz vibration, however, has been shown to cause separate resonances between 3-13Hz for the abdomen, chest and spine, whilst 20-30Hz can produce resonance of the head. The higher frequencies of between 100-200Hz have been observed to produce resonance of the lower jaw.

BODY SYSTEM VIBRATION AND SPEECH VARIABILITY

Although the literature contains significant information on vibration and its influence on body systems, knowledge on its effects on speech production is extremely sparse. The most detailed contributions were made over 25 years ago [3] [4] [5] when Nixon and Sommer conducted vibration experiments at 10Hz, 1.5g(rms); 20Hz, 2g(rms); and 30Hz, 40Hz and 50Hz at 3g(rms).

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Even though the vibration levels used in the Nixon and Sommer experiments were far higher than those likely to be experienced in undamaged aircraft, the possible influence of lower levels of vibration on speech production gives cause for concern. With the imminent introduction of automatic speech recognition equipment into high performance aircraft and the requirement for improved speech communication intelligibility, additional analysis of speech spoken under controlled vibration was felt to be of paramount importance.

SPEECH DATA ACQUISITION UNDER WHOLE-BODY Gz VIBRATION

A series of speech data acquisition activities were run by the Human Engineering Division of the Royal Aerospace Establishment Farnborough using their man-rated three axes vibration rig. The vibration rig and associated instrumentation is illustrated in Fig.1 and represents the preferred configuration [8] for multi-channel recording of speech and environmental data.

Ten adult male subjects were required to speak typical airborne command and control passages whilst seated on a vibrating Chinook helicopter seat. During the data gathering process synchronous speech, Laryngograph Lx and Gz displacement data, were digitally recorded using a multiplexed Sony PCM-F1/SL-F1UB Video Recorder. The speech recordings made during these experiments have since become known as Part II of the RAESI Speech Vibration Data Base archived at the UK National Physical Laboratory.

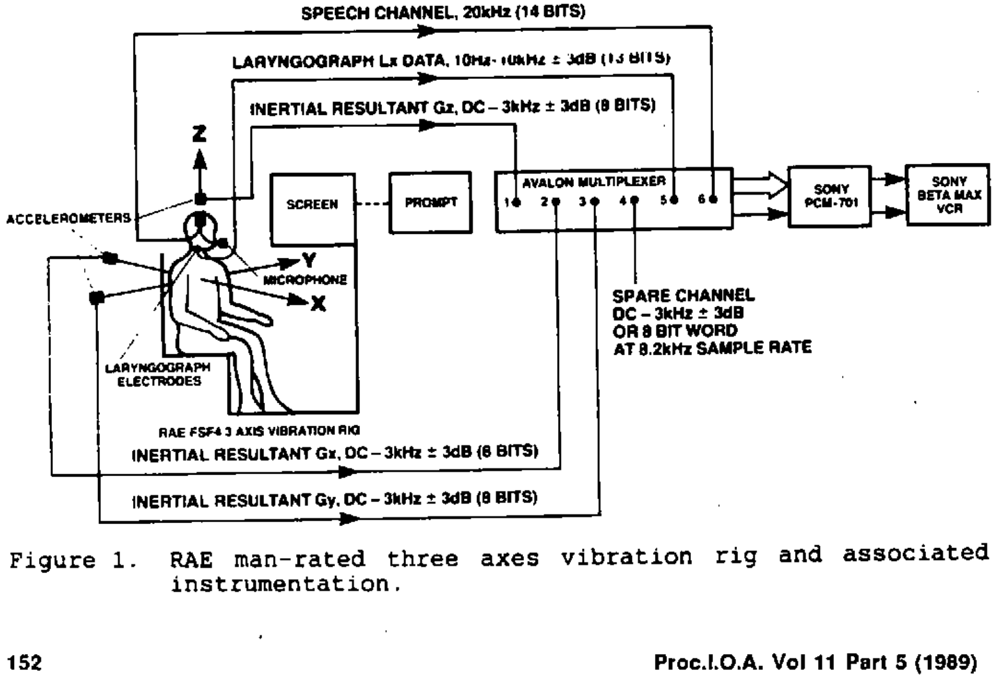

Figure 1. RAE man-rated three axes vibration rig and associated instrumentation.

During the recording sessions each subject was exposed to 90 separate vibration conditions and 36 control sessions with the vibration rig at rest. No subject was exposed to more than 30 minutes total vibration without at least a 2 hour rest before continuing with the trials.

Each vibration session was based on a frequency randomly chosen from the range 8-25Hz, at Gz acceleration levels between 0.05g(rms) and 0.25g(rms), in 0.05g(rms) steps. Control passages (no vibration) were recorded for each subject immediately prior to, and immediately following, each vibration session. In total 7 months was required to complete the data gathering exercise for all ten subjects.

SPEECH PARAMETER ANALYSIS

Fundamental Frequency, F_0

Long term mean F_0 values and standard deviations were computed for all ten subjects over a 7 month period.

Biomechanical stress. Mean F_0 frequencies were also compared before and after every vibration session to see if biomechanical stress caused any residual short term increase in excitation frequency. Although changes were observed, none were considered significant and only one subject had a mean F_0 shift which exceeded one standard deviation from his mean F_0 computed over the 7 month period.

Peak shifts in mean F_0. The mean F_0 frequency was computed for each subject under every vibration condition. These figures were then compared with the long-term mean F_0 values calculated for each subject during the 7 month recording process. Whenever an F_0 shift greater than three times the long term mean F_0 standard deviation was observed, a significant vibration condition was assumed to have been identified.

