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Scaling and Evaluation of Whole-body Vibration by the Category Judgment Method

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Abstract

Quantitative evaluation of "degree of comfort" is an important aspect to consider when evaluating the nature of products or the establishment of design-objective values during vehicle development. In this research, the category judgment method, which is one of the scaling methods, was used to create an assessment scale for evaluation of whole-body vibration to solve this problem.

To scrutinize the effect of the difference in the frequency component of the vibration on evaluation, three kinds of random signals with different spectrum were used in our experiment. Consequently, while the quantitative relation between a vibration stimulus and degree of comfort became clear, it turned out that when a vibration contained more low frequency components, the degree of comfort declines even though the acceleration level is the same.

1 PREFACE

Quantitative evaluation of "degree of comfort" is an important aspect to consider when evaluating the nature of products, or the establishment of design-objective values during vehicle development. ISO2631-1[1], which defines an acceptable standard of body vibration, is the generally accepted evaluation criteria for evaluating whole-body vibration as part of overall in-vehicle comfort.

There, whole-body vibration in the seated position is defined as the vibration received from the seat and the seat back as well as the vibration from the floor to which the feet are subjected. Meanwhile, the comfort of a seated person is evaluated in terms of frequency-weighted R.M.S. acceleration (hereinafter acceleration level) that is calculated as the sum of recorded vibration ranging from 0.5 to 80 Hz on a total of twelve axes after being weighted based on the frequency-weighting curve, and the following values are given as approximate indications of the relation between acceleration level and the degree of comfort (**Table 1**).

Table 1 Acceleration level and degree of comfort defined in ISO2631-1

Acceleration level	Degree of comfort
Less than 0.315m/s^2	Not uncomfortable
0.315-0.63m/s^2	A little uncomfortable
0.5-1m/ s^2	Fairly uncomfortable
0.8-1.6m/ s^2	Uncomfortable
1.25-2.5m/ s^2	Very uncomfortable
Greater than 2m/ s^2	Extremely uncomfortable

(Reference)
Examples are reported by Yamashita and others[2] in which the measured acceleration level was 0.737 on a bus, 0.392 on a taxi and 1.689 on a bulldozer.

However, there are areas of overlap between the two reaction groups covered by the ISO2631-1 scale and their presence is problematic in determining the appropriate presumed reaction concerning the degree of comfort based on the physically recorded vibration level (**Figure 7**).

In this research the category judgment method, which is one of the scaling methods, was used to establish an assessment scale for evaluation of whole-body vibration to solve this problem.

In order to solve this problem and to create a quantitative assessment scale for evaluation of the degree of comfort, an experiment was conducted using the category judgment method[3]. In this paper the report is focused on how this approach was used.

2 PSYCHOLOGICAL MEASURING METHOD

The methods of measurement for material not directly observable, such as human reaction to stimuli, are categorized as psychological measurement, which are roughly divisible into two types, namely scaling and constant measurement (**Figure 1**). Whereas the scaling method involves the creation of a scale to measure the psychological concepts involved, the constant measurement method involves an assignation process linking suitable evaluation to a pre-determined scale, which scale may not necessarily be suitable for expressing human beings feeling.

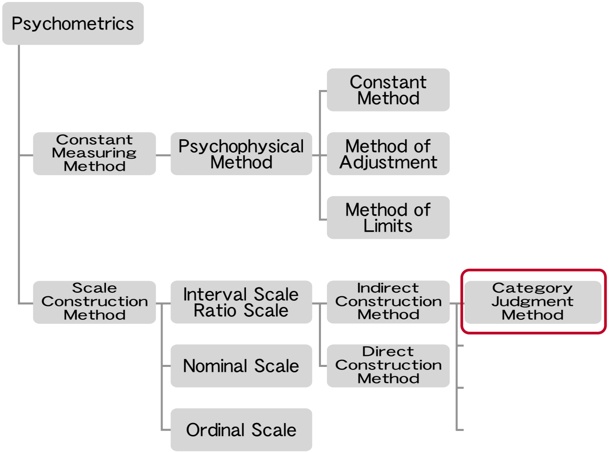


Figure 1. Psychological measuring method

Experiments which ISO2631-1 referred to were conducted by latter method and that is thought to be the reason why considerable degrees of overlap between categories were included.

