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A REVIEW OF RIDE COMFORT STUDIES IN THE UNITED KINGDOM

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SUMMARY

United Kingdom research which is relevant to the assessment of vehicle ride comfort has been reviewed. The findings reported in approximately 80 research papers are outlined and an index to the areas of application of these studies is provided. The data obtained by different research groups are compared and it is concluded that, while there are some areas of general agreement, the findings obtained from previous United Kingdom research are insufficient to define a general purpose ride comfort evaluation procedure. The degree to which United Kingdom research supports the vibration evaluation procedure defined in the current International Standard on the evaluation of human exposure to whole-body vibration is discussed.

INTRODUCTION

This paper provides an outline of United Kingdom research into areas of subjective response to vibration that are relevant to the assessment of vehicle ride quality. The desire to report on the relevant United Kingdom effort in one paper has necessitated some degree of selection. Studies have been included in the review wherever it is considered that they help to provide an overall picture of the evolution of research. Thus, while some experiments may have failed to provide any useful findings for designers, they have been included if it is considered that they may provide a foundation which will enable others to increase the practical value of their work.

Figures 1 and 2 provide a guide to the numbers of research papers on all aspects of human response to vibration that have been published in the previous years of this century. It will be seen that United Kingdom researchers produced fewer than half the number of papers published by workers in the United States of America. Of the 350 papers produced from the United Kingdom about one in four concerns ride comfort and approximately 80 of these form the subject of the present review. Almost two-thirds of these studies have been conducted in relation to ride in some specific vehicle while the remainder are concerned with human response in the laboratory with no particular vehicular application.

In 1973 the present author published the findings of a questionnaire survey of human response to vibration research in the United Kingdom (ref. 1).

Fifty-seven groups known to be interested in human response to vibration were asked to describe their experimental facilities and outline their past, present, and future research work. It was found that, between 1965 and 1972, the majority of laboratory experiments were conducted at Universities but less than half resulted in a publication. The helicopter and hovercraft environments were the principal concern of those conducting field research but again fewer than half of the studies resulted in a publication. Thirteen University theses and fifteen review papers were referenced and, of forty-nine other papers describing experimental work since 1965 most were departmental reports and memoranda. At least sixteen groups in the United Kingdom were found to employ one or more persons in some capacity to study human response to vibration. Five groups estimated that during the year beginning October 1971 they spent more than one man year on such research and the survey suggests that during that year a total effort of about 20 man years was spent directly on the study of human response to vibration. Approximately half of this effort was spent in Universities.

The specification of vibration limits for transport systems does not divide itself neatly into three separate problems concerned with human comfort, performance, and health. For example, no study of the discomfort produced by whole-body vibration can reasonably ignore the potentially large effects that can be produced by changes in body posture and seating (e.g., refs. 2, 3, and 4). However, while the physical movement of the body undoubtedly determines subjective reaction to vibration and some of the many studies of biodynamic response to vibration are highly relevant to the assessment of ride quality, they are not included in this review. Similarly, while the effect of vibration on manual control or vision (refs. 5, 6, and 7) may affect a persons' rating of a ride, findings concerning changes in performance are generally excluded. Such effects are included when in an experiment designed to measure subjects' opinions, it appears that effects other than discomfort have dominated their reactions.

In the following sections the United Kingdom research relevant to the study of ride comfort is outlined in an approximately chronological order. An index to the research conducted on the different aspects of the subject is presented in table 1.

SUMMARY OF RESEARCH

Possibly the first published scientific paper to consider human annoyance due to whole-body vibration was a 1902 report by Mallock (ref. 8). He conducted a study for a Committee of the Board of Trade who were appointed to investigate complaints about vibration by persons living in houses near the Central London Railway. The committee concluded that the high "unspring-borne" load of locomotives was the cause of the problem and were unequivocal in "recommending the adoption of a type of locomotive or motor in which the load not carried on springs is reduced as far as possible." Few studies of human response to vibration have produced such a clear and practical conclusion. In his report, Mallock states that "a variation of less than 1 percent in the effective force of gravity is noticeable, and that if the variation is as great as 4 or 5 percent the result is distinctly unpleasant." It seems probable that this conclusion mainly relates to vertical motions with a frequency of about 15 Hz in buildings.

In 1911 Digby and Sankey (ref. 9) presented a paper to the British Association in which they stated "... It has long been known that different persons are affected in different manners by the same conditions of vibration. So far as the authors are aware this subject has not yet been the subject of any very definite study and investigation ..." They proceeded to report on their own findings of large individual differences in sensitivity to vibration of the hand and an apparent decrease in sensitivity after 30 or 40 minutes of the test. They point out the possible importance of whether age, sex, state of health, over-work or railway travelling, and occupation or class affect sensitivity to vibration. They indicated their desire to study response to motions containing third and fourth harmonics and to motions containing recurrent intermittent vibration. When presenting their paper they apparently invited members of the British Association to visit their laboratory on Mondays or Thursdays and "form the subjects of experiment." Digby and Sankey presumably found their task too great (or members of the British Association were uncooperative) for no further account of these authors' studies was published. Digby and Sankey appear to have assumed that response to vibration was dependent on the vibration velocity. In 1923 Eason (ref. 10) reviewed knowledge of human susceptibility to vibration and concluded that acceleration was the unit best suited to describe human response when there were a range of frequencies present.

The determination of the manner in which response varies with frequency appears to have been one of the objectives of a study conducted by Constant (ref. 11) at the Royal Aircraft Establishment, Farnborough, in the early 1930's. He employed a wooden beam hinged at one end and mounted at the other on an eccentric driven by an electric motor. The subject was seated at some position along the beam corresponding to a chosen amplitude of vibration. The vibration frequency was increased and the subject stated "when the amount of unpleasantness reached an arbitrary level fixed by himself." In a paper to the Royal Aeronautical Society, Constant reported that it was extremely difficult to obtain consistent results from such an unreliable measurement of unpleasantness. He also found that the maximum permissible amplitude of vibration at a given frequency varied considerably according to whether the subject was sitting or standing and on the particular attitude adopted in each posture. It also depended on the susceptibility of the individual. However, the variation of the maximum permissible amplitude with frequency was always the same and he concluded that the results gave the best estimate which could be obtained at that time. The single curve covers a frequency range from about 12 Hz to 80 Hz and is shown as curve (e) in figure 3. (This curve assumes that Constant's data relate to peak to peak displacement.) It is not a coincidence that current vibration criteria for United Kingdom aircraft bear a remarkable resemblance to the 1931 curve produced by Constant.

A paper by Postlethwaite (ref. 12) in 1944 gave detailed consideration to the similarity between curves of constant vibration sensation ("trems") and the phon curves of equivalent sound sensation. His analysis of the previous research did not, unfortunately, lead to experimental studies. In 1956

Steffens of the Building Research Station (13) reviewed the application of previous research to the assessment of building vibration. He presented some measurements of building vibration due to road and rail traffic, pile driving, blasting, and machinery and concluded that the levels proposed in Germany by Reiher and Meister were the most useful for assessing this type of problem. (In 1963 the same author provided a more extensive review of a number of alternative evaluation methods (ref. 14).)

In 1956 Willis (ref. 15) considered the possibility of providing sprung seats to alleviate aircrew discomfort during high speed low level flight. He reports that some low level test flights in turbulence suggested that the predominant bumps occurred at frequencies between 1.3 and 7 Hz with levels normally less than ± 1.5 g but occasionally up to ± 3 g. The conclusion of the study conducted at the Royal Aircraft Establishment, Farnborough, was that a seat suspension having a travel of about ± 15.2 cm could be useful but that further study of seat suspensions, aircraft motion and human response was required.

Much of the research relevant to ride comfort conducted during the 1940's and 1950's took place in Germany and the United States of America. In the United Kingdom during 1958 Loach (ref. 16) presented a paper to the Institution of Locomotive Engineers in which he proposed a new method for assessing ride quality in railway carriages. The method was based on the work of Mauzin (of the Societé Nationale de Chemin de Fer) and Dr. Ing. Sperling (of the Deutsche Bundesbahn). The analysis technique detailed by Loach involved the manual determination of the distribution of peaks and the average frequency in an acceleration time history. These data were then modified by frequency weightings, that originated from the work of both Mauzin and Sperling, into a Comfort Riding Factor expressed in hours. Loach states that this is the amount of time before which an average passenger in a coach will experience a sense of fatigue and he says that a carriage regarded as adequate by an average passenger corresponds to a six hour riding factor. However, he cautions against "too literal an interpretation of what the units really mean ... that a value is numerical means that it can be compared with values similarly obtained on other tests." A curve of "equal comfort" corresponding to a three hour riding factor for vertical sinusoidal vibration is shown as curve (c) in figure 4. The corresponding curve for a six hour riding factor occurs at about half the acceleration levels of the three hour contour.