Fig.2 plots the normalised mean percentage F_0 shift across all ten subjects at vibration frequencies between 8-25Hz at a constant acceleration of 0.25g(rms). The shaded area either side of the normalised response indicates a one standard deviation spread computed from the normalised responses of the ten subjects. At least three of the major F_0 shifts show an apparent relationship between known frequencies of body system resonance.

The maximum increase in mean F_0 occurs in the range of 8-10Hz for seven of the ten subjects and can be attributed to resonance of the abdomen/thorax system. The range of variability in F_0 shift at this frequency is also the most extreme, with some subjects increasing their mean F_0 by as much as 33%, whilst others barely increased theirs by 10%.

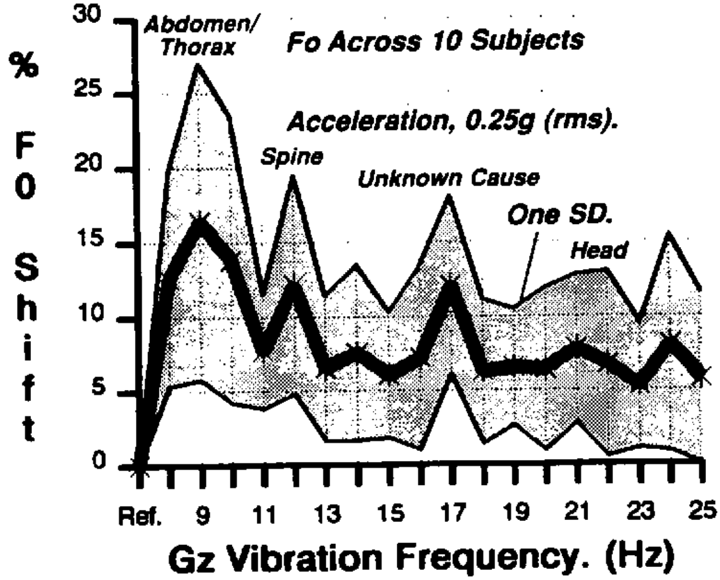

Figure 2. Normalised percentage mean F_0 shifts as a function of vibration frequency at Gz 0.25g(rms).

The second peak F_0 shift occurs at 12Hz vibration and this may be due to spine resonance, although Rowlands [9] had identified 13Hz as the frequency for this phenomenon.

The third peak shift in mean F_0 is seen to occur at 17Hz and this cannot, as yet, be attributed to a known cause.

Vibration in the range between 20-25Hz causes the fourth peak shift in F_0 and varies in exact frequency from subject to subject with possible groupings at 21Hz and 24Hz. This increase in excitation frequency may well be due to resonance of the head.

Significant Vibration Threshold Levels

Two plots of percentage mean F_0 shift against changing acceleration levels at example Gz vibration frequencies where the mean F_0 shift was greater than three standard deviations at 0.25g(rms), are shown in Fig.3 (a-b). The mean vibration acceleration threshold found to cause three standard deviation increases in mean F_0 computed across the ten subjects, was 0.17g(rms), with a standard deviation of 0.05g(rms) [10].

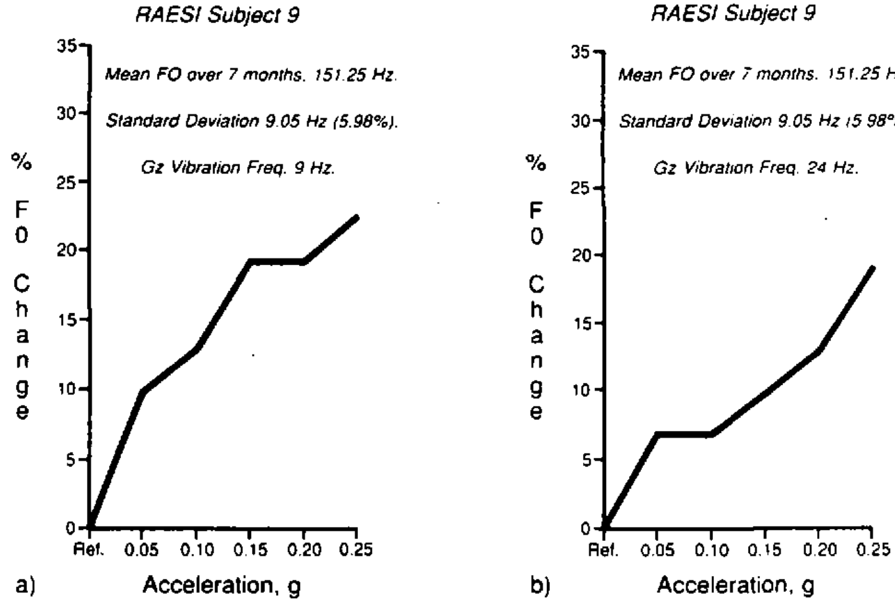

Figure 3. Changes in mean F_0 as a function of acceleration at fixed Gz vibration frequencies.

Duration of Speech Passages

Gross temporal parameters of the command and control passages were also computed in case whole body resonance caused speech to exhibit significant temporal changes. The total time taken to speak the command and control passages at each vibration frequency at 0.25g(rms) acceleration was computed for each subject. No change in overall time duration for the passages was observed to exceed two standard deviations from the mean reference duration. Fig.4 illustrates normalised time variability for the command and control passages spoken by all ten subjects under Gz vibration at frequencies between 8-25Hz at 0.25g(rms).

The result of normalising across all ten speakers has tended to flatten extremes of variability such that the one remaining peak change occurs at 22Hz. At this frequency the overall time duration of the passage is seen to increase by 13%.