Maeda et al.[4] successfully composed a scale to evaluate the localized vibration transmitted to hands and arms with the category judgment method, showing a clear relationship between the frequency and level of vibration acceleration and the respective psychological values. Moreover, Sumitomo et al.[5] used the category judgment method to successfully identify changes in the psychological values of perceived vibration from the Shinkansen bullet trains in subjects before and after the Kobe Earthquake of 1995.

In this research, by the category judgment method, an assessment scale for evaluation of whole-body vibration was created whereas the quantitative relation between the vibration stimuli and the degree of comfort became clear using three kinds of random signals with different spectrum in the experiment.

3 ESTABLISHMENT OF THE SCALE BY THE CATEGORY JUDGMENT METHOD

In the category judgment method the width of a category is adjusted so that the distribution of the category judgment to a stimulus may form a normal distribution. The process of the scale establishment using the experiment result, as shown in **Figure 2**, is described below.

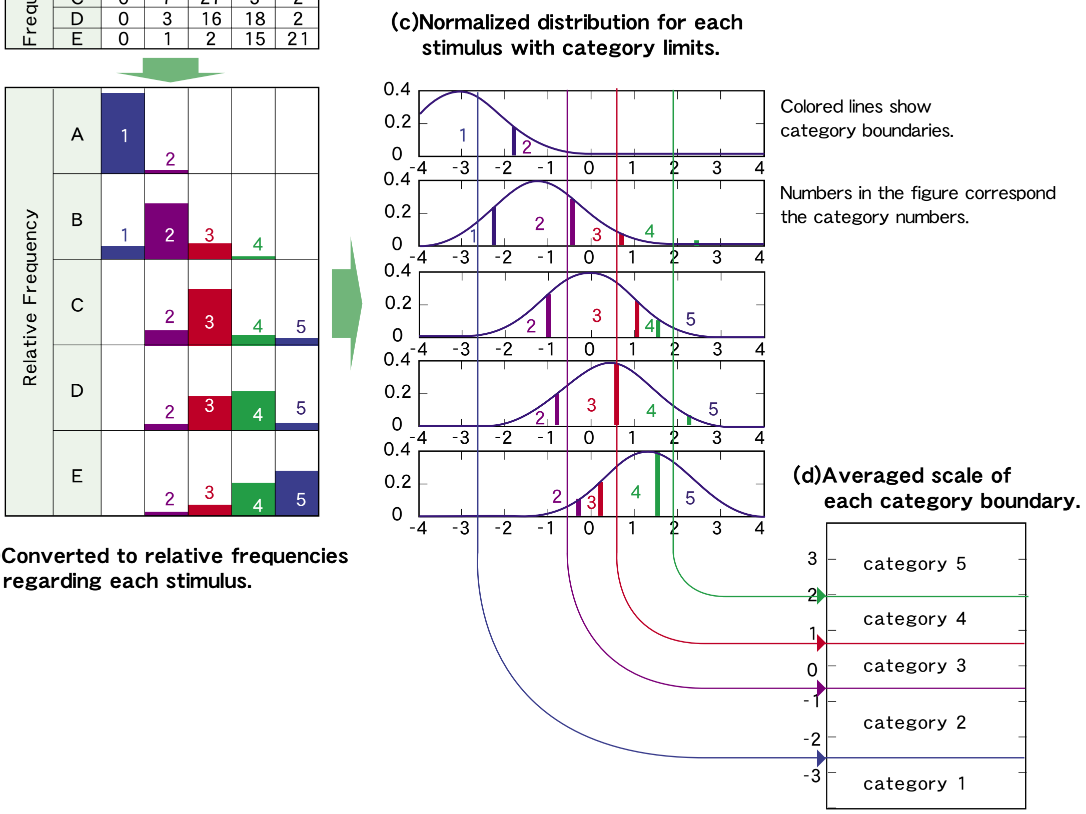
Thirteen subjects evaluated five kinds of stimuli by a unit of 3 times, respectively, making a total of 39 measurements in the experiment. **Figure 2(a)** shows the experiment result summarized in a table of frequency distribution for each category, which is converted into the relative frequency in **Figure 2(b)**.