A very similar procedure for railway carriage ride assessment was described by Batchelor in 1962 (ref. 17). A graphical vibration time history of at least ten seconds of vibration is obtained. By visual inspection the low frequency component is assessed and drawn over the complex waveform. The amplitude distribution of peaks of the low frequency component is then counted (ignoring signs) and the mean level of the peaks is calculated and called the "mean acceleration" and is associated with a "predominant frequency." The deviations of the high frequency peaks from the drawn-in low frequency components are then assessed to determine their amplitude distributions. A ride index is then determined for each component by consulting graphs showing (for vertical and lateral directions) ride indices corresponding to each frequency-amplitude combination. The ride index of the complex motion is calculated from the tenth root of the sum of the tenth powers of the ride indices of each frequency component. The frequency contours for a ride index of 3.5 (just satisfactory) are shown as curves (a) and (b) in figure 4. It appears that the methods reported by both Loach and Batchelor are intended for measurements made on the floors of carriages rather than at the passenger-seat interface.

The comparison of objective and subjective measurements of vehicle riding comfort was the basis of a study conducted at the Motor Industry Research Association Laboratories by Aspinall in 1960 (ref. 18). Using the method of paired comparison with 12 subjects he compared the subjects' rankings of the ride in seven cars with the objective data obtained by ride evaluation procedures based on recommendations published by Dieckmann, Janeway, and Loach. Subjects appeared to be confident as to which vehicle they would prefer to travel in and which gave the least vertical motion, but they had difficulty in judging the roll and pitch of the vehicles. The author concluded that the objective methods were satisfactory for detecting the wide differences in vehicle riding comfort but that they were likely to differ from a subjective assessment when fine differences are involved. In a subsequent report, Aspinall and Oliver (ref. 19) published the findings of a similar study in which groups of subjects were exposed to motions in three vehicles. The rides of the vehicles were modified by altering tyre type and pressure, spring rates, dampers, seat flexibility and types of road surface. A good correlation was reported between subjective assessment of the low frequency ride of a vehicle and the average vertical acceleration recorded between a passenger and his seat and passed by a 0.75 to 6.0 Hz filter. The average floor acceleration passed by a 7 to 75 Hz filter also showed a good correlation with subjective assessments. After further studies of car ride (ref. 20) the development of a ride meter was described by Oliver in 1968 (ref. 21). This meter had selectable integration times (30 seconds to 6 minutes) and a plug-in filter such that it could provide a measurement of the average acceleration in the 0.2 to 50 Hz band or the 7.0 to 50 Hz band.

In an experiment reported in 1961, Jones and Drazin (ref. 22) of the Institute of Aviation Medicine required pilots to control a two seater aircraft at various levels and frequencies of roll and pitch oscillation while the head motion of a subject in the rear seat was recorded. This subject was required to rate each motion condition on a four point scale of subjective tolerance. For frequencies of roll from 0.2 to 3 Hz they concluded that when the maximum linear acceleration of the head was less than 0.1 g the conditions were entirely acceptable. When this acceleration was greater than 0.2 g the condition was entirely unacceptable. With the pitch motions, all conditions (0.25 to 1 Hz in the range 3 to 6 degrees per second) produced severe and persistent nausea. Most of the vibration experiments conducted at the Institute of Aviation Medicine have been concerned with the physiological effects of vibration. However, in some cases the experimenter has taken the opportunity to obtain the subjects' opinions of the motions to which they have been exposed. Guignard (ref. 23), for example, investigated the value of an anti-g suit as an anti-vibration device by exposing eight seated subjects to vertical sinusoidal vibration at frequencies from 4.8 to 9.5 Hz at vibration levels of ± 0.5 and ± 1 g. He reported that inflation of the anti-g suit did not alter the increase in pulmonary ventilation or decreases in visual acuity and reaction time that occurred during the vibration exposure. Subjects' ratings of the vibration on a 100 mm line with ends labelled "absolutely delightful" and "tolerable" were also unaffected by inflation of the anti-g suit. However there was subjective evidence that subjects might have been prepared to tolerate the experimental situation longer with the suit inflated. On the basis of the subjects' comments the author therefore concluded that the inflated anti-g suit is of some potential value to men exposed to severe low-frequency vibration in flight.

A series of studies of human perception to low-frequency motion were conducted by E. G. Walsh at the University of Edinburgh in the early 1960's. In a paper published in 1964 (ref. 24) he reported on a study to determine perception thresholds to sinusoidal motion at 0.33 and 0.11 Hz. By studying a subject with bilateral vestibular failure he concluded that sensations in the inner ear were the principal means of first perceiving the motions. His results with normal subjects led him to conclude that peak acceleration did not adequately indicate whether the motion would be perceived and he suggested that his results implied that the appropriate receptors may respond to rate of change of acceleration (jolt or jerk).

The ride comfort of tractor operators has been the subject of a series of studies by J. Matthews and colleagues of the National Institute of Agricultural Engineering (refs. 25 to 31). After an extensive review of previous relevant research (ref. 25) the vertical, longitudinal, lateral, roll, and pitch motions of two pneumatic tyred tractors were recorded while driving on an unmetalled track, rough pasture, and newly ploughed land with deep furrows. Vertical acceleration of the tractors was concentrated in the 2 to 5 Hz frequency range and peak levels greater than 1 g were reported in all axes. The author concluded that longitudinal and transverse components were significant and possibly more important than vertical vibrations under some conditions. The construction of two tracks simulating gently undulating surfaces (with obstacles up to 2.54 cm in height) and severely uneven ground (continuous undulations of 15.2 cm or more) was recommended. The theoretical derivation of the design and construction of experimental lengths of these test tracks is presented in a later paper together with some results obtained on the tracks (ref. 27). Some measurements of vibration on different seats obtained with tractors on farm surfaces is compared with vibration spectra predicted from a knowledge of the seat transmissibilities (determined in the laboratory) and the vibrations on the tractor bodies. Agreement between the two sets of data was fairly good but the author concluded that laboratory measurements alone could not be used to assess the ride quality of seats. A more recent paper from the National Institute of Agricultural Engineering (ref. 29) discusses the design of a ride meter built to conform with the frequency weightings defined in ISO 2631-1974. Papers by Stayner and Beam in 1971 (ref. 30) and Stayner in 1972 (ref. 31) report the findings of studies in which this ride meter was used to determine the effects of driver weight, type of tractor, tyre and ground surface, and the age of the seat on the vibration attenuation performance of tractor suspension seats.

Limits for helicopter vibration were considered in a 1965 paper by Jones (ref. 32). After reviewing some of the previous research in the frequency range up to 30 Hz he concludes that "vibration levels greater than about 0.1 g are objectionable over most of this frequency range." He concludes that a vibration standard with some chance of success would be a limit of 0.1 g up to about 20 Hz and thereafter the curve obtained by Constant (ref. 11) should be followed. This is shown as curve (d) in figure 3. Jones recommends that vibration in all three linear axes should be recorded "close to his (the pilot's) head but on the seat structure."

In 1965 W. D. Bryce (ref. 33) conducted an experiment at the National Gas Turbine Establishment to determine maximum levels of lateral seat vibration for passenger comfort in a proposed rotor-borne aircraft. One hundred and twenty-one subjects took part in an experiment and were mainly exposed to a slowly increasing vibration amplitude (at each of ten frequencies) until the individual reported any particular disturbance. Three-quarters of the total subject comments concerned blurring of the visual field but many subjects reported no adverse effects up to the maximum level of vibration possible with the apparatus. The author draws the tentative conclusion that in the lateral axis levels below a peak acceleration limit of 0.2 g from 3 Hz to 8 Hz and a constant velocity limit from 8 to 40 Hz will be acceptable to 95% of the population for a short period. The limit proposed by Bryce is shown as curve (a) in figure 3.