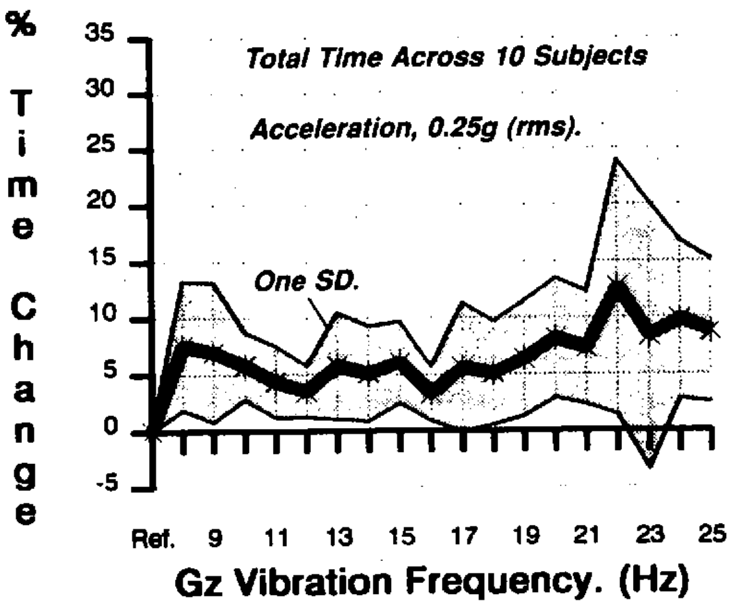

Figure 4. Normalised percentage time variability as a function of vibration frequency at Gz 0.25g(rms).

Voicing Duration of Speech Passages

All subjects exhibited significant increases in voicing time resulting from whole-body vibration. Examples for the command and control passages include a 25% increase in duration at 14Hz and 15Hz and a 30% increase at 20Hz for one subject, whilst another exhibited a 40% increase in voicing duration at 20Hz. Even though the duration changes often exceeded mean control durations by two standard deviations, they remained within the time normalisation capabilities of contemporary speech recognition algorithms.

Fig.5 illustrates the change in voicing time normalised across all ten subjects at Gz vibration frequencies between 8-25Hz at 0.25g(rms). The normalisation process has again flattened individual peak changes except those at 8Hz and 17Hz, leaving a nearly flat increase in voicing of 10% for all other vibration frequencies.

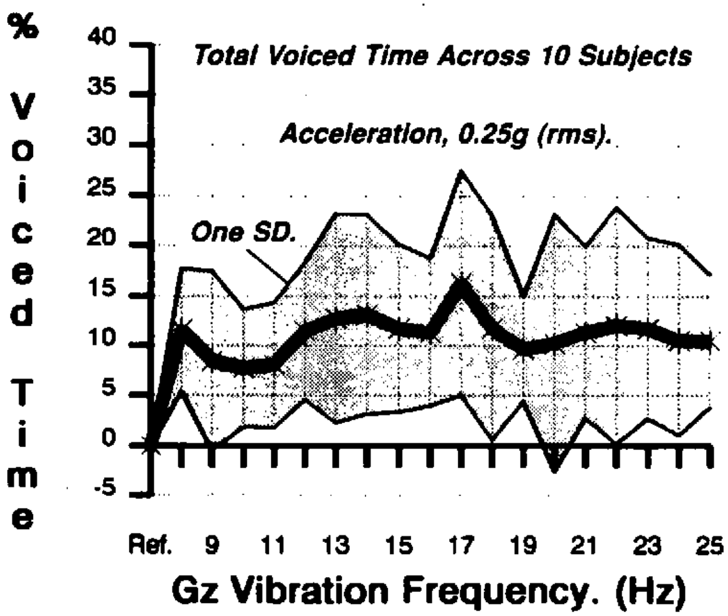

Figure 5. Normalised percentage voiced time variability as a function of vibration frequency at Gz 0.25g(rms).

CONCLUSIONS

Analysis of speech data recorded under controlled low frequency sinusoidal Gz whole-body vibration has revealed four frequency bands where the mean excitation frequency of speech, F_0, can be considerably modified.

Resonance of the abdomen/thorax system between 8-10Hz has been shown to cause the most extreme upward shift in F_0, whilst possible spine resonance at 12Hz and head resonance between 20-25Hz, have been shown to increase mean F_0 and to a lesser extent, the temporal structure of speech.

Whole body vibration at 17Hz has been observed to cause an increase in mean F_0, although this phenomenon has not been identified with a specific body system resonance.

Further acoustic phonetic analysis of the speech data gathered in the RAESI vibration trials are required in order to obtain further insights into the structure of speech spoken in vibrant environments.

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VIBRATION DOSE VALUES - NOTES FOR CONSULTANTS

A. W. JAMES

Sound Research Laboratories Ltd., Sunbury-on-Thames, Middx., UK.

INTRODUCTION

The use of the vibration dose value (VDV) in recent standards (1, 2, 3) is a major advance in vibration measurement and control. It seems likely that environmental health officers and consultants will soon be using VDVs as a matter of course for measuring and evaluating the effects of whole-body vibration. The current approach to British and International Standards however is not to establish limits but merely to specify nomenclature and methods of measurement. In fact the British Standards Institution increasingly takes the attitude that it is up to local authorities to impose limits for environmental noise or vibration, provided that the measurements have been taken in accordance with the standards. There are three problems with this approach to vibration rating:

(i) There are currently two British Standards (1, 2) and one International Standard (3) that can justifiably be applied and we will generally obtain different results depending on which standard we use. This is of course contrary to the whole concept of National and International Standards.

(ii) Very few EHOs or consultants will have the experience that would be necessary to impose reasonable limits until VDVs have been in use for some time.

(iii) This philosophy is likely to result in the same kind of anarchy that currently affects noise criteria, with different local authorities imposing wildly different criteria. This brings considerable expense and confusion to industries and developers, profit (and occasional confusion) to consultants, profit to barristers and confusion to planning enquiries. Many of these criteria are designed for simplicity rather than compatibility with current scientific thought.