Next, the accumulation ratio to the upper limit of each category is obtained by converting the frequency distribution. The deviation ratio corresponding to the category boundaries for each stimulus as shown in **Figure 2(c)**, which can be considered to be a conversion of **Figure 2(b)** to normal distribution, with the area ratio maintained.

Finally the category boundary for every stimulus is averaged and the average scale is obtained as shown in **Figure 2(d)**.

(a)Original frequency data

		category				
Stimulus		1	2	3	4	5
Frequency	A	38	1	0	0	0
	B	6	25	7	1	0
	C	0	7	27	3	2
	D	0	3	16	18	2
	E	0	1	2	15	21



(b)Converted to relative frequencies regarding each stimulus.

Figure 2. Scaling process of categories by the category judgment method

4 EXPERIMENT

Experiments were conducted using random signals for the stimuli over a frequency range of 1-100Hz and, in addition, in order to clarify the individual characteristics of the different frequencies, three kinds of signals with varying degrees of high and low frequency components were used. Spectra of the signals are shown in **Figure 3**.

The signals were modified with a frequency weighting of Wk based on the ISO2631-1 standard, and the frequency-weighted R.M.S. acceleration levels were adjusted to be equal. Furthermore, the levels of the signals were varied over a range of five steps between 0.2-1.8 m/s^2 R.M.S. to make 15 kinds of stimuli. These signals were each used three times, comprising a total of 45 stimuli applied in random order, as shown in **Figure 4**, each applied for a duration of five seconds with a two-second pause between stimuli.

The vibration load was applied in the vertical direction to the subject sitting on the vibration platform (**Figure 5**). The subjects issued verbal responses to each vibration stimulus, selecting from the five evaluation categories shown in **Table 2**, using a corresponding number.