In 1966 D. R. Leonard (ref. 34) of the Transport and Road Research Laboratory reviewed the problem of determining acceptable limits for bridge movement. He reports on some measurements of the vibration of bridges and describes some experimental work with pedestrians walking and standing on a bridge forced into vibration in the laboratory. Two new tolerance limits were then proposed for walking and standing subjects. (The limits for standing subjects are shown as curve (a) in figure 4.) This work was extended to buildings when Whiffin and Leonard (ref. 35) later published a survey of traffic-induced vibrations. This paper includes a consideration of the mechanism of vibration generation by vehicles and some vibration measurements. They conclude that the most satisfactory way to minimise the effect of traffic-induced vibration is by maintaining road surfaces to a good standard. The problem has been reviewed again in the context of the general adverse effects of road vehicles on the environment by Burt (ref. 36). He states that new roads in Britain are among the smoothest in the world (no irregularities exceeding 10 mm in a 3 m length) and it is doubtful whether there is a case for higher standards to reduce the generation of vibration. In conclusion it is suggested that a systematic survey is desirable to establish the scale of the nuisance and help estimate the financial benefits of improved standards of maintenance. A very different approach to road smoothness was adopted in 1973 by another worker at the Transport and Road Research Laboratories (ref. 37). He investigated the suitability and effectiveness of humps for alerting drivers and controlling vehicle speeds. Humps 3.66 m (12 ft) long and 0.10 m (4 in) high showed some promise for controlling vehicle speeds but the author concludes that their use should be undertaken with caution where vehicle speeds are high.

A. G. Woods (ref. 38) reported in 1967 on a combined study of the effects of low-frequency sinusoidal and random vibration on comfort and performance. For vertical motion at three levels of acceleration with frequencies from 1 to 10 Hz and lateral vibration with frequencies up to 7 Hz three or four subjects made ratings on a six point scale. While the data for vertical motion showed a very definite increase in unpleasant effects around 5 Hz, reaction to lateral vibration indicated a slight and gradual decrease in the effects as the frequency increased at constant acceleration. (Contours that correspond to the comment "some unpleasant effects cannot be ignored" are shown as curv (b) and (c) in figure 3.) There was somewhat more tolerance to lateral than vertical vibration in the 3 to 7 Hz frequency range and there was slightly greater tolerance to the random vibration spectra employed in the experiment than the corresponding sinusoidal motion.

Many measurements of vibration in aircraft have been obtained by worker in the Structures Department of the Royal Aircraft Establishment, Farnboroug (e.g., ref. 39). The analysis method has mainly consisted of an analysis of the distribution of peak accelerations recorded at some position in the aircraft and is oriented towards an understanding of aircraft response rather than human reaction. Some data obtained by this method of analysis is presented by Silverleaf and Cook (ref. 40) in a 1969 review of ride comfort high speed marine craft. They say that the ready availability and ease of operation of equipment to count peaks outweighed the possibility that the da so obtained might be of limited value in assessing ride comfort. The author interpret some previous research as implying that a reasonable acceleration limit for journeys of one hour or more should be between 0.1 g and 0.15 g at low frequencies. They state that foilcraft with submerged foils and autopilot systems have achieved this performance but that it had not been achieve by hovercraft of reasonable commercial size. Silverleaf and Cook concluded that the standard of ride comfort that can be achieved may be a crucial factc in the commercial use of high speed marine craft in open-water routes. In a 1969 review of passenger comfort in hydrofoils Shurmer (ref. 41) of the British Aircraft Corporation advocated further research to develop equipment to give an overall ride index and, in the following year, Lovesey (ref. 42) c the Royal Aircraft Establishment produced a general review of the hovercraft environment.

In 1970 Ashley reported the first use in the United Kingdom (ref. 43) of the method of intensity matching to determine the effect of vibration frequency on subjective response to whole-body vibration. He employed a method somewhat similar to that previously used with whole-body vibration by Miwa in Japan and employed in psychoacoustics research for many decades. In the firs part of the study standing male subjects were required to move from a vibrato adjusted to produce a given level of vertical sinusoidal motion at 6 Hz to a vibrator producing a random vertical vibration. For each of four levels of sinusoidal motion (corresponding to the 1, 2.5, 4, and 8 hour fatigue decreased proficiency limits in ISO 2631-1974 (ref. 44)) the level of the random motion was varied by the experimenter until the subject considered tha it was equally annoying to the sinusoidal motion. The mean levels of the random vibration determined from 27 subjects were then used as fixed levels against which six subjects compared sinusoidal motions from 0.7 to 20 Hz. By adjusting the level of the sinusoidal motions to produce 'equal annoyance' Ashley was able to determine four mean constant annoyance contours. One such contour is shown as curve (a) in figure 5. He concludes that his results are in excellent agreement with the (then proposed) ISO frequency contours.

E. J. Lovesey of the Royal Aircraft Establishment published an evaluati of the effects of bead-filled cushions upon comfort during vibration in 1971 (ref. 45). By increasing the vibration level until subjects considered the motion slightly uncomfortable he concluded that bead-filled cushions were slightly more comfortable than sponge-rubber-filled cushions with most lateral vibrations and during 2 and 4 Hz vertical vibration. The sponge cushions gave a more comfortable ride with vertical vibration at 8 Hz and 20 Hz. All cushions were preferable to a bare seat and, similar to Woods (ref. 38), Lovesey found that at 2 Hz, the maximum amplitude of the heave acceleration that was acceptable was approximately twice that of the lateral vibration. At higher frequencies the relative importance of the two axes without a cushion was reversed--the maximum level of lateral vibration was about double that of vertical vibration at 8 Hz and about treble at 20 Hz.

Human perception of whole-body vibration was the subject of an extensive study reported by McKay from the University of Southampton in 1971 (ref. 46). He determined a median threshold of perception of about ± 0.003 g in a group of forty-eight subjects over the frequency range 1.5 to 100 Hz. However, the effect of vibration frequency on the acceleration threshold was significant as were the differences between standing and sitting and male and female subjects. The median threshold determined by McKay is shown as curve (f) in figure 4. He was particularly interested in determining why the threshold of perception curves reported from previous research differed over an intensity range of 40 dB. In later work (ref. 47) he therefore conducted experiments to determine reasons for this variance and found that the background vibration frequency, acoustic noise, footrest, subject versus experimenter presentation of the stimulus, and the vision, footweat, sex, posture, and attention of the subjects all significantly influence the perception of vibration.

A study to compare response to sinusoidal and random vibration was reported to the United Kingdom Informal Group on Human Response to Vibration by Ashley and Eames-Jones in 1971 (ref. 48). A number of standing subjects adjusted the level of three different spectra of random vibration "to be equal in disturbance sensation" to a given level of a 6 Hz sinusoid. For all three spectra (which covered the frequency range of either 0.5 or 3 Hz to 20 Hz) the authors found that their subjects would accept about 50% more acceleration from random than sinusoidal vibration. At the same meeting, G. Rowlands (ref. 49) of the Royal Aircraft Establishment reported on an experimental demonstration of some International Organization for Standardization vibration levels to subcommittee and panel members of the British Standards Institution. The subjects were required to read, write, talk, and indicate their reactions while exposed to conditions of vertical and lateral vibration corresponding to the 4 and 25 minute ISO fatigue decreased proficiency times. It was reported that most subjects found the levels extremely disturbing and all stated that they would not accept or tolerate these levels in most forms of transport.

A survey of the vibration and ride comfort problems of various transport organisations was compiled by Allen (ref. 50) of the Royal Aircraft Establishment, Farnborough, in 1971. The survey, conducted to assist the Science Research Council in considering research grant applications from Universities, includes the opinion of about twenty different organisations. The author concluded that there was an urgent need for further research which should be equally divided between the study of the effects of vibration on crew and driver efficiency and passenger comfort. Particular areas of research considered to require attention were response to multiaxis, random, long duration, and low-frequency motions. Study of the interactions between seat design and vibration effects, vibration, and other environmental stresses as well as the application of laboratory research to real life environments were also considered to require attention.

A further 1971 report by a worker at the Royal Aircraft Establishment (ref. 51) provides data obtained from three axis vibration measurements made on the floor of fourteen commercial and military vehicles. The data show tha motion was not restricted to the vertical axis and the author therefore suggested that future laboratory studies should include the study of response to fore and aft and lateral vibration.