It is therefore necessary that a single set of criteria, or at least of guidelines, for vibration exposure should be determined by some competent body such as might exist within the Institute of Acoustics.

This paper illustrates some of the concepts involved in the measurement of environmental vibration by comparison with well established methods of measuring environmental noise, and considers some of the problems that will have to be taken into account by consultants, local authorities and by any body which is involved in setting criteria.

VIBRATION DOSE VALUES AND ROOT MEAN QUADS : AN ANALOGY WITH LEQ AND SEL VALUES

The continuous equivalent noise level (Leq) is now well established as the most suitable parameter for the assessment of both intermittent and continuous noise (by definition, for continuous noise the Leq tends to the continuous SPL, L90 or L95). It is now widely accepted that for many sources of noise, subjective annoyance is a function either of the absolute Leq level or of the difference between Leq and background L90 or L95 level (4, 5, 6).

The Leq is easy to measure and relate to annoyance; it is also easy to calculate. For repetitive sources (e.g. piling, clay pigeon shooting, even sometimes trains or lorries) the single event noise exposure level (SEL, previously Lax) can be measured. It is then easy to calculate the Leq resulting from any number of such events over any period (7).

The VDV is most simply thought of as analogous to the SEL, with the root mean quad (rmq) levels being analogous to the Leq. This can be seen from the following definitions:

Leq: The sound pressure level of a continuous noise which would contain the same acoustic energy as the measured intermittent noise over the period of measurement.

$$L_{eq} = 10\log_{10}\left[\frac{1}{T}\int_0^T \frac{p^2(t)}{p^2_0}dt\right]$$

rmq: The magnitude of a continuous vibration which would have the same subjective effect as the measured intermittent vibration over the period of measurement.

$$rmq = \sqrt[4]{\frac{1}{T}\int_0^T a^4(t)dt}$$

SEL: The sound pressure level of a steady noise which, if it lasted for one second, would contain the same acoustic energy as the event measured.

$$SEL = 10\log_{10}\left[\int_0^T \frac{p^2(t)}{p^2_0}dt\right]$$

$$L_{eq} = 10\log_{10}\left[\frac{1}{T}\sum_{n=1}^{N} 10^{\left(\frac{SEL_n}{10}\right)}\right]$$

VDV: The magnitude of a steady vibration which, if it lasted for one second, would have the same subjective effect as the event measured.

$$VDV = \sqrt[4]{\int_0^T a^4(t)\,dt}$$

$$rmq = \sqrt[4]{\frac{1}{T}\sum_{n=1}^{N} VDV_n}$$

Where:

T is the measurement period in seconds

P is the instantaneous sound pressure level in Pascals

a is the vibration acceleration in metres /second;

p is the reference sound pressure level, 2x10-5Pa

To say that a factory worker should not be exposed to an 8 hour Leq(A) exceeding 90, a 4 hour Leq(A) of 93, etc., is equivalent to saying that he should not be exposed to an SEL of more than 134.6dB(A) in any one day. Similarly, rather than impose a limit for rmq vibration over a certain time period, as is suggested in BS6472, we can simply specify a maximum vibration dose value for any one day.

In fact, provided that we remember to take fourth powers the VDV and rmq are even easier to use than the SEL and Leq because we do not have to worry about logs and powers of Ten. The use of the fourth power is the aspect of VDVs and rmqs which seems to cause most alarm and despondency among potential users who may discount the index as being too complex or academic for commonplace use. In fact, the reasons for the inclusion of the fourth power are very clearly explained by Griffin (8) and in Appendix A of BS6841:1987 (1). Its use, both in manual calculations and computer programs, is extremely straightforward and certainly no more complicated than using Leqs.

SOURCES OF CONFUSION

The following questions are common causes of confusion and hysteria among consultants trying to think hard about rmqs and VDVs:

VIBRATION DOSE VALUES - NOTES FOR CONSULTANTS

1. Question : Should the "raw input" to our VDV/rmq calculation be in terms of peak, peak to peak or rms acceleration?

   Answer : As long as we are consistent, it does not matter. Of course we must measure rms acceleration if criteria are set for rms acceleration, or if the vibration is sinusoidal in form we can use the appropriate multiplying factor to convert between rms, peak to peak or peak acceleration. Do not be confused by the "root mean square" and "root mean quad" nomenclature; the rms is an operation at the input stage of the measuring instrument whereas the rmq calculation is carried out totally independently at a later stage of signal analysis.

2. Question : Instead of measuring acceleration directly, can I measure velocity or displacement and convert my results to acceleration?

   Answer : There are two answers to this question:

   a) According to BS6472 - yes, provided that the vibration is a sum of pure sine waves and its frequency is between 8Hz and 80Hz. It must be sinusoidal because the simple relationship between acceleration, velocity, displacement and frequency is only true for sine waves. This means that for impulsive vibration you must measure acceleration. (Accurate frequency analysis of impulsive vibrations is in any case meaningless, regardless of what your FFT analyser may tell you.) It must be between 8Hz and 80Hz, because, according to BS6472, human response to vibration in this range is a function of vibration velocity alone.

   b) According to BS6841 - no. The filtering networks recommended in BS6841 are substantially different from those in BS6472 and vary continuously over the range of measurement. It may be permissible to use transducers which give an output voltage proportional to velocity or displacement. You can convert this to acceleration at the input stage and then apply the built in filters and calculate the overall VDV - but again, this will only work for purely sinusoidal waveforms.