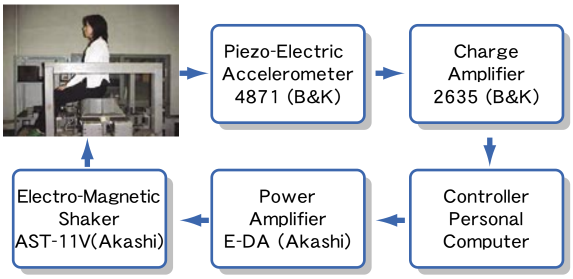


Figure 5. The experimental apparatus

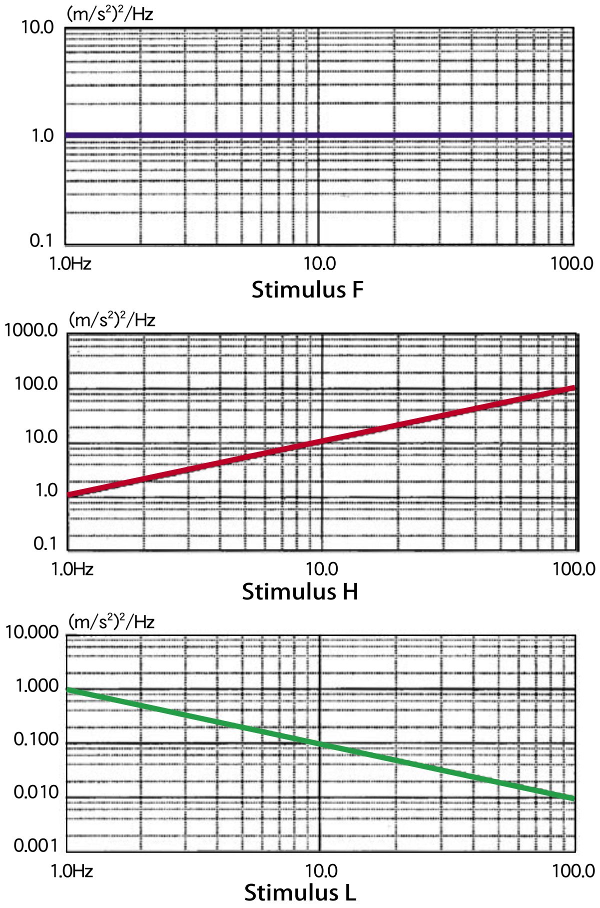


Figure 3. Spectra of the vibration stimuli

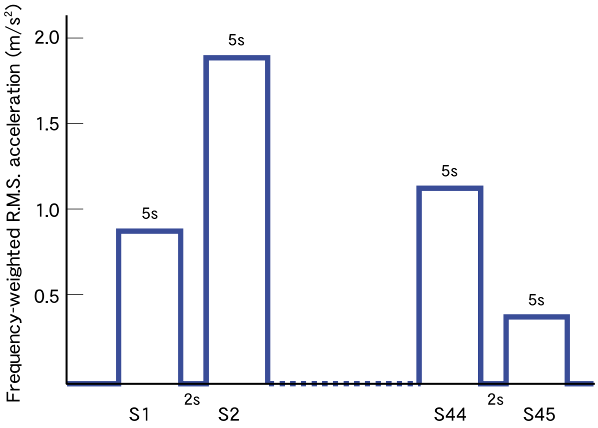


Figure 4. Series of the signal

Table 2. Categories used in the experiment

1. Not uncomfortable
2. A little uncomfortable
3. Fairly uncomfortable
4. Uncomfortable
5. Very uncomfortable

By processing the experiment results using the program (shown in Appendix) which was created along with the above-mentioned procedure, the regression equations expressing the relationship between the acceleration level *V* and corresponding psychological value *U* on the absolute scale were obtained as shown by equation (1).

Here, *U* is the value given by 50% of the 13 subjects as their psychological evaluation of the vibration stimulus at the acceleration level *V*. The result is shown in **Figure 6**.

$$U = a\log_{10}V+b \tag{1}$$

where

a=6.8, b=0.7 :in the case of spectral F

a=5.4, b=−0.4 :in the case of spectral F

a=8.6, b=2.0 :in the case of spectral L

Then corresponding acceleration levels to the category boundaries on the absolute scale were obtained for each spectrum respectively by using equations (2) which are variants of equations (1).

$$Vc = 10^{(Lc - b)/a} \tag{2}$$

In this way category boundaries without overlap between adjacent categories were obtained. This result is shown in **Figure 7** along with the ISO 2631-1 scale.

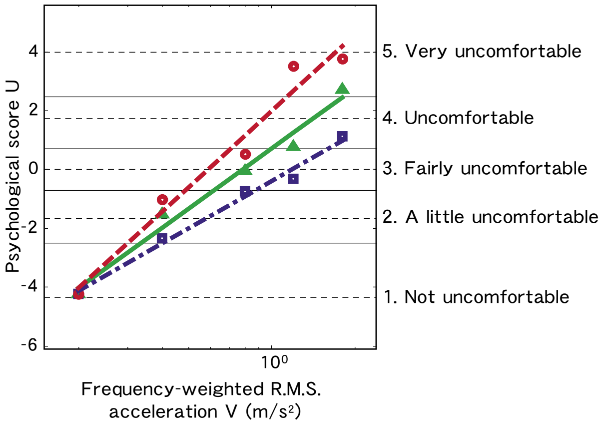


Figure 6. Relationship between psychological score and frequency-weighted R.M.S. acceleration

