N-96-01
II-A-327

UNIVERSITY OF SOUTHAMPTON

# institute of sound and vibration research

# A DESIGN GUIDE FOR VISUAL DISPLAYS AND MANUAL TASKS IN VIBRATION ENVIRONMENTS

## PART II: MANUAL TASKS

R.W. McLeod
M.J. Griffin

ISVR TECHNICAL REPORT NO. 134

May 1986

# A DESIGN GUIDE FOR VISUAL DISPLAYS AND MANUAL TASKS IN VIBRATION ENVIRONMENTS

## PART II: MANUAL TASKS

by

R W McLeod and M J Griffin

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

ISVR Technical Report No. 134

1986

*The production of this Design Guide was supported by the Ministry of Defence under Research Agreement AT/2040/0180 between the University of Southampton and the Royal Aircraft Establishment, Farnborough.*

## SUMMARY

Design guidance relevant to the effects of vibration on manual activities is provided. The information describes the mechanisms by which vibration may affect task performance and shows how effects are dependent upon characteristics of both the vibration environment and the task. Data from published experimental studies are used as the basis of a series of design recommendations which may be used to minimise the influence of vibration on manual tasks.

## CONTENTS

## 1.0 GENERAL INTRODUCTION

This part of the guide concerns effects of whole-body vibration on the performance of manual tasks. The guide is subdivided into four sections. Section 1 defines the scope of the guide and outlines the mechanisms by which vibration may disrupt performance. Section 2 defines the relationship between performance and vibration variables. Section 3 concerns the major system variables which determine the sensitivity of a control system to vibration-induced disruption. The final section provides a list of selected references and further information.

Part I of this guide provides similar guidance for visual tasks to be performed in vibration environments (see Moseley and Griffin, 1986).

Vibration effects are highly task specific and laboratory findings are often difficult to generalise to real-life tasks. The effect of any vibration environment can depend upon a combination of system variables. Furthermore, the variability in effect with different people is large: consequently the guidance provided concerns effects on an 'average' person. To obtain accurate predictions of individual variability or the effects on specific systems, experimental evaluation will be required.

The guide presents procedures which may be useful in predicting disruption and describes principles to assist in choosing between design alternatives. A procedure for applying the information provided is included. The guide is based on published experimental studies of the effects of vibration on performance. Some of the experimental data were obtained for the purpose of formulating the guide during a research program conducted over a 10 year period at the University of Southampton (see Griffin et al, 1986).

### 1.1 Scope of the Guide

The guide concerns tasks in which a seated operator performs a manual task while exposed to translational whole-body vibration. The vibration may enter the body through the seat, backrest, and the controls. (A recommended procedure for measuring and reporting human whole-body vibration exposures is given in the current British Standard (BSI, 1986)).

The effects of vibration, and the mechanisms producing them, vary according to the type of task being performed. It is useful to define three types of task:

Type A continuous tasks in which the subject controls the hand freely in space: examples include reaching and pointing. In some type A tasks the hand may hold an object which will itself be affected by motion, such as fluid in a cup.

Type B continuous tasks in which the subjects' hand manipulates a control at a fixed position attached to the vibrating structure: examples include the operation of joysticks and knobs.

Type C tasks in which the operator performs a single, discrete operation, such as changing a switch setting or pressing a button. Discrete tasks will often be preceded by Type A tasks: for example locating a switch in space. Type C tasks should be considered separately from the accompanying Type A task.

## 1.2 Mechanisms

The relationship between a vibration environment and its effect upon task performance is dependent upon the transmission of vibration through the operator's body. Greatest disruption occurs in the region of whole-body resonance which is dependent upon the axis of vibration. For vertical, z-axis vibration, whole-body resonance normally occurs between about 2 and 10 Hz. For horizontal, x- and y-axis motion, resonance normally lies below 3 Hz.

There are three mechanisms which may mediate the disruption of a task by whole-body vibration:

(i) Vibration breakthrough - defined as motion or force at the hand directly caused by, and linearly correlated with, the vibration input. The significance of breakthrough depends upon such factors as whether a control is held and, if so, its type, sensitivity, sensitive axes and whether or not the arm is supported. The effect of breakthrough at the hand on system performance depends upon the amplification of the system dynamics at the vibration frequency.

(ii) Visual interference - relative motion between a subject's eyes and a display can give rise to a blurred image of the display The effect of visual blur depends upon, for example, the angular size of the information being viewed, the angular separation of detail and the display contrast as well as the accuracy of performance required. (If a task requires an operator to obtain information from a visual display the reader should refer to Part I of this design guide.) Motion of the element controlled by an operator on a display may be influenced by vibration breakthrough and give rise to perceptual confusion causing a reduction in tracking performance (see Lewis and Griffin, 1978a).

(iii) Other mechanisms - these may include interference with feedback loops within the neuro-muscular system and changes in the operators' perceptual-motor workload and state of arousal. Any increase in operator workload could impair performance, particularly when the operator is already performing near the limits of his ability. In such cases the designer should consider whether any increase in work load would be acceptable.

For type A tasks, the main effect of vibration is breakthrough causing motion of the arm, hand and fingers. The ability to accurately hold a position in space is reduced by the motion. The mechanisms of disruption for type B tasks can be more complicated and include all three mechanisms outlined above. Effects depend upon the type of control being manipulated, its size, shape, location and gain (ie sensitivity), as well as the system dynamics, viewing conditions and task difficulty. Little is known about effects of vibration on type C tasks. They are likely to be relatively free from breakthrough effects although overall efficiency may be reduced if a type A task is included in the operation.

## 2.0 THE VIBRATION ENVIRONMENT

### 2.1 Vibration frequency and axis

### 2.1.1 The vertical (z-) axis

Most experimental investigations of the effects of whole-body vibration on manual skills have used vertical, z-axis motion. Both type A and type B tasks typically show greatest disruption at vibration frequencies in the region of whole-body resonance. Figure 1 shows subjective ratings of the difficulty of a writing task performed during exposure to one-octave band random vibration with superimposed sinusoidal motion at frequencies between 0.5 and 10 Hz (Corbridge and Griffin, 1985). Subjects were asked to copy letters of the alphabet in their normal handwriting. The task was clearly felt to be most difficult with vibration between 4 and 6 Hz.

