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Digital frequency-weighting filters for evaluation of human exposure to building vibration

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According to some International and National Standards, frequency weighting is the preferred method for evaluation of human exposure to broadband vibration in buildings. The weighting functions are defined by prototype filters that may be implemented in analog or digital form. For this paper, frequency-weighting functions specified by the ISO 8041 and BS 6841 Standards were simulated in software as time-domain digital filters. Simulation procedures, software implementation, and verification of tolerance requirements are presented. The digital filters implemented here conformed closely to specifications in the Standards. A FORTRAN subroutine is provided for calculating the coefficients of the digital filters.

Primary subject classification: 49.1; Secondary subject classification: 49.3

1. INTRODUCTION

Building vibration induced by road and rail traffic, machinery, and construction activities can reach magnitudes that may be annoying to building occupants. The International Organization for Standardization (ISO) and several countries have published Standards that provide guidance on evaluation of human response to vibration in buildings, e.g., International Standard ISO 2631-2,¹ British Standard BS 6472,² and American National Standard ANSI S3.29.³ Criteria for human exposure to vibration are defined in those Standards in terms of root-mean-square (rms) acceleration and velocity in one-third-octave bands with mid-band frequencies in the range from 1 to 80 Hz.

According to the above Standards, broadband vibration signals (i.e., vibrations with spectra covering more than one one-third-octave band) may be evaluated using (1) the rating method or (2) the frequency-weighting method. In the rating method, a measurement of one-third-octave-band vibration is evaluated with respect to a criterion vibration at each one-third-octave band in the specified frequency range. This evaluation can be performed by means of one-third-octave-band filters or by one-third-octave-band digital-filtering software.⁴

For the frequency-weighting method, measured vibration signals are frequency-weighted according to the equal-human-response curves specified in the Standards. Frequency-weighted vibration signals are then evaluated with respect to a criterion in the frequency range where humans are most sensitive to vibration, i.e., at the lowest vibration criterion for the equal-human-response curves specified in the Standards. Because of research evidence suggesting that there are summation effects for vibrations at different frequencies,¹ frequency weighting is the preferred method in ISO 2631-2 and BS 6472. There is no clear preference given in ANSI S3.29 for an evaluation method.

Frequency weighting is achieved by passing vibration signals through filters that conform to a specified frequency response. The filters may be realized in analog or digital

form. Frequency weightings are provided in ISO 2631-2, BS 6472, and ANSI S3.29 as curves composed of straight lines with slopes of -3, 0, and +6 dB per octave. The lines are "asymptotic approximations" to the mathematical equations of the frequency weightings specified in ISO 8041⁵ and British Standard BS 6841.⁶ The full equations are normally preferred over the asymptotic approximations for design of frequency-weighting filters.⁶

For this paper, prototype analog frequency-weighting filters specified in ISO 8041 and BS 6841 were simulated by software in the form of time-domain digital filters. Simulation of filters by software is economical and reliable as it eliminates a piece of hardware that could be subject to various environmental effects and the need for periodic calibration. The weighting functions simulated in this paper included those specified in ISO 8041 for *x*-, *y*-, and *z*-axis whole-body mechanical vibration. The weightings W_b and W_d specified in BS 6841 for evaluation of the effect of whole-body vibration with respect to human perception and discomfort were also implemented. The frequency weightings are applicable to measurements of acceleration.

2. FREQUENCY-WEIGHTING FILTERS

In ISO 8041 and BS 6841, frequency-weighting functions are defined as analog filters in the form of a Laplace transform. The number of poles, resonance frequencies, and transfer functions are all specified by definitions. The specified filters consist of two parts: (a) a frequency-band-limiting filter, and (b) a frequency-weighting filter. The transfer functions of these filters $H(s)$, where s is the Laplace operator, are given in the Standards as described in the next sections.

The design-goal frequency weightings described below are nondimensional quantities as given in ISO 8041 and BS 6841. However, the tolerances around the design goals are specified in decibels. Tolerances are discussed in Sec. 5.

A. ISO 8041

The band-limiting filter for *x*-, *y*-, and *z*-axis whole-body vibration is defined in ISO 8041 by the following expression:

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$$H^{bl}(s) = \frac{(2\pi f_u 10^{0.1})^2}{[s^2 + \sqrt{2} 2\pi f_l 10^{-0.1}s + (2\pi f_l 10^{-0.1})^2][s^2 + \sqrt{2} 2\pi f_u 10^{0.1}s + (2\pi f_u 10^{0.1})^2]} \quad (1)$$

The frequency-weighting filter for z-axis whole-body vibration is defined from

$$H_z^{fw}(s) = \frac{0.42 + 0.045s}{1 + 0.044s + (0.03s)^2} \quad (2)$$

and the frequency-weighting filter for x- and y-axis whole-body vibration is defined from

$$H_{xy}^{fw}(s) = \frac{1 + 0.08s}{1 + 0.125s + (0.08s)^2} \quad (3)$$

In Eq. (1), f_l and f_u are the lower and upper limiting frequencies, respectively. These frequencies are specified, in hertz, by the following formulas for the exact one-third-octave midband frequencies: $f_l = 10^{0.1N_l}$ and $f_u = 10^{0.1N_u}$, where N_l and N_u are integer numbers equal to 0 and 19, respectively.