Three papers (refs. 52 to 54) describing the Ph.D. research conducted by Jones at the University of Salford were published during 1972 and 1973. In his first experiment sixty seated subjects (thirty men and thirty women) were alternately exposed to two vertical sinusoidal motions for eight seconds. On of the motions was a reference of 20 Hz and the other was set by the experimenter to one of thirteen frequencies in the range 4 to 80 Hz. For each of six levels of the reference (± 0.1 to ± 0.6 g) the subject was required to vary the level of the other motion until he considered it to be "equal in sensation on a comfort basis to the reference vibration." The authors report some significant differences between the response of men and women. Compared to their sensitivity at 20 Hz the females were more sensitive than the males to 60 and 80 Hz and to the lower two levels of 4 and 6 Hz. Jones and Saunders suggest that their results are in fairly good agreement with the shape of the curve given in ISO 2631-1974 (ref. 44). This experiment is also presented in a later paper (ref. 53) together with some results obtained with the same experimental method using ten standing male subjects and when employing a 10 Hz reference vibration with sitting male subjects. Compared to their sensitivity to 20 Hz the standing subjects were less sensitive to 4, 5, and 6 Hz than seated subjects. (Curve (c) in figure 5 shows a contour obtained with standing male subjects.) Jones and Saunders report no change in the shape of the curve due to the change of reference frequency. The third paper from these authors (ref. 54) reports on the use of the method of magnitude estimation with sixty seated subjects (thirty men and thirty women) and ten standing males. They determined 'growth functions' from Stevens' Psychophysical Law and concluded that, because the effects of vibration frequency, subject sex and subject posture were small, a value of 0.93 for the exponent in this law will give an adequate overall approximation. By analogy with the phon curves and sone scale in acoustics they proposed units of vibration intensity VICS (Vibration Contours) and units on a subjective ratio scale VIMS (Vibration Magnitude Scale).

At the University of Salford Hempstock and Saunders (ref. 55) were also concerned with Stevens' Psychophysical Law. They exposed subjects to noise and vibration sequentially and required them to alter the level of the dependent variable (noise or vibration) until it produced a sensation equivalent to a fixed value of the independent variable (vibration or noise). Assuming Stevens' Psychophysical Law for both noise and vibration with an exponent value of 0.6 for noise, they proceeded to use the results of their experiment to calculate exponents for vibration. They found that the vibration exponent was two or three times greater when noise was used as the independent variable than when vibration was the independent variable. Thus, for example, the mean values suggest that while subjects would adjust 65 dB(A) noise to be equivalent to 1.0 m/s^2 rms of vibration, they would adjust 1.0 m/s^2 rms of vibration to be equivalent to 80 dB(A) noise! The authors conclude that for whole-body vibration there exists no single value of the exponent in Stevens' Psychophysical Law.

Another study of combined noise and vibration is reported by Fleming and Griffin (ref. 56) from Southampton University. They conducted an experiment to determine the subjective equivalence of 1000 Hz pure tone noise and 10 Hz sinusoidal whole-body vertical vibration. Each of 20 male subjects was exposed to all 64 possible combinations of 8 levels of noise (65 dB to 100 dB SPL) and 8 levels of vibration (0.20 m/s^2 rms to 1.2 m/s^2 rms). Both stimuli were presented simultaneously for a period of 10 seconds and subjects were required to indicate whether, if they were to be presented with the combination again, they would prefer that the noise or the vibration should be reduced. The conditions for equivalence ranged from 0.2 m/s^2 rms at 69 dB to 1.2 m/s^2 rms at 94 dB. The authors present their results in a form that enables an estimate to be made of the percentage of subjects who prefer noise or vibration at any of the given combinations of the two stimuli. It is claimed that the results could be employed as a practical guide to reducing either the noise or the vibration in some environments. A study of subjective responses in a combined noise and vibration environment is also reported by Innocent and Sandover (ref. 57) of Loughborough University. They conclude that "noise and vibration acting together give rise to a discomfort level which is equivalent to the summated discomfort levels of the stresses acting separately."

Pilot reaction to helicopter vibration has been studied in recent years by Griffin (refs. 58 to 61) and workers at Westland Helicopters Ltd. (refs. 62 to 65). Griffin conducted three inflight experiments in Army Scout AH Mk 1 helicopters (ref. 58). A subsidiary finding from the experiments was that pilots often failed to detect changes of up to four to one in the level of vibration that occurred when the aircraft were flown in different flight conditions. There was good evidence that pilots based their judgements of the amounts of vibration on their anticipation of what happens in the various flight conditions rather than the physical levels of the motions they experienced during the particular experimental flights. Since the acceptability of the vibration in aircraft is often based on the judgement of a pilot, it was recommended that further consideration should be given to the benefits of supplementing this method with objective measurement systems. The study also provided some detailed data on the vibration encountered in the helicopter, and the degree to which it was transmitted to the pilot.

The studies of pilot vibration conducted by Westland Helicopters Ltd. have also produced large amounts of data on the vibration in some helicopters. Attempts to correlate the objective measurements with pilot assessments of the motion have shown that the mean vibration levels corresponding to the points on a 10 point rating scale tend to increase as the rating increases. However, there are many vibration conditions that deviate from this trend. Jackson and

Grimster (ref. 65) report that measurements made on some rigid structure within production helicopters show that when the peak level of any vibration component in any axis exceeds ± 1.8 cm/sec the crew consider the aircraft "rough" and unserviceable.

New limits for helicopter vibration have recently been proposed by Griffin (ref. 66) in collaboration with the Royal Aircraft Establishment, the Institute of Aviation Medicine and Westland Helicopters Ltd. Two alternative evaluation methods allow for the specification of limits for the whole-body vibration of aircrew in terms of vibration measured on either the structure c the aircraft or at the crew-seat interface. In summary, the 'normal' limits correspond to 0.4 m/s^2 rms in the vertical (a_z) axis (for frequencies from 4 to 8 Hz) and 0.3 m/s^2 rms in the fore and aft (a_x) and lateral (a_y) directior (for frequencies from 1 to 2 Hz). The frequency weightings defined in ISO 2631-1974 (ref. 44) are used to determine the effect of other frequencies. Data taken from previously published studies have been analysed and it is claimed that they show that these new limits (largely based on laboratory studies) are reasonable. The proposed limit for vertical vibration is shown as curve (f) in figure 3.

Ashley and Rao (ref. 67) of the University of Birmingham reported on an experiment in which subjects, seated in the laboratory on a car seat, were subjected to separate sources of whole-body vertical vibration and vertical foot vibration. In the first experiment five subjects were exposed to random foot vibration and required to ask the experimenter to adjust the level of sinusoidal seat motion until it gave an "equal sensation effect." This was repeated for frequencies in the range 2 to 20 Hz to give an equal sensation contour for sinusoidal vibration. In the second experiment a random seat vibration was adjusted to give equal sensation to a random foot motion. In the third experiment various frequencies of sinusoidal foot vibration were adjusted to be equivalent to a random vibration and so give a contour of equivalent sensation for foot vibration. In the fourth experiment various frequencies of sinusoidal seat vibration were adjusted to equivalence with sinusoidal foot vibration and so yield a second sensation contour for seat vibration. The authors state that the two equivalent sensation contours for seat vibration differ by less than 25% and conclude that this is a good justification for the use of the equal sensation technique.

Human response to vibration research at Swansea University has been concentrated on the study of subjective response to vibration and is mainly described in four papers (refs. 68 to 71). In 1973 Oborne and Clarke (ref. 68) presented an account of the not insignificant practical problems that hav to be surmounted when conducting a survey of passenger comfort. McCullough and Clarke (ref. 69) discussed the problems inherent in the semantic scales employed by many previous researchers. They state that such scales have only ordinal properties and that there will be inaccuracies when they are translated from one language to another. Further, they point out that words can b understood to mean different things to different people at different times an they claim that this effect is undoubtedly responsible for a large proportion of the variance in the previous data. McCullough and Clarke then suggested that by using Stevens' Psychophysical Law, it may be possible to construct a family of equal sensation contours based upon a single vibration threshold contour. The authors present a brief outline of two experiments on response to cutaneous and whole-body vibration and conclude that "attention should be directed away from experiments in which semantic labels are used to classify the intensity of vibration and towards experiments which are designed to develop a ratio scale relating subjective and physical magnitudes."

In 1974 Oborne and Clarke (ref. 70), describing a study in which they determined semantic 'comfort labels' for the intervals between frequency contours, rejected both a semantic category selection method and the method of intensity matching for the determination of the frequency contours. Subjects were required to rate various levels of 11 frequencies of vibration on a 10 cm line with ends labelled 'smooth' and 'rough.' Four equal sensation contours were then constructed for ratings of 2, 4, 6, and 8 cm along the rating line. Further, subjects were presented with the vibration stimuli again and asked to rate the motions on a six point semantic scale. The experimenter placed five appropriate phrases between and above the four equal sensation contours. (The contour dividing 'neutral' and 'uncomfortable' for standing subjects is shown as curve (b) in figure 5.) The authors add a note of caution on the use of rating lines. They say that there is evidence that passengers make ratings not only in terms of the scale ends but also in terms of what levels of vibration they expect to experience in the vehicle. In their most recent paper Oborne and Clarke (ref. 71) report on a laboratory experiment in which standing subjects were each required to rate ten different vibration stimuli on thirty different 10 cm rating lines (five different sectionings of the lines combined with six different semantic ends). Finding that all thirty different lines produced generally similar results the authors concluded that the fears of other authors over the confusion generated by the use of different sectioning and semantics is unfounded.