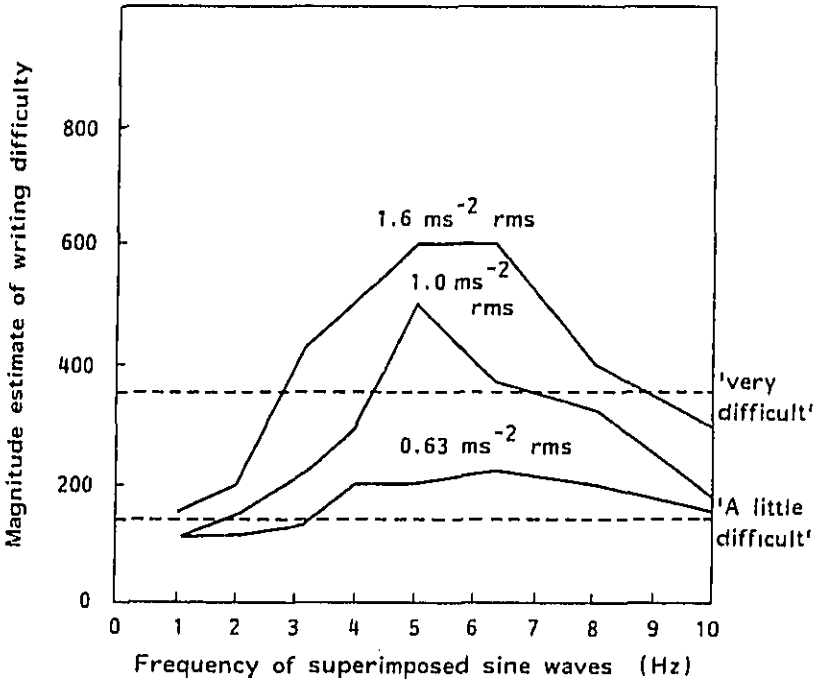

Figure 1: Subjective ratings of the difficulty of a writing task performed during exposure to low magnitude octave-band random, z-axis, whole-body vibration with superimposed sinusoidal motion at frequencies between 0.5 and 10 Hz (from Corbridge and Griffin 1985).

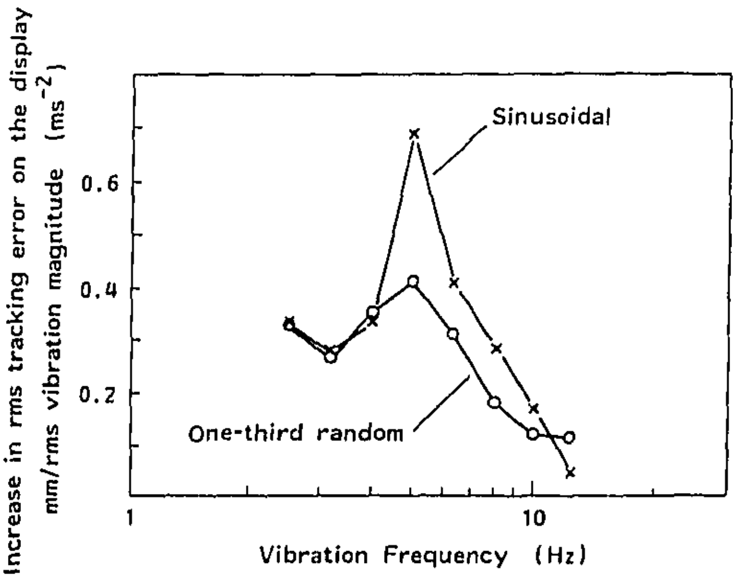

Figure 2: Pursuit tracking performance using a force type control with simple zero-order system dynamics during sinusoidal and one-third octave random z-axis whole-body vibration (From Lewis, 1981).

Figure 2 shows typical results obtained with a pursuit tracking (Type B) task using a force type (ie isometric) control and with simple zero-order system dynamics (Lewis, 1981). With both sinusoidal and one-third octave-band random vibration there is a clear frequency dependence showing maximum disruption at around 5 Hz.

Figure 1 shows that increasing the magnitude of vibration increased the perceived difficulty of the task. Figure 3 shows the increase in mean-square tracking error as a function of acceleration magnitude with a zero-order pursuit tracking task during vibration at 3.15 and 5.0 Hz (Lewis and Griffin, 1978a). At both frequencies there is an approximately linear relationship between rms tracking error and rms acceleration magnitude up to 2.0 ms$^{-2}$ rms. The rate of increase is greater at 5.0 Hz than at 3.15 Hz. For this simple zero-order task, the increase in total error is due largely to the increase in vibration breakthrough. The remainder of the effect was caused by perceptual confusion arising from vibration-induced motion of the controlled element on the display.

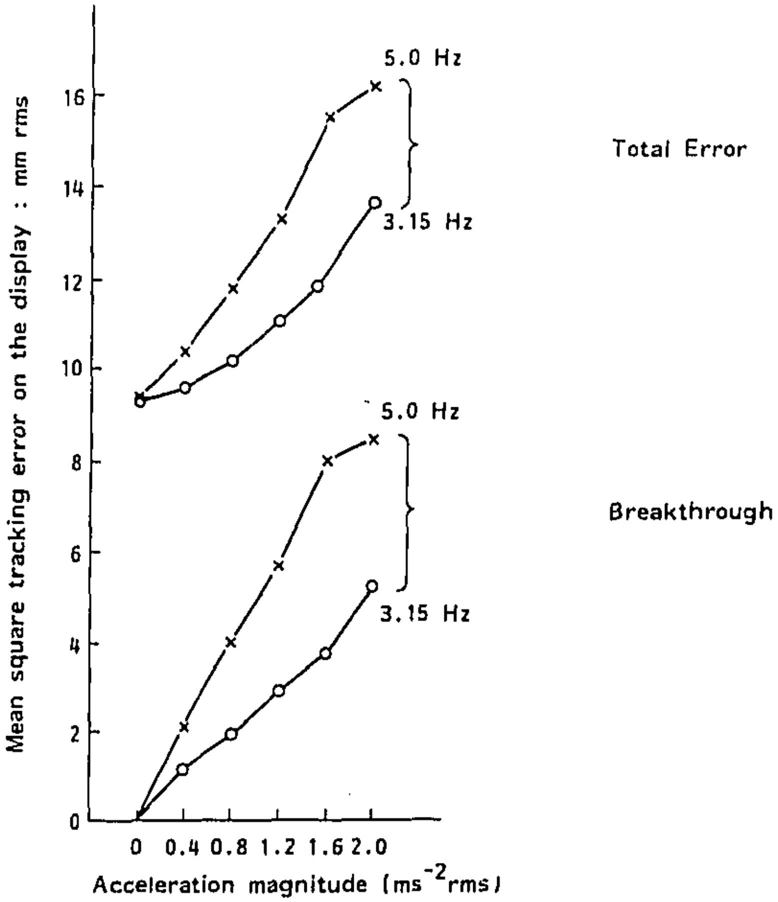

Figure 3: Mean-square tracking error against acceleration magnitude with a zero-order pursuit tracking task during exposure to sinusoidal, z-axis, whole-body vibration at 3.15 and 5.0 Hz (From Lewis and Griffin, 1978a).

For many simple type A and B tasks, tracking error increases approximately linearly with increasing acceleration magnitude. Section 2.2 describes a procedure for evaluating the effect of vertical vibration.

### 2.1.2 Fore-and-aft (x-) and lateral (y-) axes

Considerably less is known about the effects of x- or y- axis vibration on performance than for z-axis vibration. Whole-body resonance for horizonatal motion typically occurs below 3 Hz. Task disruption due to horizontal vibration is therefore usually greatest at frequencies below about 3.0 Hz (Allen et al, 1973). The sensitive axes of controls often lie in the axes of horizontal vibration. In these cases, vibration breakthrough may be greater with horizontal than with vertical vibration. Section 2.2 describes a procedure for evaluating the effect of horizontal vibration.