Apart from the contradiction between the two current British Standards in terms of frequency weighting, there are other problems with BS6472. Perhaps the most obvious of these is the "provisional relationship" for blasting vibration given in the Standard. It would seem that the only information contained in BS6472 which is not contained in the new Standard is the table of "multiplying factors to specify satisfactory magnitudes of building vibration with respect to human response". This table contains values which seem to be rather arbitrarily defined and in some cases are nonsensical. For example in critical working areas the permissible vibration level is not controlled by human response at all. In an operating theatre, vibrations should never be allowed to reach a point at which they might interfere with delicate equipment or operations. This requirement is always more stringent than the comfort of the people working in the operating theatre.

It seems therefore that we can safely discard BS6472 if we are to adopt the recommendations given in the new standard BS6841:1987.

FREQUENCY WEIGHTING AND BACKGROUND

In measurements of acoustic noise, the overall 'A' weighted SPL is rarely satisfactory for predicting annoyance. This is primarily because of the existence of a background noise spectrum which rarely follows an equal loudness contour. Hence, our evaluation of airborne noise must be based on the difference between the source noise and the background at each frequency and on the increased annoyance caused by intermittency and pure tones.

With vibrations, there is normally no perceptible background level. Furthermore, there is no established evidence, as far as the writer is aware, that tonal components in the source vibration cause any more annoyance than a continuous spectrum. In any case, the smooth continuous vibration spectrum is very rare and the vast majority of vibrations likely to be encountered are either continuous and tonal or intermittent. Hence, the need for frequency analysis is removed and a simple set of weighting networks is all that is required with the current state of the art.

Provided that we accept the more recent frequency weightings in BS6841 in preference to the simpler, but apparently outdated curves in BS6472, an instrument similar to an Leq(A) meter seems to be sufficient to evaluate environmental vibration nuisance. Such an instrument will, of course, not identify the source of vibration or predict the effects of transmission paths.

MEASUREMENT LOCATIONS, TRANSMISSION PATHS AND VIBRATION AXIS

In measuring and predicting vibration levels, we face two major difficulties that do not exist for airborne noise:

1. The different sensitivity of humans to vibration on different axes.

2. The difficulty of predicting how a vibration will be amplified or attenuated along its transmission path.

These two factors are often inter-related and, as will be seen in the following example, it can be difficult even to predict the direction of the vibration that would cause most annoyance.

AN EXAMPLE OF VIBRATION DOSE VALUES:
TRAIN INDUCED VIBRATION

Consider the case of a gravel quarry with a rail link. In order to operate efficiently, the quarrying operations will involve heavy goods trains using railway lines in residential areas and in order to fit into the British Rail timetable, many of these trains will have to run at night. Residents in houses adjacent to the line have complained that vibrations from existing freight trains are already causing severe annoyance and structural damage.

In most cases, it should be possible to persuade residents that structural damage is not being caused unless vibration levels are so high that it is extremely uncomfortable to remain in the building. The assessment of nuisance to residents however is more difficult as we must measure vibrations in three directions at a large number of positions around each house. Vertical vibration levels on a wooden floor can vary considerably with the measurement position. Similarly, vibrations are generally amplified as they travel up a building: for lightweight wooden framed buildings this amplification can be as much as a factor of ten. Tall steel-framed buildings are also prone to this problem.

For night-time vibration the most sensitive axis of most residents is in a horizontal direction because they are in bed. Hence, the consultant must know the orientation of the bed or must use the highest component of horizontal vibration. Even this is not sufficient, however, because the bed itself has a response to vibration and from a simple structural analysis it can be seen that an amplification of horizontal vibrations is quite likely at some frequencies. BS6841 states definitively that the vibration should be measured at the interface between the human body and the source of vibration. This requirement will, of course, make the consultant's job much more interesting. Alternatively, there is scope for valuable research into the vibration responses of different types of beds. Whether the SERC would take applications for funds for this research seriously is of course another matter.

VIBRATION NUISANCE

Determining whether or not a vibration is a nuisance simply because it is perceptible is even more complex and controversial than the same process for airborne noise. Many residents believe that if any vibration at all is perceptible directly or indirectly there must be some long-term structural damage to the building. It is not uncommon for residents to become alarmed when pot plants become animated, mirrors shake and glasses rattle, although vibration levels are imperceptible to the resident. As far as the writer is aware, the subject of animated pot plants is not covered in the technical literature.

In the past it has not been unusual for local authorities to control vibration nuisance by specifying an absolute maximum level close to the source. It should by now be obvious that this approach is wrong. It is, however, possible with the use of comparatively inexpensive computer driven multi-channel vibration analysers to determine a transfer function from a given monitoring point to the most sensitive areas in surrounding buildings. Instruments capable of carrying out this work are commercially available at the time of writing. The advantage of this method however is that once the transfer function has been calculated a simple vibration dose value can be set at the monitoring point without further inconveniencing the residents.

CONCLUSIONS

In spite of their apparent complexity, Vibration Dose Values are similar in concept to SELs and Leqs but are, if anything, easier to calculate. The frequency weightings in BS6841 : 1987 are different from those in BS6472 : 1984 and given the other inconsistencies in the old Standard it would seem reasonable to discard this standard altogether in favour of the new one. It is important however that a nationally applicable set of guidelines for vibration criterion in terms of VDVs should be produced to forestall the problems that currently exist in the evaluation of environmental noise.

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MEASUREMENT AND ANALYSIS TECHNIQUES FOR THE EVALUATION OF HUMAN EXPOSURE TO VIBRATION

C M Nelson

Human Factors Research Unit, Institute of Sound and Vibration Research, The University, Southampton, SO9 5NH.