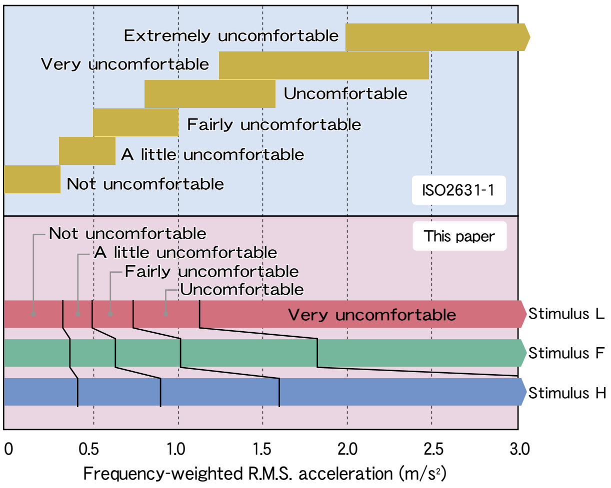


Figure 7. Scales of comfort

5 DISCUSSION

Figure 7 shows that although the lower limits for each category exceed the ISO2631-1 values, the results for the type F stimuli are the closest to the ISO2631-1. In addition, based on the fact that the category values obtained by the H stimuli shifted toward higher acceleration level compared to the values by the F stimuli, it can be surmised that the H stimuli were perceived to be less uncomfortable than the F stimuli with the same acceleration level.

Conversely, the current results show that with the L-type stimuli, there was a tendency to perceive a stimulus as more uncomfortable than the F stimuli even though the degree of acceleration levels was the same.

According to these results it became clear that vibrations with different spectra caused differences in the perception of the degree of comfort for individual stimuli even when the acceleration levels were the same. It was also observed that the degree of discomfort increased when the stimuli used contained a higher percentage of lower frequency components. **Figure 6** shows that this tendency was more remarkable when the acceleration level was large.

The frequency weighting Wk of ISO2631-1 was established based on experiments using combinations of single frequency sine waves as the vibration stimuli. That is considered to be the reason why the random signals used in this research were not appropriately modified.

6 CONCLUSION

By using the category judgment method an assessment scale for evaluation of whole-body vibration was created without overlap between adjacent categories.

Using this method, the relation between subjective and mental evaluation, which is rather difficult to measure, and a physical value actually measurable like the acceleration level of a vibration can be clarified.

Furthermore, since this method makes it possible to evaluate the so-called feeling numerically with regard to the size, color, velocity and acceleration etc., it can be efficiently employed in research and development for quantitative evaluation of a product's nature and quantitative establishment of design-objective values.

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■APPENDIX: A sample program for the scaling by the category judging method

This program runs on MATLAB[6] with command "CJM". The data obtained in the experiment are already written in the program as sample data for easier use. To use other data, correction of the program by rewriting this part or adding an input part to read the data file is needed. The outline of the process is described below.

(1) Make the frequency-distribution matrix F arranging the evaluation results according to the categories.
(2) Convert it into the accumulation ratio G regarding categories 1-5.
(3) Obtain the deviation ratio Z corresponding to the accumulation ratio to the upper limit of each category.
(4) Calculate the category average width D, the category upper limit L and the category median C.
(5) Convert C into the absolute scale value A based on the idea that the median point of the center category 3 represents a significant zero.
(6) Calculate the scale value M which represents the median of the frequency distribution of each vibration stimulus using the category upper limit L.
(7) Using this result, obtain the equation of regression which represents the relation between acceleration level V and corresponding psychological value U for each vibration stimulus. The result is shown in Figure 6.

Since the process (7) is customized to plot a figure of the sample data, it is necessary to be modified to deal with other data while generalized process (1) - (6) need no modification.