### 2.1.3 Multiple-axis vibration

There is some evidence that vibration presented simultaneously in more than one axis will produce greater disruption than that caused by motion in any single axis (Shurmer, 1969, Lovesey, 1971). The way in which the effects of vibration in different axes combine depends upon the axes involved, the vibration magnitudes and the task being performed.

For environments in which vibration occurs in more than one axis, the weighted rms acceleration should be determined and assessed in each single axis using the procedure descibed in Section 2.2. Where significant magnitudes occur in more than one axis, greater disruption should be assumed than when the motion is confined to a single axis.

### 2.2 Vibration Waveform

It has been demonstrated that effects on manual performance of dual-frequency and random vibration may be predicted from a knowledge of the effects of sinusoidal motion over the same frequency range (Lewis, 1981, Lewis and Griffin, 1979). Good predictions of rms tracking error during broad-band random vertical vibration have been obtained using the formula:

$$e_p = e_0 + \left(\int_{f_1}^{f_2} S^2(f).G_{vv}(f).df\right)^{\frac{1}{2}} \qquad (1)$$

where:

| | |
|---|---|
| $e_p$ | is the predicted rms tracking error |
| $e_0$ | is the measured rms tracking error with no vibration |
| $G_{vv}(f)$ | is the power spectral density of the vibration acceleration |
| $S(f)$ | is the experimentally determined function describing the sensitivity of the task to disruption by sinusoidal vibration (i.e. the sensitivity function), and |
| $f_1$ and $f_2$ | define the range of frequencies covered. |

For many simple zero-order or first-order tracking tasks, it may be possible to predict performance during exposure to vertical or horizontal vibration by experimentally determining a sensitivity function and applying equation 1. Sensitivity functions vary according to the task performed: it is therefore preferable that they be determined using a task as similar as possible to the task of interest. Particular care should be taken in simulating the viewing conditions, seating, arm supports, controls and the order of the system dynamics used in the real-world task. An experimentally determined sensitivity function for a particular task will provide the most accurate predictions of vibration effects on that task.

To evaluate the possible effect of a given vibration environment on manual activities when a sensitivity function for the task has not been established, it is recommended that a frequency weighted rms magnitude for the acceleration time history should be calculated. Figure 4 shows a suggested weighting function for evaluating the severity of z-axis vibration, and figure 5 shows a weighting function for vibration in the horizontal axes. (Details of these weightings may be found in Defence Standard 00-970, (1985) and the current British Standard (BSI 1986)).

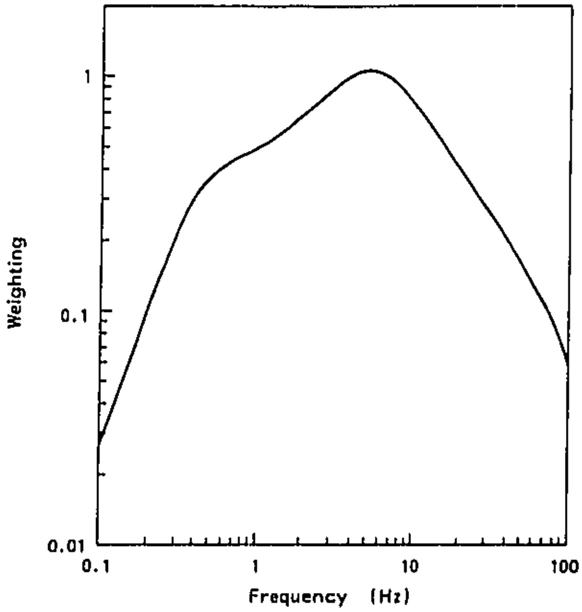

Figure 4: Suggested weighting function for evaluating the severity of vibration in the z-axis (vertical).

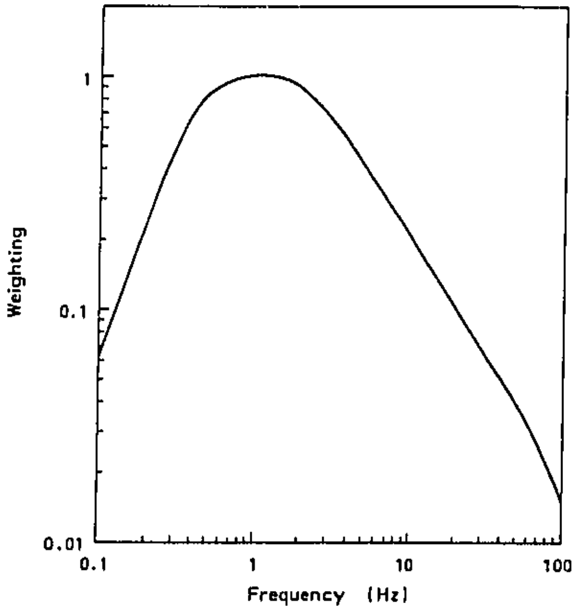

Figure 5: Suggested weighting function for evaluating the severity of vibration in the x- (fore-and-aft) and y- (lateral) axes.

The weighting functions shown in Figures 4 and 5 are based on consideration of the combined results of various experimental studies. They may be used to evaluate the likely disruption to type A and type B tasks when the arm is not supported. One method of calculation is the formula:

$$\text{weighted r.m.s.} = \left(\int_{f_1}^{f_2} W^2(f) \, . \, G_{VV}(f) \, .df\right)^{\frac{1}{2}} \qquad (2)$$

where : $W(f)$ is the appropriate frequency weighting, and
$G_{VV}(f)$ and $f_1$ and $f_2$ are defined as for equation (1)
(for these weightings, $f_1$ is 0.5 Hz for x- and y-axis vibration and 1.0 Hz for z-axis vibration, $f_2$ is 80 Hz).

Figure 6 shows an approximate relationship between weighted rms acceleration at the seat and the forces or displacements which may arise at the hand due to vibration breakthrough.