A somewhat similar experiment included in a series of studies conducted at the University of Southampton was reported in 1972 by Fothergill (ref. 72). This investigation involved three experiments designed to determine whether subjects differentiated between various adjective scales, whether results obtained by category selection methods differ from those obtained by category production, and whether background acoustic noise affects a subject's rating of vibration. The first experiment tested the hypothesis that subjects disregard the adjectives on which they are asked to scale their sensations and substitute some personal psychological scale. A group of 20 subjects were divided into two subgroups such that one group rated a small number of motions on an open ended 10 cm scale with ends marked "not unpleasant" and "very unpleasant." The second group rated the same stimuli presented in the same order on a similar scale marked "not annoying" and "very annoying." There was good evidence to conclude that the difference in adjective did initially result in different ratings but that after a small number of judgements other variables associated with the scale and range of stimuli became more dominant sources of variance. In a second experiment with a five point semantic scale it was found that the levels corresponding to the extremities of the scale were higher when determined by a category production method than when determined by category selection. The reverse occurred for the three central descriptors of the scale. In a third experiment it was found that when a background white noise at 85 dB(A) was presented the subjects considered that the lowest point on a five point semantic scale generally corresponded to a slightly higher vibration level than when a lower noise level of 54 dB(A) was present. The other four points on the scale, particularly the highest point, corresponded to slightly lower vibration levels in the presence of the higher noise level.

More recent experiments at the University of Southampton have employed an intensity matching technique in which the subject adjusts the level of one stimuli to produce the same degree of discomfort as some other stimuli. Fothergill and Griffin (ref. 73) first studied the method and investigated th between and within subject variability and the effect of varying the frequenc of the standard vibration against which other frequencies are matched. Although subjects had only a low confidence in their matches, the within subject variability was low and very much smaller than between subject variability. As the frequency separation of the two vibrations to be matched became greater, the subject variability also increased. Although only small differences were found between the results obtained with different frequency standards, it was concluded that a 10 Hz sinusoid was the best choice for th future research.

Fothergill and Griffin have conducted three experiments to study the discomfort of multiple frequency whole-body vertical vibration (ref. 74). Subjects were required to adjust the level of a 10 Hz sinusoidal vibration such that it produced a degree of discomfort equivalent to that caused by a variety of multiple frequency stimuli including motions containing predominant beats and up to four sinusoidal components. The levels of the 10 Hz vibration equivalent to the complex motions were always well predicted by the root mean square of the levels of 10 Hz equivalent to the individual sinusoidal components in the complex motion. The authors point out that the equivalent discomfort of the multiple frequency motions could therefore be determined by weighting the vibration spectrum with an electronic network having a frequency response given by the manner in which the discomfort due to vibration varies with vibration frequency. They considered the possibility of inhibition occurring in the response to multiple frequency motions but concluded that the complexity inherent in methods based on models of inhibition was unnecessary. They also compared the results of the study with the recommendations published in the International Standard ISO 2631-1974 (ref. 44). Some more recent research by Griffin (ref. 75) shows that for practical purposes the above method for assessing the discomfort of multiple frequency motions can also be employed to evaluate some random motions, including motions with crest factors greater than three.

Fothergill and Griffin have also conducted a detailed study of the determination of the subjective magnitude of 10 Hz sinusoidal vertical vibration by both magnitude estimation and magnitude production methods (ref. 76). In brief, it was found that for all fourteen subjects participating in the experiment the rate of increase of subjective reaction with increasing vibration level was greater when determined by magnitude production than when determined by a magnitude estimation method. The mean exponents of Stevens' Psychophysical Law were 1.7 (magnitude production) and 1.1 (magnitude estimation). This compares with a mean value of about 1.0 determined by Fleming and Griffin (ref. 56) in the same laboratory at Southampton University from the combined noise and vibration experiment described earlier.

In a recent paper presented to the Institute of Acoustics in 1975 Griffin reported on vibration measurements made in cars, trucks, and buses driven over four different roads (ref. 77). The roads varied in roughness from 'good' to 'poor.' Fore-and-aft, lateral, and vertical vibration were recorded at the subject-seat interface of a person sitting in a passenger seat and, simultaneously, on the vehicle floor beneath this seat. The recorded data were analysed to determine the frequency, amplitude, and axis distribution of the motions at the two measuring locations. The seat vibration data were weighted by the frequency weightings defined by the International Organization for Standardization and the seat transmissibilities were determined. The author reported that the ISO weighting procedure for vibration evaluation indicates that vertical vibration was the predominant motion. Frequencies below about 10 Hz contributed most to the weighted value in the vertical axis and the frequency associated with the peak weighted acceleration level was found to depend on the vehicle type. The weighted vibration levels varied according to the type of road and type of vehicle. On the 'good' road the weighted vertical levels were 0.2 m/s^2 rms and greater, while on the 'poor' road the levels were 0.5 m/s^2 rms or more. In trucks and buses weighted levels higher than the one minute reduced comfort boundary were recorded on the 'good' road and well in excess of the 1 hour fatigue decreased proficiency level on the 'poor' road. In the vertical direction crest factors at the seat were normally in excess of three. The vertical transmissibility of the seats varied but all showed an amplification at some frequencies below 10 Hz and attenuation at higher frequencies.

OTHER PUBLICATIONS

The United Kingdom was one of the two countries to vote against accepting the proposals that became International Standard ISO 2631-1974(E), Guide for the evaluation of human exposure to whole-body vibration. However, before copies of the International Standard became available in 1974 the British Standards Institution published a Draft for Development, Guide to the evaluation of human exposure to whole-body vibration (ref. 78). The Draft for Development is very similar to the International Standard and there is no conflict between the vibration evaluation methods given in the two documents. The reasons for the issue of a BSI Draft for Development as opposed to a British Standard (or approval of the International Standard) was that it was felt that the proposals were only "of a provisional nature because much of the available information relating to the effects of vibration on humans is in fact of a provisional or even contradictory nature."

An earlier publication from the British Standards Institution provides a "Guide to the safety aspects of human vibration experiments" (ref. 79). This document discusses some of the ethical and safety measures that experimenters should consider and it proposes that experiments should be classified into four schedules according to the levels of the vibration and the fitness of the subjects. These schedules range from experiments with levels below the ISO 'fatigue decreased proficiency limits' for which with fit subjects no medical certification or supervision is required, to experiments with levels exceeding the ISO 'exposure limits' when subjects should be required to have medical certification and a medical officer should be present during the experiment. The document also provides a list of medical conditions which would generally render a person unfit to be a subject in a vibration experiment.

Many other aspects of human response to vibration are currently under consideration by sub-committee and panel members of the British Standards Institution (e.g., response to building vibration, multiple frequency vibration, hand-arm vibration, and impacts). One study of great importance and having a wide interest concerns the specification of limits for human exposure to low frequency vibration. Suitable simulation facilities have not been available in the United Kingdom to conduct relevant experimental work but some limits for vibration in the frequency range 0.1 to 1 Hz have been formulated on the basis of previously published research (ref. 80). G. R. Allen of the Royal Aircraft Establishment at Farnborough has undertaken the task of evolving the limits which, at present, comprise "Severe Discomfort Boundaries" and a "Reduced Comfort Boundary." The Severe Discomfort Boundaries are based on motion sickness data and, for a 20 minute exposure, take the form of a constant acceleration limit of 1.0 m/s^2 rms from 0.1 to 0.3 Hz rising to 3 m/s^2 rms at 0.6 Hz and tentatively extrapolated to 6.7 m/s^2 rms at 1 Hz. For longer periods of exposure the acceleration limits decrease in inverse proportion to the square root of the exposure duration. The reduced comfort boundary is based on laboratory studies of discomfort due to factors other than motion sickness during vibration. At present it is described by a contour which increases by a factor of five in acceleration as the frequency is increased from 0.1 to 1.0 Hz.

CONCLUSIONS

The findings of about eighty studies conducted in the United Kingdom to investigate the effect of vibration on human discomfort have been summarised. The laboratory studies of the effects of frequency of sinusoidal vertical vibration on comfort have produced some agreement on the shape of the curves (see figure 5) with the mean sensitivity of subjects showing a maximum around 5 Hz. Although there are also data to show how to assess some non-sinusoidal motions the available results fall far short of that which is required to provide a complete general procedure for assessing the complex multiaxis motions, that characterise most vehicle rides. There are some data on the relative differences in the sensitivities of individual subjects to different frequencies but, above threshold, little understanding of the absolute differences in individual sensitivity to any vibration condition.