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%       Category Judgment Method         %
%   Programmed by T.Hagiwara 2003.7.30   %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function CJM()

% (1) Arrangement of the frequency-distribution matrix F .
%        --- 1 --- 2 --- 3 --- 4 --- 5 ---                   % Category number
F = [      38     1     0     0     0                 % Flat 0.2    m/s^2 R.M.S.
             6    25     7     1     0                 % Flat 0.4
             0     7    27     3     2                 % Flat 0.8
             0     3    16    18     2                 % Flat 1.2
             0     1     2    15    21                 % Flat 1.8
            38     1     0     0     0                 % High 0.2
            18    19     2     0     0                 % High 0.4
             4    16    17     2     0                 % High 0.8
             2    13    17     7     0                 % High 1.2
             1     2    13    16     7                 % High 1.8
            38     1     0     0     0                 % Low  0.2
             4    19    14     2     0                 % Low  0.4
             0     5    17    16     1                 % Low  0.8
             0     0     0    10    29                 % Low  1.2
             0     0     1     5    33    ];           % Low  1.8
[n,g] = size(F);                                       % Obtain the size of the matrix    n:stimulus g:category
Td = zeros(35,1); L = Td; Sm = 0; Su = 0; Suu = 0;        % Initialization of each variable.
cr = setstr(13);                                       % A local constant for figure plot
```

```
% (2) Conversion to accumulated ratio G
G = cumsum(F./repmat(sum(F,2),1,g),2);           % G(i,j): accumulated ratio

% (3) Calclation of deviation ratio Z
for i = 1:n                             % Repeat for stimuli
   for j = 1:g                          % Repeat for categories
      Z(i,j) = ZSCORE(G(i,j));                   % Z(i,j): Upper limit of category
   end                                  %
end                                     %

% (4) Calculation of the average category width D, the category upper limit L and the category median C
for j = 1:g                             % Repeat for categories
   c = 0;                               %
   for i = 1:n                          % Repeat for stimuli
      if j == 1                         % An exception case for category 1
         if Z(i,j) ~= -3.75             % When frequency exists in category 1
            d(i,j) = Z(i,j)-(-3.75);    % Lower limit is assumed to be ξ3.75
            Td(j) = Td(j)+d(i,j);       %    Category width is accumulated
            c = c+1;                    %    Number of accumulated categories is counted
         end                            %
      elseif (Z(i,j) ~= -3.75) & (Z(i,j-1) ~= 3.75)       % Skip when the limit exists in the adjacent category
         d(i,j) = Z(i,j)-Z(i,j-1);      %    d(i,j): Width of category
         Td(j) = Td(j)+d(i,j);          %     Category width is accumulated
         c = c+1;                       %    Number of accumulated categories is counted
      end                               %
   end                                  %
   if c == 0, c = 1; end                         % Avoid zero division
   D(j) = Td(j)/c;                      % D(j): Average value of category
end                                     %

for j = 1:g                             % Repeat for categories
   if j == 1                            % For category 1
      L(j) = D(j);                      % Upper limit of category
      C(j) = L(j)/2;                    % Median of category
   else                                 % For other categories
      L(j) = L(j-1)+D(j);               %    L(j): Upper limit of category
      C(j) = (L(j-1)+L(j))/2;           %    C(j): Median of category
   end                                  %
end                                     %

% (5) Conversion into the absolute scale value
A = C-C((g+1)/2);                       % A(j): Median of category on the absolute scale

% (6) Calculation of the scale value U which represents the median of each stimulus
for i = 1:n                             % Repeat for stimuli
   for j = 1:g                          % Finds a category
      if G(i,j) > 0.5, break, end    %    in which the accumulation ratio exceeds 50%
   end      %
   R = j-1;             % The category in front of one is set to R.
   if R == 0, M(i) = L(j)/G(i,j)*0.5;            % In case median exists in category 1
   else                                 % In other cases
      M(i) = L(R)+(L(j)-L(R))/(G(i,j)-G(i,R))*(0.5-G(i,R));% Locate the median value by interpolation
   end      %
   U(i) = M(i)-C((g+1)/2);                       % Median is converted to absolute scale value
   Sm = Sm+M(i);      %
   Su = Su+U(i);      %
   Suu = Suu+U(i)^2;             %
end         %
```