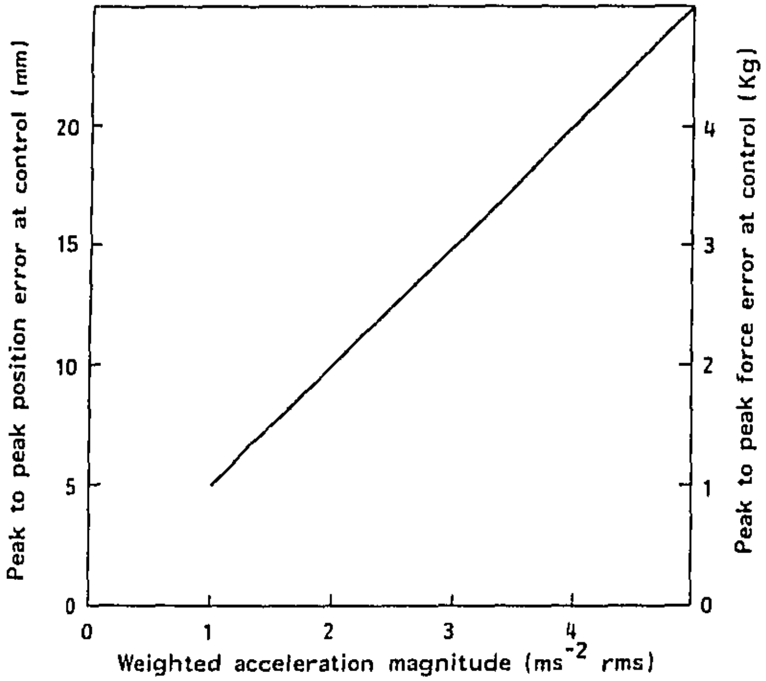

Figure 6: An approximate relationship between weighted r.m.s. acceleration at the seat and the forces or displacements which may arise at the hand due to vibration breakthrough.

The relationship defined in Figure 6 will provide only an approximate value, due to the many variables which influence breakthrough to the hand. The absolute magnitude of breakthrough for a particular task may vary considerably from that estimated by this procedure which should only be used when no other more accurate guidance is available.

Performance disruption for many simple tasks will be linearly related to the magnitude of breakthrough occurring at the hand (eg Lewis and Griffin, 1978a). For first and higher-order type B tasks, the form of the relationship between weighted rms acceleration and performance will depend upon factors including the control order, viewing distance and task difficulty. It is not in general possible to provide precise predictions of the amount of disruption which may occur. Experimental results have found that type A tasks and simple, zero-order, type B tasks can be disrupted if the weighted acceleration magnitude exceeds about 0.4 ms$^{-2}$ rms. Some higher-order type B tasks have been found to be disrupted when the weighted magnitude exceeds about 1.5 ms$^{-2}$ rms.

## 2.3 Duration

The current International Standard on human response to vibration defines a time-dependent relationship between vibration exposure and performance (ISO 2631, 1985). Experimental evaluation, however, has shown that exposures which equal the ISO 2631 'fatigue-decreased-proficiency', boundary do not impair performance on a variety of tasks compared with performance for the same duration without vibration (eg Guignard et al, 1976). Published data provide little support for any single simple relationship between exposure duration and performance (see the literature reviews by Lewis and Griffin, 1978b, McLeod and Griffin, 1986d). The British Standard does not include a time-dependency for effects of vibration on performance (BSI, 1986).

Whether a particular task will show any time-dependence in its sensitivity to vibration may depend upon both the task performed and the nature of the vibration environment. The motivation and experience of subjects have also been found to be important. Recent evidence indicates that subjects will adapt to the length of exposure: effects of duration both with and without vibration were reduced if subjects were exposed to the duration on more than one occasion (Seidel et al, 1980, McLeod and Griffin, 1986c).

During prolonged exposures, vibration has been found to both improve and impair performance compared with performance without vibration. With tasks which provide little motivation, vibration may act as an arousing stimulus acting to counteract impairments in performance which may occur due to fatigue, boredom or distraction. Some time-dependent effects of vibration may not be detected by simple performance measures. For example, in some situations humans may be able to partly overcome effects of fatigue by increasing their effort: performance may therefore not be affected. In considering effects of extended vibration exposures for a real-world environment, therefore, it is important to consider the operators' ability to perform the full range of tasks which may be required. Duration effects, or thresholds for duration effects, cannot at present be predicted without evaluation of the full range of tasks and conditions of interest.

## 2.4 Other vibration variables

Any factor which substantially changes the transmission of vibration to the head, shoulder or hand may alter the vibration-induced disruption of a manual task. Changes in the performance of type A tasks will follow changes in transmission most closely. Factors which often influence the transmission of vibration to the body include the operators' seating, posture, body restraints and arm supports.

The seat can either amplify or attenuate the transmission of vibration to the body depending upon the frequency of vibration and the characteristics of the seat (Griffin, 1978a). Seats should be selected which minimise the effective vibration entering the body. This may be achieved by minimising the frequency weighted acceleration as defined in Section 2.2.

Body posture and seat harnesses may either increase or decrease the magnitude of vibration in the body depending upon the frequency and axis of the vibration. These factors must be considered when determining the transmission of vibration through the body.

There are conflicting experimental data on the influence of arm supports on performance of manual tasks in vibration environments (McLeod and Griffin, 1986d). For many type A tasks involving movements of the whole arm, the provision of arm supports may be unduly restrictive. Effects of vibration on type B tasks may be reduced by providing suitable arm supports (Torle, 1965). Arm supports which minimise the relative motion, or forces, between the hand and the pivot point of the control may reduce the amplitude of breakthrough to the control. Relative motion, or forces, should be minimised across the entire bandwidth of the vibration which may be encountered. For tasks performed using the thumb, providing hand grips may minimise vibration effects. For some tasks, the provision of arm or hand supports may impair performance in static environments by restricting movements or causing discomfort. Careful consideration should be given to the type of support provided.

## 3.0 TASK VARIABLES

### 3.1 Type of Task

This section outlines those aspects of a task which alter its sensitivity to disruption by vibration. The guidance provided may be used to design tasks so that any disruption due to vibration is minimised.

Type A tasks will often require the operator to make both gross positioning movements with the unsupported hand and arm, as well as precisely controlled movements with the hand and fingers. Gross movements may be expected to be disrupted by large amplitude vibration-induced movements of the arm. These may occur with large vibration displacements at low frequencies. Precise control of the hand and fingers may be disrupted by relatively low magnitudes of vibration (with weighted rms accelerations above about 0.4 $ms^{-2}$) at frequencies up to above 20 Hz. To reduce the effects of vibration on a type A task without altering the vibration environment, it will be necessary to reduce the transmission of vibration to the limb, redesign the task or reduce the precision of required movements.

For Type B tasks, a number of variables associated with the control system affect the sensitivity of the task to disruption by vibration. Sections 3.2 and 3.3 discuss the influence of these variables.

Although there is little experimental evidence available, Type C tasks may be expected to be relatively unaffected by vibration. Disruption to accompanying Type A tasks, however, may cause an overall reduction in efficiency.

### 3.2 System Dynamics

Each integration performed by the system dynamics halves the amplification of control activity for each doubling of control output frequency.
(Zero-order systems perform no integrations, first-order systems perform one-integration etc). In first and higher order tasks the involuntary movements due to vibration breakthrough, which occurs predominantly around 4 Hz, is therefore attenuated relative to voluntary movements which occur at much lower frequencies.

Breakthrough may produce little direct disruption in first and higher-order tasks at vibration frequencies above about 0.5 Hz (Allan et al, 1973).