There have been no satisfactory studies which suggest how comfort limits should change with the duration of exposure to vibration or how to assess motions whose level varies greatly during an exposure.

Studies conducted in relation to specific transport systems (aircraft as in figure 3 or the railways as in figure 4) show a high degree of agreement. (The curves (a) to (d) in figure 4 could be raised or lowered to allow for different ride indices or exposure times but those shown seem reasonable in the light of the context in which the limits are reported.) In these figures two curves could be identical but, being associated with different evaluation procedures (e.g., the method of assessing non-sinusoidal motion), could correspond to widely different limits. Evaluation methods have not always been adequately defined by those proposing limits and it is often not clear where the vibration levels are to be measured. Where there are such differences between two procedures, their importance is dependent on the motions being assessed. Since it is not possible to evaluate this in the present paper, the following comparison of the curves in figures 3 and 4 assumes that their proposers would expect them to apply to sinusoidal motion at a passenger-seat interface. It may be observed that for vertical vibration around 5 Hz all authors (Batchelor, Loach, Woods, Jones, Griffin, Jackson, and Grimster) quote limiting levels in the range 0.4 to 0.7 m/s^2 rms. They all advocate the same or higher levels at higher frequencies and, with the exception of Jackson and Grimster (ref. 65), they advocate the same or higher levels at lower frequencies. Although some authors of the above limits quote measurements of transport vibration to support their proposals there has been relatively little systematic investigation of their validity. In view of the differing applications of the limits and the limited attempts at verification it is surprising to find such a high degree of agreement.

One of the objectives of research in this area is to define a ride evaluation procedure which will not only give a numerical indication of vehicle ride but also provisionally indicate how the ride changes as the many physical variables change. The United Kingdom research outlined in this paper comes close to providing the most simple procedure for stationary vertical vibration with only two variables: level and frequency. There is very little information originating from the United Kingdom on how these variables interact with motion in other axes, on the importance of vibration duration or variations in vibration level, frequency or axis with time. There are some data on the relative importance of noise and vibration but reports of the significance of other physical variables that may affect human response without changing the vibration exposure are largely apocryphal.

An hypothesis as to how human response to vibration depends on four physical variables (vibration level, frequency, axis, and duration) was published as International Standard ISO 2631-1974(E) (ref. 44). From research conducted in the United Kingdom, the United States of America and many other countries this document defined vibration limits for the preservation of comfort, the preservation of working efficiency, and the preservation of health and safety. The data presented in figure 5 show a broad similarity to the shape of the ISO contour for vertical vibration although some curves depart from the shape by up to a factor of two in acceleration level at some frequencies. The vibration limits shown in figure 3 and figure 4 approximately correspond to the ISO 25 minute reduced comfort boundary and, in view of the many other potential sources of variation in analysing a ride motion, this may seem to be reasonable agreement. Debate over the contention in the ISO standard that levels three times greater are required before there is a significant risk of impaired working efficiency and that, for 25 minutes, it would be unsafe to exceed levels six times greater does not come within the scope of this paper.

It appears therefore that both the vertical frequency weighting and some of the limits for human comfort defined in the ISO Standard can be considered to be in harmony with some United Kingdom research. However such agreement is not generally sufficient for design purposes. There is discord between United Kingdom Research (Fothergill and Griffin (ref. 74)) and the ISO preferred method of assessing complex vibration. There are data which lead t the conclusion that the suggestion in ISO 2631-1974 that the limits may not apply to motions having crest factors greater than three is a very severe practical limitation. However there are also some United Kingdom data to suggest that, while the crest factor may not be the most appropriate unit to describe the 'peaky' nature of a motion, the tentative limit of three given i ISO 2631-1974 could possibly be increased to 5 or 6 for some motions. Finall there are no United Kingdom data to support the time dependency defined in IS 2631-1974 and at present there are insufficient published data to draw conclu sions regarding the validity of the data for non-vertical vibration.

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TABLE I

AUTHOR	DATE	REFERENCE	PAGE	AIR	RAIL	ROAD	SEA	AGRICULTURAL	BUILDING	LABORATORY
Allen	1971	50	479	X	X	X	X	X		
Allen	1974	80	486	X	X	X	X	X		X
Ashley	1970	43	478							X
Ashley and Eames Jones	1971	48	479							X
Ashley and Rao	1972	67	482							X
Aspinall	1960	18	475			X				
Aspinall and Oliver	1964	19	475			X				
Batchelor	1962	17	474		X					
Bryce	1965	33	477	X						X
B.S.I.	1973	79	485							X
B.S.I.	1974	78	485	X	X	X	X	X	X	X
Burt	1972	36	477			X			X	
Constant	1932	11	473	X						X
Digby and Sankey	1911	9	473							X
Eason	1923	10	473						X	
Fleming and Griffin	1975	56	481							X
Fothergill	1972	72	483							X
Fothergill and Griffin	1975	73	484							X
Fothergill and Griffin	1975	74	484							X
Fothergill and Griffin	1975	76	484							X
Griffin	1970	61	481	X						
Griffin	1972	58	481	X						
Griffin	1973	1	471	X	X	X	X	X	X	X
Griffin	1974	59	481	X						X
Griffin	1975	3	472							X
Griffin	1975	5	472							X
Griffin	1975	77	485			X				
Griffin	1975	66	482	X						X
Griffin	1975	75	484							X
Grimster	1974	63	481	X						
Grimster et al	1974	62	481	X						
Guignard	1959	4	472	X						X
Guignard	1959	6	472							X
Guignard	1964	23	475	X						X
Hawkins and Griffin	1972	60	481	X						
Hempstock and Saunders	1973	55	480							X
Hilton	1970	29	476					X		
Holliday	1974	64	481	X						
Innocent and Sandover	1972	57	481							X
I.S.O.	1974	44	478	X	X	X	X	X	X	X
Jackson and Grimster	1972	65	481	X						
Jones, A. J. and Saunders	1972	52	480							X
Jones, A. J. and Saunders	1972	53	480							X
Jones, A. J. and Saunders	1974	54	480							X
Jones, G. M. and Drazin	1961	22	475	X						
Jones, J. P.	1965	32	476	X						
Leonard	1966	34	477						X	
Loach	1958	16	474		X					
Lovesey	1970	42	478				X			
Lovesey	1971	45	479							X
Lovesey	1971	51	480	X	X	X	X			X
Mallock	1902	8	472		X				X	
Matthews	1964	25	476					X		
Matthews	1964	26	476					X		
Matthews	1966	28	476					X		
Matthews and Talamo	1965	27	476					X		X
McCullough and Clarke	1974	69	482							X
McKay	1971	46	479							X
McKay	1972	47	479							X
Mitchell	1969	39	478	X						
Oborne and Clarke	1973	68	482	X			X			
Oborne and Clarke	1974	70	482							X
Oborne and Clarke	1975	71	482							X
O'Hanlon and Griffin	1971	7	472							X
Oliver	1968	21	475			X				
Oliver and Whitehead	1966	20	475			X				
Postlethwaite	1944	12	473							X
Rowlands	1971	49	479							X
Rowlands and Maslen	1973	2	472							X
Shurmer	1969	41	478				X			
Silverleaf and Cook	1969	40	478				X			
Stayner	1972	31	476					X		
Stayner and Bean	1971	30	476					X		
Steffens	1952	13	474						X	
Steffens	1963	14	474						X	
Walsh	1964	24	476							X
Watts	1973	37	477			X				X
Whiffin and Leonard	1971	35	477						X	
Willis	1956	15	474	X						
Woods	1967	38	477	X						