```
Tm = Sm/n;                              % The average scale value of all stimuli
Tu = Su/n;                              % The average absolute scale value of all stimuli
Tnn = sqrt(Suu/n-Tu^2);                           % The standard deviation of all stimuli

disp(‘d’), disp(d)                      % The width of category
disp(‘D’), disp(D)                      % The average of the width of category
disp(‘L’), disp(L(1:g)’)                % The accumulated value of the average category width
disp(‘C’), disp(C)                      % The median of category
disp(‘A’), disp(A)                      % The median of category on the absolute scale
disp(‘SCALE VALUES’)          %
disp(‘  Stimulus    Median  Absolute scale value’)        %
disp([[1:n]’ M(1:n)’ U(1:n)’])        %
disp([‘       Tm    ‘, num2str(Sm), ‘    ‘, num2str(Su)])      %
disp([‘        M    ‘, num2str(Tm), ‘    ‘, num2str(Tu)])      %
disp([‘       SD           ‘, num2str(Tnn)])      %

% (7) Obtain the regression equation that represents the relation between acceleration level V and corresponding psychological value U, and
plot a figure
s = 3; v = 5;                           % Number of spectra / steps of acceleration levels
Va = [0.2 0.4 0.8 1.2 1.8];                       % Acceleration level
XV = [0.75*Va(1) Va(5)/0.75];                     % Plot range of X-axis
m=[‘g^’; ‘bs’; ‘ro’];    % Marking color and figure of point U
l=[‘g- ‘; ‘b-.’; ‘r--’];    % Color and figure of regression line
Lc = L-C((g+1)/2);                      % Scale value of category boundary
for i=1:s    %
   p=polyfit(log10(Va(1:v)),U((i-1)*v+1:i*v),1);          % Calculation of liner regression line a=p(1), b=p(2)
   semilogx(Va(1:v),U((i-1)*v+1:i*v),m(i,:)), hold on     % Plotting of  U
semilogx(Va(1:v),polyval(p,log10(Va(1:v))),l(i,:))        % Drawing of the regression line
   Vc = 10.^[(Lc(1:g-1)-p(2))/p(1)];                      % Conversion of the category limit to a physical value
   disp([cr ‘Spectrum No.’ num2str(i) cr ‘    Regression coefficient(a, b)   ‘ num2str(p)])
   disp([   ‘    Physical value of category boundary  ‘ num2str(Vc’)])               %
end          %
             %
semilogx(XV,A(1:g)’*[1 1],’k:’)                   % The center line of the category
semilogx(XV,Lc(1:g-1)*[1 1],’k’)                  % The boundary line of the category
axis([XV Lc(1)-D(1) Lc(g)])                       % Plot range arrangement
ylabel(‘Psychological Score U’)  %
xlabel(‘Frequency-weighted R.M.S acceleration V (m/s^2)’)          %
title(‘Category Judgment Method’)             %

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Sub-program to convert accumulation ratio G to deviation ratio Z (Approximation by Hastings et al7)) %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function Z = ZSCORE(G)

a = [2.516 0.803];       %
b = [1.433 0.189];       %
eps = 0.0001;                           % The lower limit of accumulation ratio
if (abs(G) > eps) & (abs(G-1) > eps)          %
   if G > 0.5, P=1-G; else P = G; end         %
   X = sqrt(log(1/P^2));              %
   Z = X-(a(1)+X*a(2))/(1+X*(b(1)+X*b(2)));             %
else Z = 3.75; end                      % Corresponding to the upper or lower limit
if G < 0.5, Z = -Z; end               %

% program end
```