Complex systems are more difficult to control than zero-order systems, however, and may be more sensitive to disruption arising from visual interference and other mechanisms. Figure 7 shows a comparison of performance with zero- and first-order tasks during exposure to z-axis sinusoidal vibration at frequencies between 2.5 and 12.5 Hz (Lewis, 1980). Although the magnitude of breakthrough was very much smaller with the first-order task than with the zero-order task at all vibration frequencies, the overall disruption was as great with both tasks. This was explained by the greater sensitivity of the first-order task to mechanisms other than vibration breakthrough. For tasks involving tracking on a visual display, collimation of the display may reduce the sensitivity of first and higher-order tasks to disruption by vibration (McLeod, 1984).

Increasing the order of the system dynamics may introduce time lags proportional to the frequency of response. Any proposed change in system dynamics, therefore, should consider the overall performance required of the system.

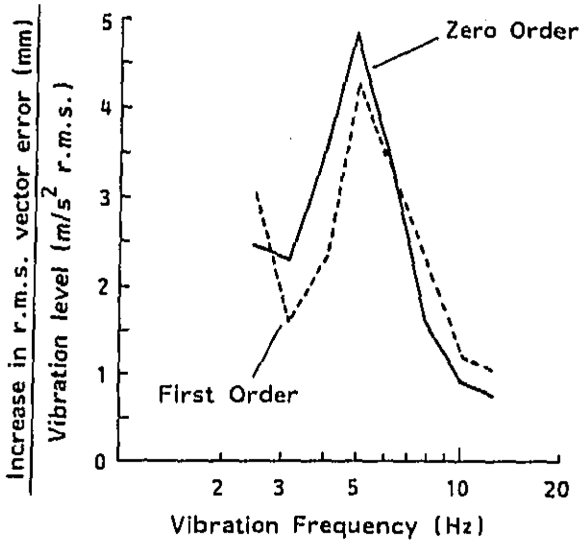

Figure 7: Pursuit tracking performance with zero- and first-order tasks during exposure to sinusoidal, z-axis, whole-body vibration at frequencies between 2.5 and 12.5 Hz (From Lewis, 1980).

## 3.3 Control Variables

A control has four relevant parameters:

- physical shape
- location
- gain (or sensitivity), and
- whether it moves.

If it moves, it is also necessary to consider:

- the force required to move it through a given distance,
- whether it incorporates any spring force, and
- whether it incorporates any damping force

Controls which respond only to the applied force are known as isometric controls; those which respond to displacement are known as isotonic controls. Pure isometric controls do not move, and pure isotonic controls offer no resistance to movement. In practice, these extremes rarely occur. Spring-centred controls resist movement in proportion to the displacement of the control, and viscously damped controls resist movement in proportion to the velocity of the control movement. Many controls incorporate both spring and damping forces.

### 3.3.1 Sensitive axes and location

Vibration in a single axis at the seat can give rise to vibration in more than one axis at the hand. Translational seat vibration can produce both translational and rotational motion at the hand. It has therefore been found that performance with rotary knobs may be disrupted as much as with joystick type controls during translational seat vibration (Lewis and Griffin, 1977). In all cases, the most sensitive axis of a control should be orientated so as not to correspond with the axis of greatest vibration breakthrough at the hand.

Locating a control in front of the operator or at one side appears not to affect the sensitivity of a task to vibration-induced disruption as long as suitable arm supports are provided (Levison and Houck, 1975).

### 3.3.2 Mechanical characteristics

Controls which respond to displacement and have stiffness less than about 0.01 kg $mm^{-1}$ have been shown to produce poorer performance than other types of controls in both vibration and no vibration environments (eg Lewis and Griffin, 1979). Controls which respond to the applied force, and have stiffness greater than about 0.7 kg $mm^{-1}$ have consistently produced superior performance than other types of controls in environments without vibration.

Figure 8 compares closed-loop human operator transfer functions from a pursuit tracking task performed in a static environment with isotonic, isometric and spring-type controls. The faster speed of response with the isometric control (reduced phase lag) was attributed to the lack of inertial resistance with this type of control. Due to their lack of damping however, this type of control tends to be sensitive to vibration breakthrough and other sources of vibration-induced disruption (Allan et al, 1973, Levison and Houck, 1977).

<u>Increasing the stiffness of moving controls from about 0.01 kg $mm^{-1}$ to about 0.2 kg $mm^{-1}$ has been found to reduce their sensitivity to disruption by vibration</u> (Levison and Houck, 1975, Lewis and Griffin, 1976). It may therefore often be found that the optimum force-displacement characteristics for controls for use in vibration environments will occur in this region. Too much stiffness, however, may induce excessive fatigue in operators if the task is performed for extended durations.

### 3.3.3 Gain

Control gain (or sensitivity) is defined as the relationship between the input to the control (eg kg or mm) and the resulting signal to which the system dynamics respond (eg volts).

The optimum control gain for performance in a static environment will depend upon the range of frequencies over which the task will be performed. If the gain is set below the optimum the operator may become excessively fatigued through the need to exert high forces or make large movements. Larger movements take longer to perform, and the effective response of the operator may therefore be slower. If the control gain is too high, inadvertent movements by the operator may introduce 'noise' into the system. There is therefore a compromise between the speed and accuracy of performance (Chapanis, 1972).