Summary

The measurement and analysis of vibration and motion with respect to their effects on humans can be complex. The characteristics of the vibration (e.g. magnitude, frequency, direction), other environmental factors and subject differences all play a role in determining the resulting effects on people. The effects of vibration exposure may be purely subjective (e.g. discomfort in vehicles, annoyance in buildings), physiological (e.g. seasickness, back pain, vibration-induced white finger) or related to performance (e.g. impeded vision, manual performance). Several standards have been evolved to provide guidance for those wishing to measure and evaluate human exposure to vibration and motion. These include BS 6841, BS 6842, ISO 2631 and ISO 5349. These documents define frequency weightings and time dependencies which can put many investigations beyond the scope of a simple r.m.s. meter. The non-stationary characteristics of many vibration exposures also prohibit the use of this simple form of analysis.

The recent availability of compact, portable and affordable computers has made possible the digital recording and analysis of vibration in the field. Complex mathematical operations, such as spectral analysis and true integration, may be carried out on digitised time histories which may also be stored for further analysis. An investigation of the vibration in a building due to passing trains is described as an illustration of the use of a portable computer-based vibration analysis system.

Introduction

In recent years, a large and, perhaps, confusing number of standards have been published concerning the measurement and assessment of human exposures to vibration and motion. The human effects of exposure to vibration can be dependent on the individual's own characteristics – both physical and psychological – in addition to those of the vibration itself: magnitude, frequency, direction, duration etc. The adverse effects of vibration may be considered in three categories:

1. Health effects. These may be temporary (e.g. motion sickness) or long-term (e.g. vibration-induced white finger in users of vibrating hand tools, low back pain in drivers).

2. Performance effects. These include impairment of vision (e.g. reading instruments) and manual control difficulties (e.g. writing, drinking, standing, performing manual tasks).

3. Comfort effects. This category includes factors such as perceived ride quality in vehicles and perception of, and annoyance from, vibration in buildings.

Vibration Standards

In 1974 the first version of ISO 2631 was published [5]. This standard dealt with the evaluation of whole-body vibration exposures and defined a set of frequency weighting curves, time dependencies etc. as well as recommended exposure limits. This document has been ammended and also supplemented by several addenda since its original publication. It has been under consideration for revision during recent years. Its British counterpart, BS 6841, was published in 1987 [2] and benefits from the advances in knowledge and changes in thinking since the early 1970s. It is similar to a current draft revision of ISO 2631. The British Standard does not define limits, but rather describes standard methods for the quantification of vibration exposures so that decisions may be made by competant authorities regarding the severity of vibration exposures in specific environments. Griffin [4] made a comprehensive comparison of these standards. A separate British Standard, BS 6472 [1], predates BS 6841 and deals specifically with human exposure to vibration in buildings. This specifies frequency-dependent base curves as acceptable magnitudes for building vibration, together with a set of multiplying factors and time dependency information for specifying "satisfactory" vibration magnitudes for specific situations.

For the assessment of hand-transmitted vibration, the British Standards Institution published a Draft for Development in 1975. This was DD43 and was similar in concept to Draft International Standard ISO/DIS 5349 (first published 1979), although different magnitudes were specified as vibration limits. The finished standards ISO 5349 [6] and BS 6842 [3] were published in 1986 and 1987 respectively and are broadly compatible. Here, as with the British Standard dealing with whole-body vibration, the concept of an imposed limit has been replaced by a new philosophy whereby frequency-weighted magnitudes may be measured by standard procedures for subsequent assessment in conjunction with available data (included in appendix form) on the likely health effects.

Frequency Weighting

The relative importances of different vibration frequencies vary depending on the axis of vibration, the posture of the subject and the aspect of human response under investigation. Six different weighting curves are defined in BS 6841. In addition to these, a weighting curve for hand-arm vibration is defined in BS 6842.

The provision of measuring equipment to enable comprehensive and flexible assessments of human vibration exposures would require an expensive and elaborate set of filter networks if traditional analogue methods were to be used. In the recent British Standards, the weighting filters are described by a set of linear differential equations. This makes it possible to implement them exactly by analogue methods, which may be necessary if real-time frequency weighting is required. However, the precise mathematical definitions also make digital filtering of sampled vibration time histories a practical proposition, especially if real time operation is not a necessity. Lewis [7] described methods for frequency weighting, using both digital and analogue techniques, in accordance with the curves then proposed for BS 6841.

Time Averaging and Dose Values

The method traditionally used for averaging a varying vibration signal is the root-mean-square calculation:

$$a_{rms} = \left[\frac{1}{T} \int_0^T a^2(t)\ dt \right]^{\frac{1}{2}}$$

where a(t) is the acceleration time history, frequency-weighted as appropriate.

Modern true r.m.s-to-d.c. convertors have made possible extremely accurate analogue r.m.s. measurements (other analogue methods, such as exponential averaging, tend to give different results where high crest factors exist).

ISO 2631 uses r.m.s. averaging throughout, in conjunction with complex time dependencies for the evaluation of human exposures to vibration. For vibration exposures involving high crest factors, r.m.s. averaging is considered inappropriate, since it does not place enough weight on the peak acceleration values. The ISO standard therefore imposes a crest factor limit of 6, above which the methods are considered invalid. BS 6841 suggests the use of the root-mean-quad averaging technique for high crest factor motions:

$$a_{rmq} = \left[\frac{1}{T} \int_0^T a^4(t)\ dt \right]^{\frac{1}{4}}$$

This calculation is not easily performed by simple analogue instrumentation, and has not, therefore, been adopted as widely as would otherwise have been expected. If digital techniques are employed, however, the calculation of r.m.q. is no more difficult than the calculation of r.m.s., consisting simply of arithmetic operations on data values sampled from the acceleration waveform.