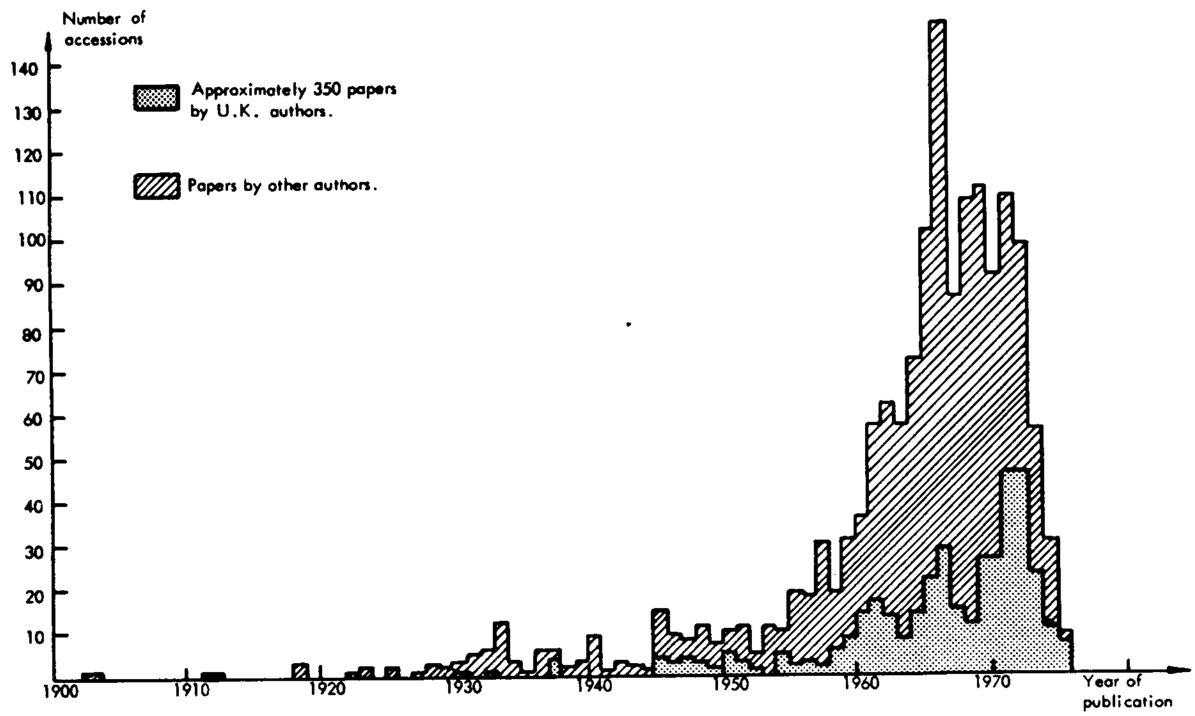

Figure 1.- Histogram showing the year of publication of accessions to the human response to vibration literature collection at the Institute of Sound and Vibration Research (June 1975).

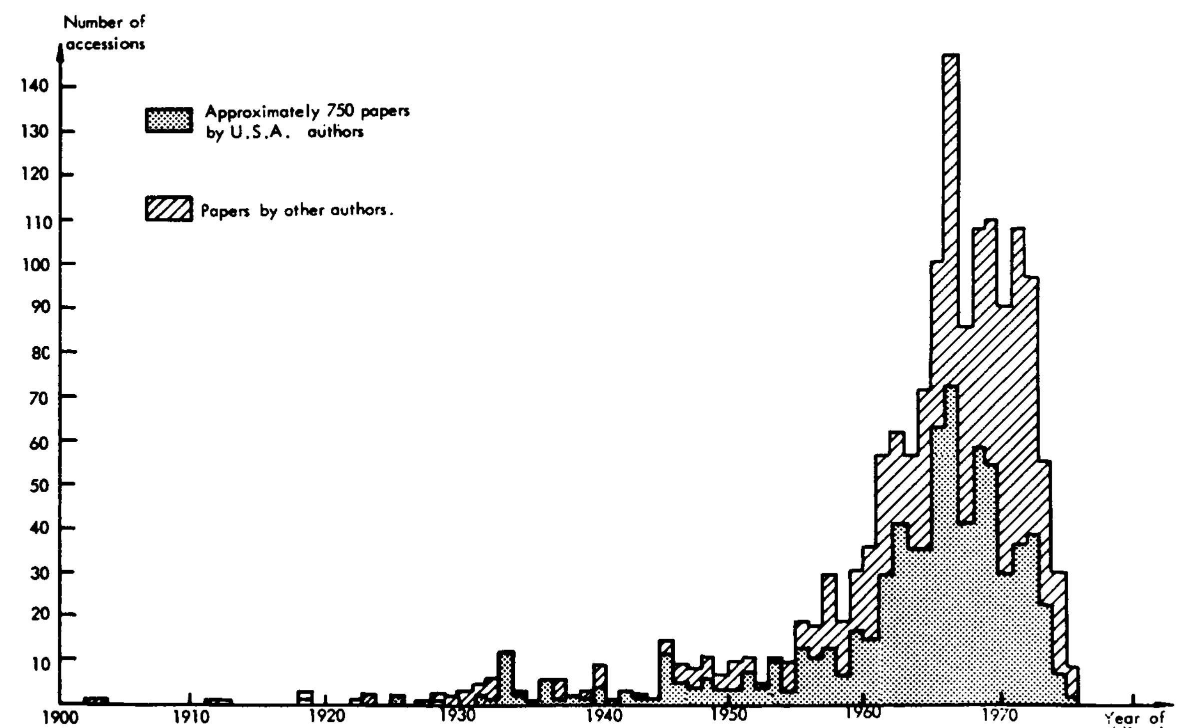

Figure 2.- Histogram showing the year of publication of accessions to the human response to vibration literature collection at the Institute of Sound and Vibration Research (June 1975).

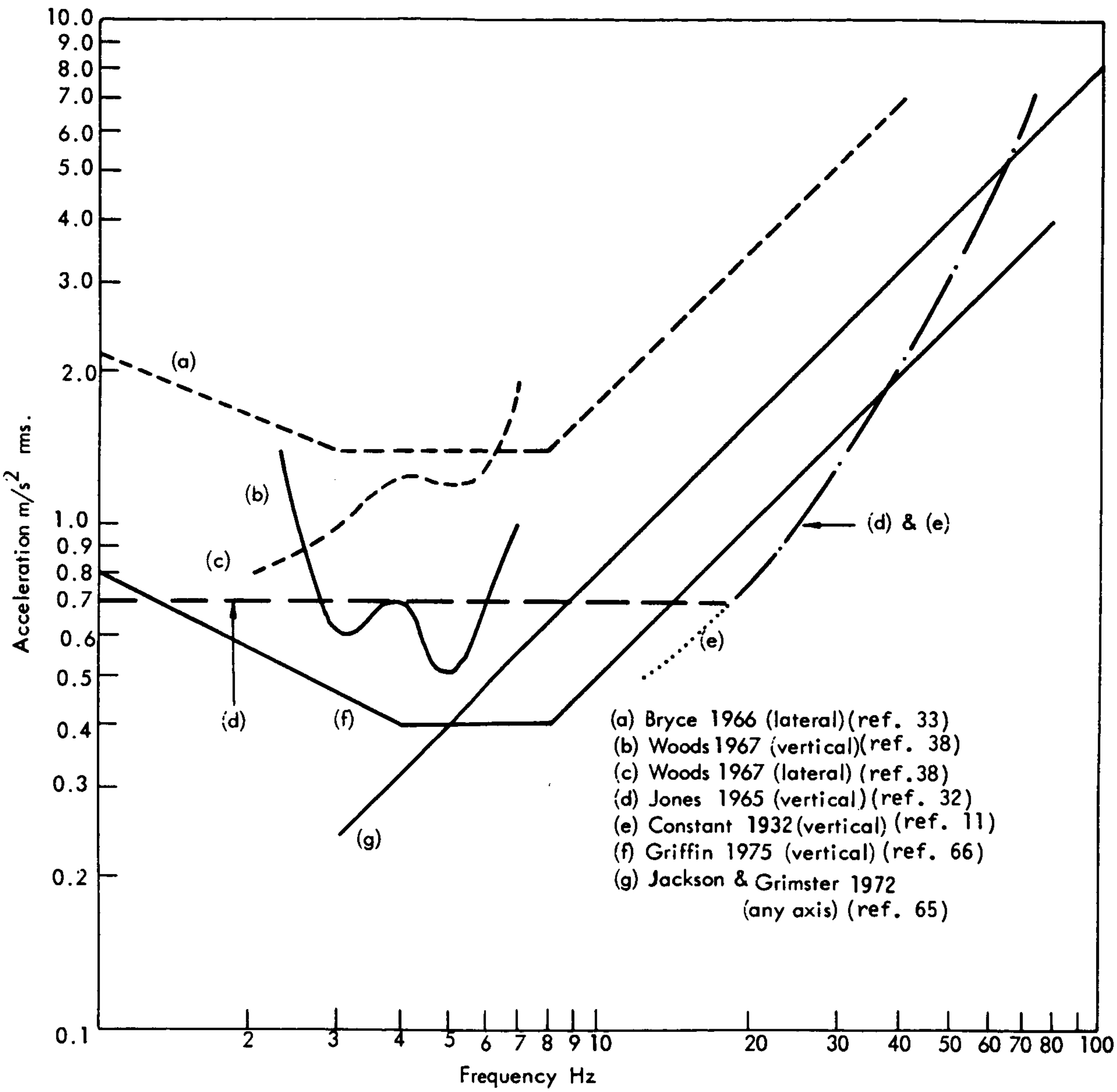

Figure 3.- Aircraft vibration limits proposed in the United Kingdom.