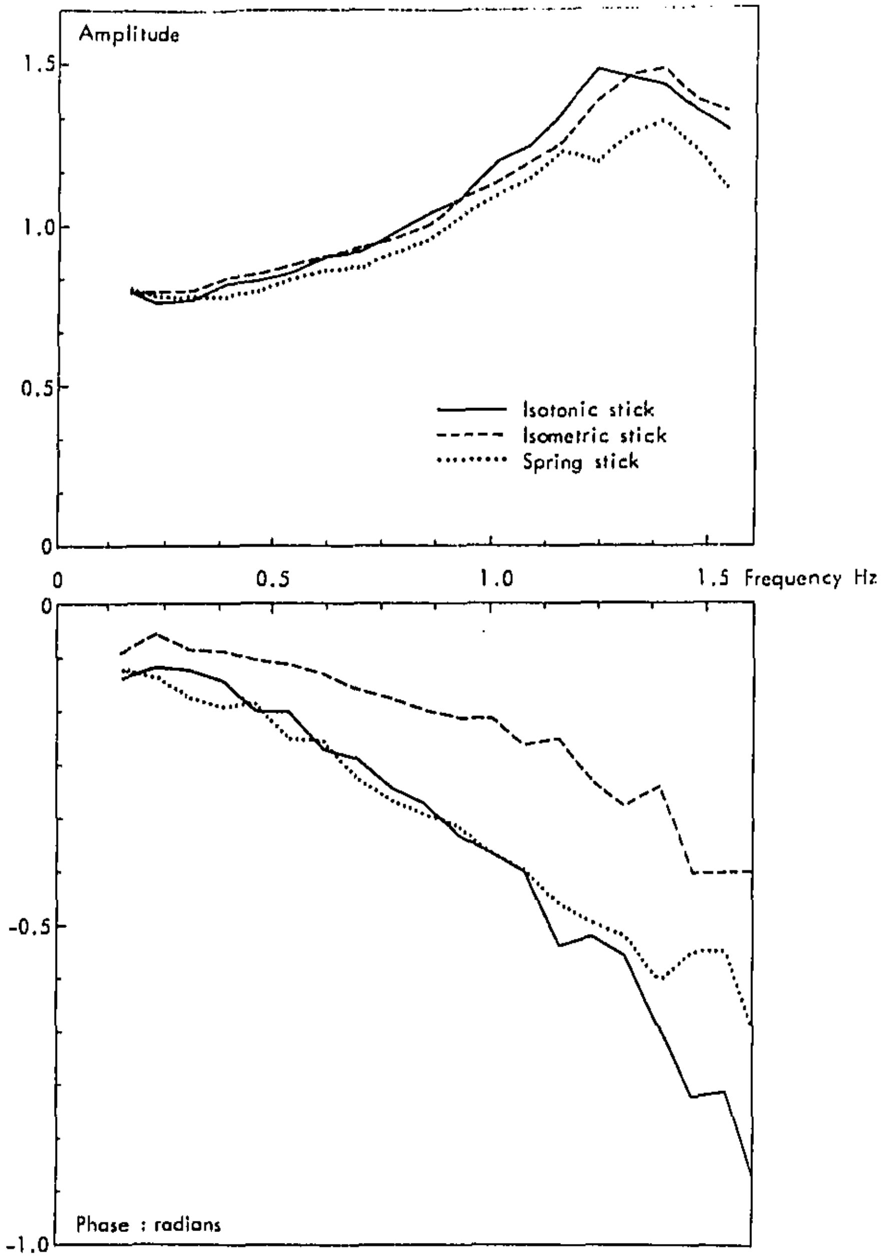

Figure 8: Closed-loop human operator transfer functions from a pursuit tracking task using isotonic, isometric and spring-type controls. No vibration. (From Lewis and Griffin, 1979)

In a vibration environment, the amount of breakthrough transferred from the hand to the control will be proportional to the gain of the control. Figure 9 shows the effect of control gain on mean-square tracking error with an isotonic, joystick-type control during sinusoidal z-axis whole-body vibration at 4 Hz (Lewis and Griffin, 1977). Reducing the gain of the control (from 500 to 125 mm per radian) reduced the amount of operator-generated 'noise', or remnant, in both vibration and static environments. With vibration, reducing the control gain also reduced the proportion of vibration breakthrough. The optimum control gain was found to be a compromise between vibration breakthrough as well as the speed and accuracy of performance.

For a task to be performed in a vibration environment, the optimum control gain should be determined in an environment as similar to the real-world environment as possible. The optimum control gain will often be lower in a vibration environment than without vibration.

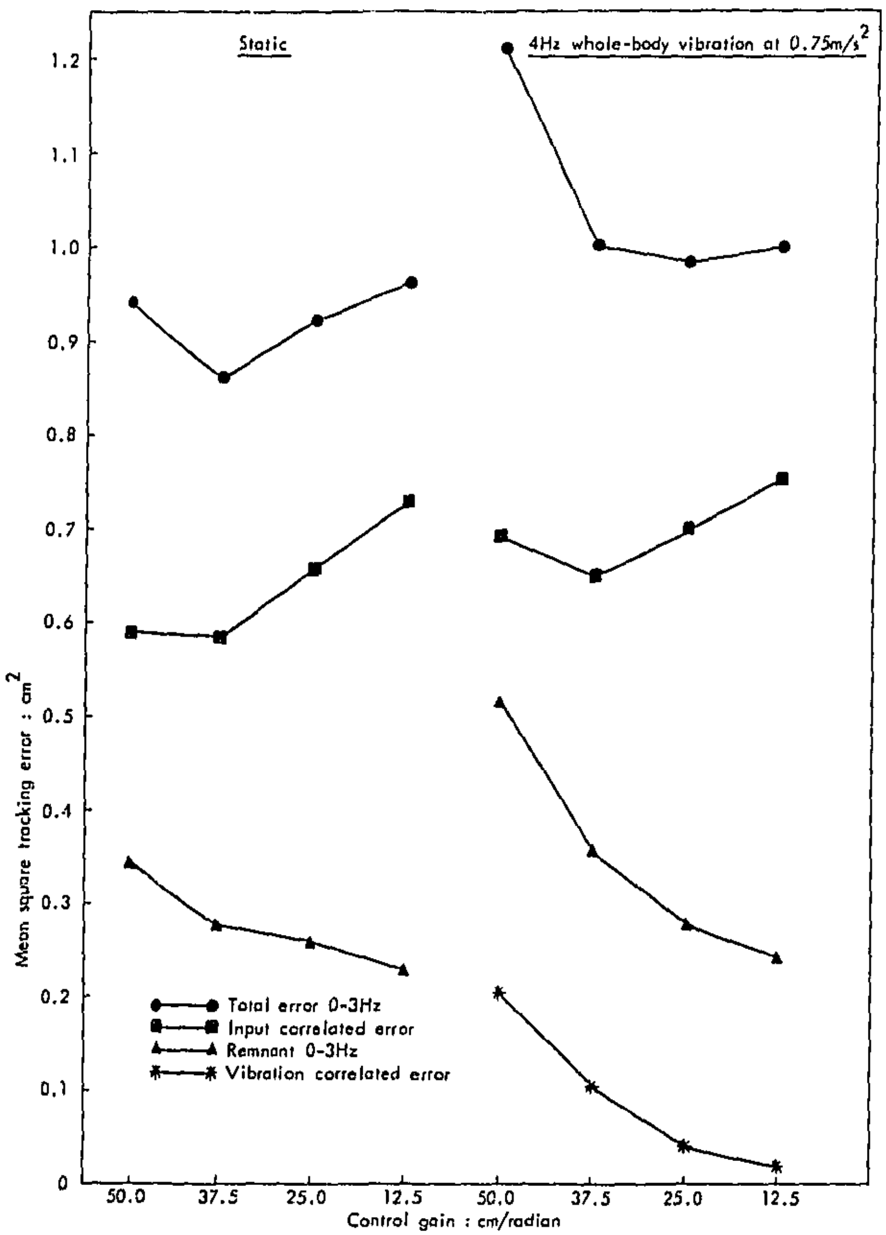

Figure 9: The effect of control gain on mean square tracking error on a pursuit tracking task with an isotonic, joystick-type, control during sinusoidal, z-axis, whole-body vibration at 4 Hz (Lewis and Griffin, 1977).