The use of any time averaging method makes the assumption that the vibration time history is ergodic during the period of measurement. This is not the case with many real vibration exposures – indeed, an exposure may consist of several vibration "events", separated by periods of zero motion. To use an r.m.s. or r.m.q. procedure over the whole period would obviously be foolish. The technique favoured in ISO 2631 uses r.m.s. averaging during each (approximately ergodic) event, before applying a complex time dependency to calculate exposure limits.

A solution to the problem of assessing non-ergodic signals is to use a cumulative or 'dose' measure instead of an averaging technique. The vibration dose value (VDV) is now widely accepted as a useful indicator of the magnitude of a vibration exposure:

$$VDV\ (ms^{-1.75}) = \left[\int_0^T a^4(t)\ dt \right]^{\frac{1}{4}}$$

This measure also uses the fourth-power relationship between weighted acceleration and time, and is currently thought to express adequately the severity of a human vibration exposure. The need for complex time dependency calculations is dispensed with because the time dependency is implicit in the dose calculation. BS 6841 recommends the use of vibration dose values for evaluating effects of vibration on health and also specifies a method for estimating the VDV from an r.m.s. acceleration for motions which have low crest factors (<6) and are approximately ergodic:

$$eVDV = 1.4\ a_{rms}\ T^{\frac{1}{4}}$$

where eVDV is the estimated vibration dose value ($ms^{-1.75}$), a_{rms} is the r.m.s. value of the frequency-weighted acceleration (ms^{-2}) and T is the duration (s) of the measurement.

Example: Building Vibration

Because the time dependency is implicit in the definition of the vibration dose value, the VDV is a most useful quantity for the assessment of vibration exposures, if a practical means of calculation is available. This section describes the use of a digital computer-based analysis system for an investigation of vibration in a building due to passing trains. This approach allows such operations as frequency-weighting and calculation of vibration dose values without the need for dedicated electronics.

The portable recording and analysis system, developed at the I.S.V.R. for research into human response to vibration, consists of a battery powered portable computer (IBM-PC compatible) which is fitted with an expansion card containing the necessary circuitry for the simultaneous digitisation of four analogue signals. The software (*HVLab* version 3.3) allows the user to set parameters for data acquisition (sampling rate, duration, cut-off frequency of on-board anti-aliasing filters etc.) using a simple menu. Once acquired, the data from each input channel are stored on disk in separate files. The data files may then be operated on by the analysis routines. In this example, further computation involved spectral analysis, frequency weighting and the calculation of the VDV. See Figure 1.

Figure 2 shows the time history of vertical acceleration due to a passing train, measured on the floor in a house close to a railway line. This was digitised at a rate of 260 samples per second. The frequency content of the vibration was established by computing the power spectral density. This is presented in Figure 3. It is apparent that most of the vibrational energy lies in the range 10 - 30 Hz. The shape of the base curve for vertical building vibration specified in BS 6472 is similar to the inverse of the weighting W_g in BS 6841. By digitally filtering the original time history (Figure 2) using the W_g weighting, the waveform shown in Figure 4 was produced. The magnitude is reduced because the weighting attenuates at frequencies above 8 Hz.

This type of vibration environment, where each event (i.e. a passing train) is separated from the next by a period of no vibration, illustrates well the problems inherent in the use of r.m.s. averaging. Calculated over the whole of the 12 second data file shown in Figure 4, the r.m.s. magnitude of the weighted vibration is 0.035 ms^{-2}. However, if the r.m.s. value is computed only over the 7.5 second portion of this time history which contains the vibration "event", the result is a magnitude of 0.044 ms^{-2}. For intermittent vibration an averaging procedure such as r.m.s. or r.m.q. would only give a meaningful result if the points at which the averaging begins and ends were established by some standardised and practical method. Clearly, this would make real-time averaging extremely difficult.

The use of a cumulative measure, such as the vibration dose value, however, is an ideal means of assessing vibration exposures of this kind. The VDV continues to increase with time if vibration is present; the value remains constant during periods of no vibration. The vibration dose value of the passing train event was calculated from the frequency weighted time history and found to be 0.113 $ms^{-1.75}$. (The same value is, of course, obtained whether the computation is performed with the 12 second or the 7.5 second time history.) The vibration dose values for all events occuring in a specified period may be combined using a root-sum-of-4th powers procedure to give the overall VDV:

$$VDV = \left[\sum_{n=1}^{n=N} VDV_n{}^4 \right]^{\frac{1}{4}}$$

If, for example, 20 trains passed the house during a period of 16 hours duration, and each train produced the same vibration in the building, the VDV for the period would be:

$$[\ 20 \times 0.113^4\ ]^{\frac{1}{4}} = 0.239\ ms^{-1.75}$$

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The "acceptability" of this vibration environment may be evaluated in accordance with BS 6472. This standard gives a 'base curve' which represents the magnitudes of approximately equal human annoyance to vertical vibration in buildings over the frequency range 1 to 80 Hz. Multiplying factors are applied to the base curve; these are dependent on environmental criteria such as the type of building, and the time of day. As the curve is similar in shape to the inverse of the W_g weighting, the weighted acceleration value of the base curve corresponds to the magnitude at the frequency of greatest sensitivity (4–8 Hz). This is 0.005 ms^{-2} r.m.s. The multiplying factor is specified as being between 2 and 4 for continuous vibration in residential buildings in day time (the variability being due to social and cultural factors). The acceptable maximum VDV over the 16 hour period would therefore be expected to lie between the following values:

$$\left[(2 \times 0.005)^4 \times (16 \times 60 \times 60) \right]^{\frac{1}{4}} = 0.155 \ ms^{-1.75}$$

$$\left[(4 \times 0.005)^4 \times (16 \times 60 \times 60) \right]^{\frac{1}{4}} = 0.310 \ ms^{-1.75}$$

The VDV of 0.239 $ms^{-1.75}$, calculated for the 20 trains passing in this period lies between the above values and therefore represents a severity of vibration which is close to the maximum acceptable in such environments according to BS 6472.