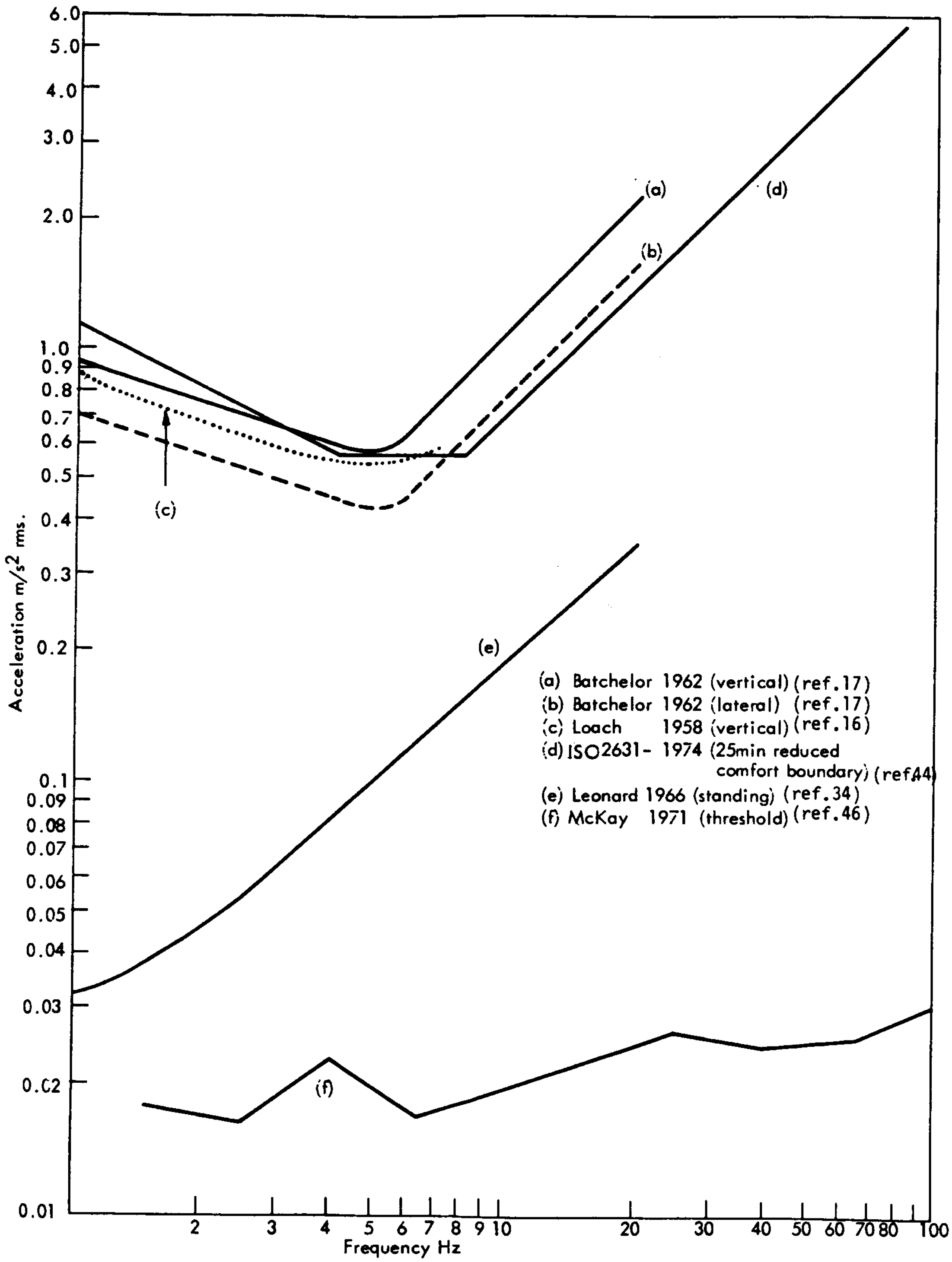

Figure 4.- Frequency contours for railway vibration, bridge vibration, and the threshold of perception of whole-body sinusoidal vibration as reported by some United Kingdom workers.

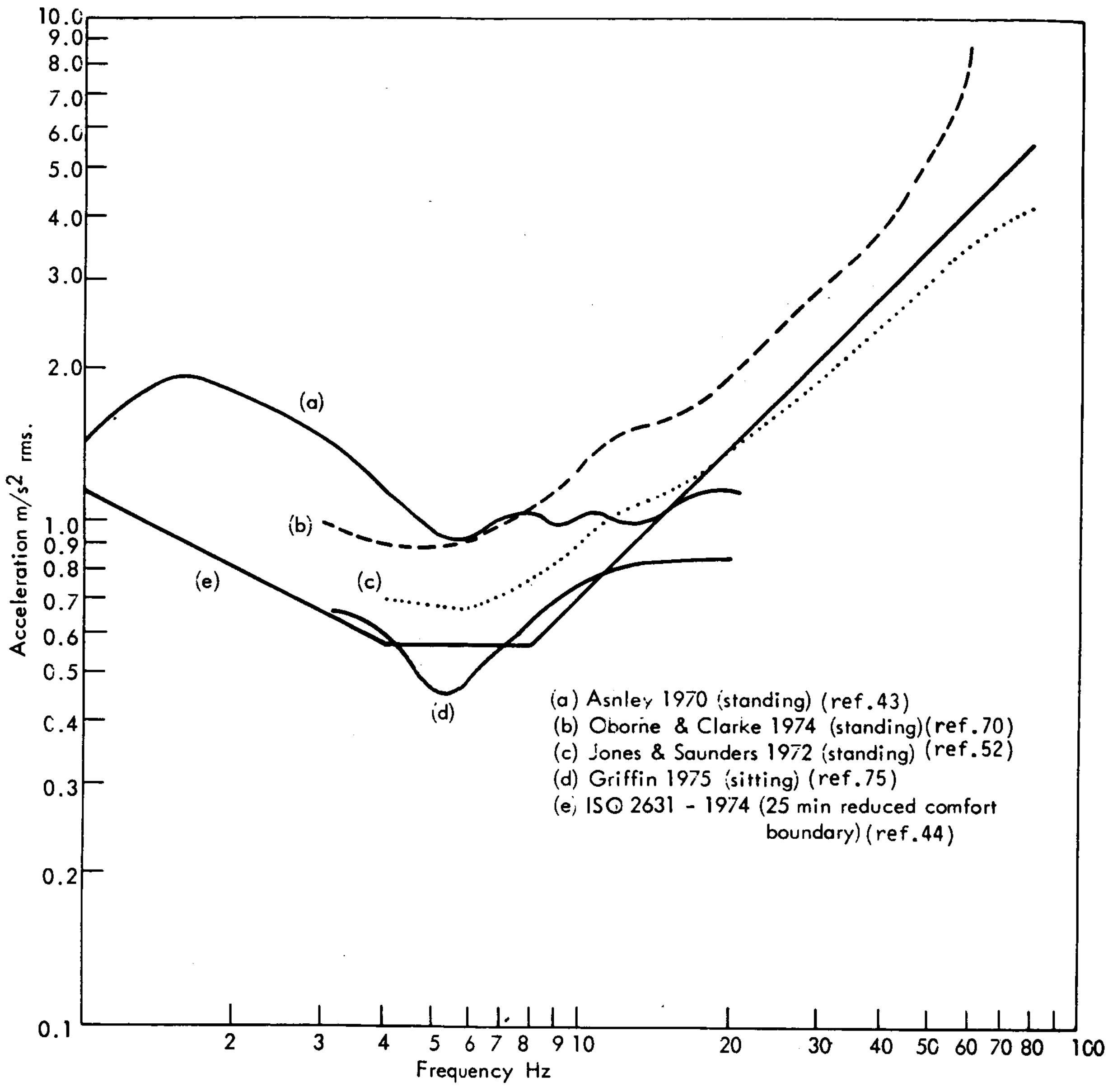

Figure 5.- A comparison of contours of equivalent sensation to whole body sinusoidal vertical vibration determined in the United Kingdom.