## 4.0 FURTHER READING AND BIBLIOGRAPHY

This section provides a source of reference for the designer seeking further information. The guidance provided is based upon consideration of more than one experimental study. It is therefore not normally possible to identify a given part of the guide with a single experiment.

| TOPIC | SECTION NUMBER | REFERENCES |
|---|---|---|
| General | | |
| Mechanisms | 1.2 | Lewis (1980, 1981)<br>Lewis and Griffin (1978a,b,1979)<br>McLeod (1984, 1986)<br>McLeod and Griffin (1986b)<br>Shoenberger & Wilburn (1973) |
| Transmission of vibration to the hand | 1.2 | Allan, Jex and Magdaleno (1973)<br>Levison (1975) |
| Sensitivity functions, frequency weightings and prediction procedures | 2.2 | Lewis (1981)<br>Lewis and Griffin (1978a) |
| Standards and evaluation procedures | 1.1 | ISO (1974,1978,1982, 1985)<br>Defence Standard 00-970 (1985)<br>BSI (1973, 1986) |
| Literature reviews | | Lewis and Griffin (1978b)<br>McLeod and Griffin (1986d) |
| Models | | Lewis and Griffin (1976)<br>Allan, Jex and Magdaleno (1973)<br>Levison (1978)<br>McLeod (1986) |

| TOPIC | SECTION NUMBER | REFERENCES |
|---|---|---|
| Vibration Variables | 2 | |
| Frequency | 2.1 | Allan, Jex and Magdaleno (1973)<br>Levison and Houck (1975)<br>Lewis (1980, 1981)<br>Lewis and Griffin (1979)<br>Shoenberger (1970)<br>McLeod and Griffin (1986a) |
| Waveform | 2.2 | Levison (1975)<br>Lewis (1981)<br>Weisz, Goddard and Allen (1965)<br>McLeod and Griffin (1986b) |
| Magnitude | 2.1 and 2.2 | Levison (1978)<br>Lewis and Griffin (1979) |
| Axis | 2.1 | Allan, Jex and Magdaleno (1973)<br>Levison (1976)<br>Shoenberger (1970) |
| Duration | 2.3 | McLeod and Griffin (1986c)<br>Seidel et al (1980) |
| Arm supports | 2.4 | Shoenberger and Wilburn (1973)<br>Torle (1965) |
| Seating | 2.4 | Griffin (1978a) |
| Posture and seat restraints | 2.4 | Griffin (1978b) |
| Task Variables | 3 | |
| System dynamics | 3.2 | Lewis (1980)<br>Allan, Jex and Magdaleno (1973) |
| Control sticks | 3.3 | |
| General guidance | | Chapanis (1972)<br>McCormick (1976)<br>Black and Moorhouse (1979) |

| TOPIC | SECTION NUMBER | REFERENCES |
|---|---|---|
| Location | 3.3.1 | Levison (1975)<br>Levison and Houck (1975)<br>Shoenberger and Wilburn (1973) |
| Mechanical characteristics | 3.3.2 | Allan, Jex and Magdaleno (1973)<br>Black and Moorhouse (1979)<br>Levison and Houck (1975)<br>Lewis and Griffin (1976, 1977) |
| Gain | 3.3.3 | Black and Moorhouse (1979)<br>Lewis and Griffin (1977) |
| Sensitive axis | 3.3.1 | Allan, Jex and Magdaleno (1973)<br>Lewis and Griffin (1978a) |

## 5.0 ACKNOWLEDGEMENTS

The production of these design guides was supported by the Ministry of Defence under Research Agreement AT/2040/0180. The authors also wish to acknowledge the advice of Mr Howard Du Ross (RAE, Farnborough) and Dr Graham Barnes (Institute of Aviation Medicine, Farnborough).

## 6.0 REFERENCES

Allan R.W. Jex H.R. and Magdaleno R.E. (1973)
Manual control performance and dynamic response during sinusoidal vibration. Areospace Medical Research Laboratory AMRL-TR-73-78.

British Standards Institute (1973)
DD23. Guide to the safety aspects of human vibration experiments.

British Standards Institute (1986)
Guide to the evaluation of human exposure to whole-body mechanical vibration and repeated shock. Draft for public comment.

Black F.T. and Moorhouse D.J. (1979)
Flying qualities design requirements for sidestick controllers.
AFFDL-TR-79-3126.

Chapanis A. (1972)
Design of Controls. Chp. 8 in 'Human Engineering Guide to Equipment Design'. Eds Van Cott H.P. and Kinkade R.G. US Govt. Printing Office, Washington.

Corbridge C. and Griffin M.J. (1985)
Effects of 0.5 to 10 Hz vertical vibration on discomfort, writing and drinking tasks. Final report to ORE Committee D-160. Human Factors Research Unit, ISVR, University of Southampton.

Defence Standard 00-970 (1985). Volume 2, Chapter 501, leaflet 100/2.
Guide to the evaluation of human exposure to helicopter vibration.

Griffin M.J. (1978a)
The evaluation of vehicle vibration and seats. Applied Ergonomics 9.1 15-21.

Griffin M.J. (1978b)
The biodynamic response of the human body and its application to standards. A28 in: Models and analogues for the evaluation of human biodynamic response, performance and protection. AGARD. Conf. proc. No. 253.

Griffin M.J., McLeod R.W., Moseley M.J., and Lewis C.H. (1986)
Whole-body vibration and aircrew performance. ISVR Tech. Rpt. No. 132. University of Southampton.

International Organisation for Standardisation (1974, 1978, 1985)
ISO 2631. Guide for the evaluation of human exposure to whole-body vibration.

International Standards Organisation (1982)
ISO 2631 - 1978/A1 - 1982. Guide for the evaluation of human exposure to whole-body vibration: Amendment 1.

International Standards Organisation (1984)
Guide to the evaluation of human exposure to whole-body mechanical vibration and repititious shock: revision of ISO 2631 Draft No. 5. Committee document.

Jex H.R. and Magdaleno R.E. (1978)
Progress in measuring and modelling the effects of low frequency vibration on performance.
A29 in: Models and analogues for the evaluation of human biodynamic response, performance and protection. AGARD. Conf. proc. No. 253.

Levison W. (1975)
Effects of control stick parameters on tracking performance in a vibration environment. 11th Annual Conference on manual control. Ames Research Centre, Moffettfield, California.

Levison W. (1976)
Biomechanical and performance response of man in six different directional axis vibration environments. AMRL-TR-77-71.

Levison W. (1978)
A model for human controller performance in vibration environments.
Aviat. space. Environ. Med. <u>49</u> (1) Section II 321-327.

Levison W. and Houck P. (1975)
A guide for the design of control sticks in vibration environments.
AMRL-TR-127.

Lewis C.H. (1980)
The interaction of control dynamics and display type with the effect of vibration frequency on manual tracking performance. In: Proceedings of the UK Informal Group Meeting on Human Response to Vibration, Swansea.

Lewis C.H. (1981)
A comparison of the effects of sinusoidal and random whole-body vibration on manual tracking performance. In: Proceedings of the UK Informal Group Meeting on Human Response to Vibration, Edinburgh.

Lewis C.H. and Griffin M.J. (1976)
The effects of vibration on manual control performance. Ergonomics, 19 (2), 203-216.

Lewis C.H. and Griffin M.J. (1977)
The interaction of control gain and vibration with continuous manual control performance. Journal of Sound and Vibration, 55 (4), 553-562.

Lewis C.H. and Griffin M.J. (1978a)
Predicting the effects of dual-frequency vertical vibration on continuous manual control performance. Ergonomics, 21 (8), 637-650.