Conclusion

The most recent standards concerning the assessment of human exposures to vibration indicate that the fourth power relationship between acceleration and time is currently believed to provide a convenient and appropriate time-dependent representation of vibration magnitude over a wide range of durations and vibration waveforms. For impulsive or high crest factor vibration, the use of the root-mean-quad averaging procedure is therefore preferable to the root-mean-square method. In many circumstances the vibration dose value is a more appropriate quantity than an averaged vibration magnitude. Frequency weighting of measured acceleration, using one of several recommended weighting curves, is also required by current standards.

With the recent introduction of cheap and portable computers, the use of digital calculations on sampled acceleration time histories may be considered to be a more reliable and accurate means of performing analysis in accordance with current standards than the use of traditional analogue instrumentation. An example of the assessment of railway-induced building vibration has been used to illustrate the method by which such a system may be applied to real situations.

References

[1] British Standards Institution (1984) British Standard Guide to Evaluation of human exposure to vibration in buildings (1 Hz to 80 Hz). BS 6472:1984.

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[3] British Standards Institution (1987) British Standard Guide to Measurement and evaluation of human exposure to vibration transmitted to the hand. BS 6842:1987.

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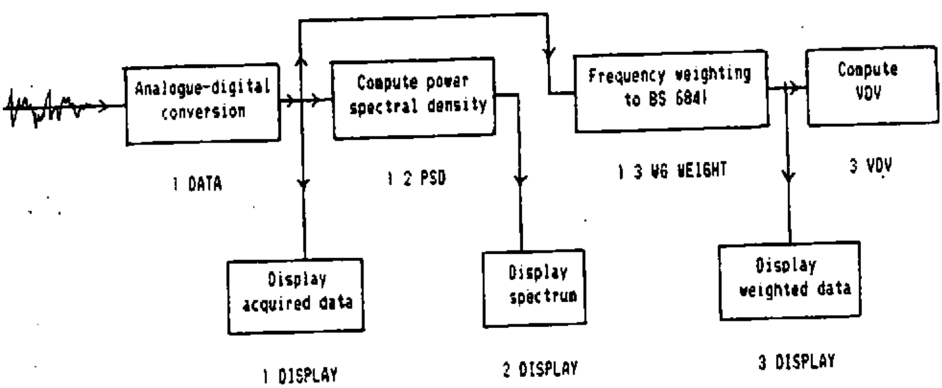

Figure 1 Analysis procedure for building vibration example, showing *HVLab* commands.

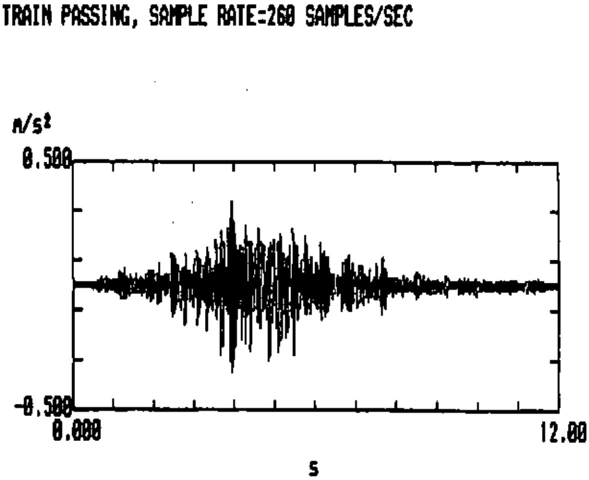

Figure 2 Sampled acceleration time history for vertical building vibration due to a passing train.

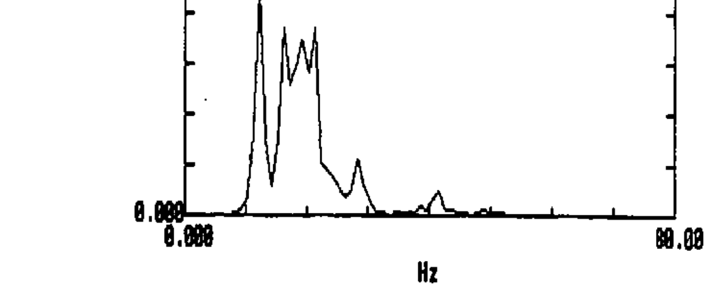

Figure 3 Acceleration power spectral density for vertical building vibration due to a passing train.

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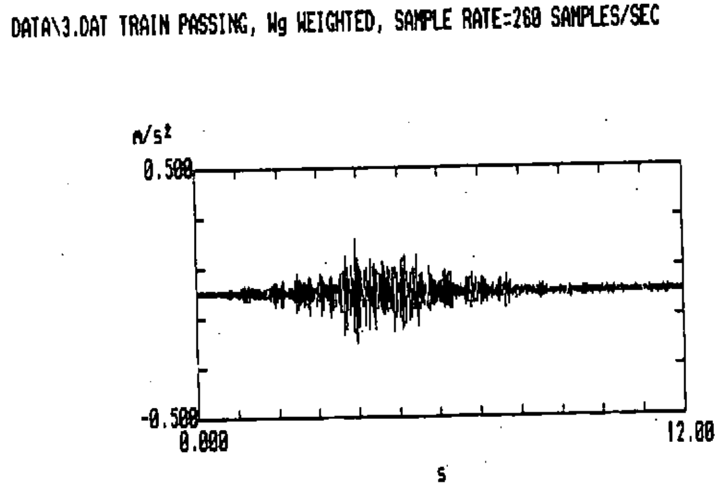

Figure 4 Frequency-weighted acceleration time history for vertical building vibration due to a passing train.