Lewis C.H. and Griffin M.J. (1978b)
A review of the effects of vibration on visual acuity and continuous manual control, Part II: Continuous manual control. Journal of Sound and Vibration, 56, 415-457.

Lewis C.H. and Griffin M.J. (1979)
Mechanisms of the effects of vibration frequency, level and duration on continuous manual control performance. Ergonomics, 22 (7), 855-889.

Lovesey E.J. (1971)
An investigation into the effects of dual axis vibration, restraining harness, visual feedback and control force on a manual positioning task. RAE Tech. Rpt 71213 (EP588).

McCormick E.J. (1976)
Human Factors in Engineering and Design. Fourth edition. McGraw Hill, New York.

McLeod R.W. (1984)
The effect of display collimation on performance of a complex manual control system during vertical whole-body vibration between 2.5 and 5.0 Hz. UK Informal Group Meeting on Human Response to Vibration, Edinburgh.

McLeod R.W. (1986)
The effects of low frequency z-axis whole-body vibration on performance of a complex manual control task. Ph.D. Thesis. Southampton University. In preparation.

McLeod R.W. and Griffin M.J. (1986a)
Complex manual control performance during vertical whole-body vibration between 0.5 and 5.0 Hz. In preparation.

McLeod R.W. and Griffin M.J. (1986b)
Performance of a complex manual control task during vertical whole-body vibration: effects of display collimation and vibration waveform. In preparation.

McLeod R.W. and Griffin M.J. (1986c)
Effects of task duration and vibration on performance of a complex manual control task. In preparation.

McLeod R.W. and Griffin M.J. (1986d)
A review of the literature on the effects of translational whole-body vibration on manual control performance. In preparation.

Moseley M.G. and Griffin M.J. (1986)
A design guide for visual displays and manual tasks in vibration environments. Part I: Visual Displays. ISVR Technical Report No. 133. University of Southampton, England.

Seidel H. Bastek R. Brauer D. Buchholz Ch. Meister A. Metz A-M. and Rothe R. (1980)
On human response to prolonged repeated whole-body vibration. Ergonomics 23 (3), 191-211.

Shoenberger R.W. (1970)
Human performance as a function of direction and frequency of whole-body vibration. AMRL-TR-70-71.

Shoenberger R.W. (1974)
Mechanisms of vibration effects on aircrew performance. AGARD-CP-145, paper B17.

Shoenberger R.W. and Wilburn D.C. (1973)
Tracking performance during whole-body vibration with side-mounted and centre-mounted control sticks. AMRL-TR-72-120.

Shurmer (1969)
Tracking performance in single and multi-axis vibration environments. Paper presented at E.R.S. conference.

Torle G. (1965)
Tracking performance under random acceleration: effects of control dynamics. Ergonomics, 8, 481-486.

Weisz A.Z., Goddard C., and Allen R.W. (1965)
Human performance under random and sinusoidal vibration. AMRL-TR-65-209.

## APPENDICES

### A.1 A procedure for using the Guide

This appendix describes a procedure for applying the guide to the design of manual tasks for vibration environments. The procedure is intended to assist the designer in asking appropriate questions in an appropriate order. The information presented in the guide should help to answer the questions. It should be clear that for most cases this part of the guide can only provide general information, and will not lead to detailed quantitative results. In particular, least is known about the quantitative relationship between a vibration environment and the magnitude of performance disruption which may occur. The guide can only make a probabilistic statement as to whether a task is likely to be disrupted. The designer must determine, in view of the system performance required, the vibration environment to be encountered and the financial and other constraints which may exist, whether vibration-induced disruption of the task will be important. If a significant vibration problem is predicted, it is recommended that design alternatives should be evaluated in a vibration environment as similar to the operational environment as possible.

This part of the guide may be applied in five stages:

Stage 1 : Define tasks - Section 1

- i) Determine all tasks involved, A, B or C.
- ii) Identify possible mechanisms for each task.
- iii) If any task involves the operator obtaining information from a visual display, refer to Part I of the guide.

Stage 2 : Define the vibration environment - Section 2

- i) Determine the weighted rms acceleration magnitude in each vibration axis.
- ii) Determine the duration of task performance and vibration exposure.
- iii) Identify the variables which may alter the transmission of vibration to the body, such as seating, harnesses, arm supports, etc.

Stage 3 : Determine whether task disruption likely - Sections 2 and 3

i) If possible obtain sensitivity functions for the task over the range of vibration frequencies determined in Stage 2. Use equation 1 to predict task disruption.

ii) For type A and zero-order type B tasks, if the weighted magnitude exceeds about 0.4 $ms^{-2}$ rms in one or more axes, assume disruption will occur. Use Figure 6 to relate the weighted rms to the magnitude of breakthrough which may occur at the hand. Determine whether performance will be acceptable by reference to Stage 1 above.

iii) For higher order tasks, if the weighted magnitude exceeds about 1.2 $ms^{-2}$ rms in one or more axes, assume disruption will occur.

Stage 4 : Reduce disruption - Section 3

i) Reduce the vibration of the operator and the work-station.

ii) Provide arm-supports or hand grips. Their suitability requires evaluation in both static and dynamic environments.

iii) Alter the task variables to minimise the disruption; eg control type, control gain, system dynamics, etc. accuracy of tracking, precision of writing, etc.

(iv) Alter the task demands, such as the required accuracy of tracking, precision of writing, etc.

v) Redesign the task.

vi) Accept the impaired performance.

## A.2. MODELS

Two general approaches have been made to modelling the effects of vibration on manual control performance. Lewis and Griffin (1976) describe a taxonomic model of the human operators' functional processes contributing to task performance. They argue that by determining the effects of vibration on individual processes and integrating the effects across the range of processes involved, gross effects on a task may be predicted. This model does not allow precise predictions of the likely effects, nor does it indicate how effects on individual processes may combine. However, this model may be useful in identifying weaknesses in proposed systems.

A number of authors have proposed models of the biodynamic response of the human body during vibration. These models attempt to quantify the way in which vibration is transmitted through the body to produce vibration breakthrough at the control and interference with perceptual and motor processes involved in task performance. Jex and Magdaleno (1978) provided an overview of some of these models. Such models tend to be complex and their generality is limited by the number of parameters which must be specified for each task and environement. However, they may be useful in identifying the mechanical and physiological processes which contribute to disruption by vibration.

A major limitation of the mechanical models described by Jex and Magdaleno is in relating predicted body motion and control breakthrough to effects on system performance. A model described by Levison (1978), attempts to predict changes in the parameters of the Optimal Control Model of manual control performance as a function of variables associated with both the vibration and the control system. This model is also complex, and its ability to predict performance has only been demonstrated for a limited range of tasks and environments.

In common with the information provided in the body of the guide, these quantitative approaches can only attempt to predict the performance of an average person. Furthermore, due to the assumptions of linear behaviour required, they are restricted to describing the performance of highly trained and motivated operators performing highly constrained tracking tasks for short periods of time in idealised situations.