B. BS 6841

The band-limiting filter for both frequency weightings W_b and W_d is defined in BS 6841 from

$$H^{bl}(s) = \frac{4\pi^2 f_2^2 s^2}{(s^2 + (2\pi f_1/Q_1)s + 4\pi^2 f_1^2)(s^2 + (2\pi f_2/Q_1)s + 4\pi^2 f_2^2)} \quad (4)$$

The frequency-weighting W_b for z-axis whole-body vibration is defined from

$$H_b^{fw}(s) = \frac{(s + 2\pi f_3)(s^2 + (2\pi f_5/Q_3)s + 4\pi^2 f_5^2)}{(s^2 + (2\pi f_4/Q_2)s + 4\pi^2 f_4^2)(s^2 + (2\pi f_6/Q_4)s + 4\pi^2 f_6^2)} \cdot \frac{2\pi K f_4^2 f_6^2}{f_3 f_5} \quad (5)$$

and the frequency-weighting W_d for x- and y-axis whole-body vibration is defined from

$$H_d^{fw}(s) = \frac{s + 2\pi f_3}{s^2 + (2\pi f_4/Q_2)s + 4\pi^2 f_4^2} \cdot \frac{2\pi K f_4^2}{f_3} \quad (6)$$

In Eqs. (4) and (5), f_n ($n = 1$ to 6) designates a resonance frequency (or cutoff frequency) of the filter, Q_n ($n = 1$ to 4) designates a filter selectivity, and K represents a gain or amplification. For a specific frequency weighting, coefficients f_n , Q_n , and K are all constants.

For H^{bl} in Eq. (4), $f_1 = 0.4$ Hz, $f_2 = 100$ Hz, and $Q_1 = 0.71$.

For H_b^{fw} in Eq. (5), $f_3 = 16$ Hz, $f_4 = 16$ Hz, $f_5 = 2.5$ Hz, $f_6 = 4$ Hz, $Q_2 = 0.55$, $Q_3 = 0.90$, $Q_4 = 0.95$, and $K = 0.4$.

For H_d^{fw} in Eq. (6), $f_3 = 2$ Hz, $f_4 = 2$ Hz, $Q_2 = 0.63$, and $K = 1$.

Frequency weightings W_b and W_d specified in BS 6841 differ from those specified in ISO 8041. The ISO weighting for x- and y-axis vibration and the BS weighting W_d are almost identical except that the former extends to 1 Hz whereas the latter extends to 0.5 Hz. For z-axis vibration, the frequency range that has maximum sensitivity extends from about 5 to 16 Hz in the BS weighting W_b instead of 4 to 8 Hz as in the ISO weighting. For frequencies greater than 16 Hz, the BS weighting indicates greater sensitivity to acceleration (about two times greater) than the ISO weighting. Frequency weighting W_g provided in BS 6841 for z-axis vibration (not considered here) is consistent with the z-axis weighting provided in ISO 8041. However, BS 6841 recommends the use of the W_g weighting for evaluation of human exposure to vibration with respect to perfor-

mance of activities, rather than to discomfort and perception.

3. CONVERSION OF FILTERS

To simulate analog filters by software, they have to be first converted into digital filters. In filter design, the transfer function of a digital filter is usually represented in the form of a z transform $H(z)$ while the transfer function of an analog filter is represented in the form of a Laplace transform $H(s)$. The relationship between the input and output of a digital filter, in the z domain, is given by

$$Y(z) = H(z)X(z), \quad (7)$$

where $X(z)$ and $Y(z)$ are the z transforms of the input and output signals, respectively, and $H(z)$ is the z transform of the filter response.

Transfer function $H(z)$ can be expressed in the form of a rational function of two polynomials in $1/z$ as

$$H(z) = \frac{\sum_{i=0}^M b_i z^{-i}}{1 + \sum_{i=1}^N a_i z^{-i}}, \quad (8)$$

where a_i and b_i are constant coefficients, and M and N are the number of zeros and poles, respectively.

The equivalent expression for Eq. (7) in the time domain is

$$y(t_i) = \sum_{k=0}^M b_k x(t_i - k) - \sum_{j=1}^N a_j y(t_i - j), \quad (9)$$

where $x(t_i)$ and $y(t_i)$ are input and output signals, respectively, at time t_i . The design of a digital filter involves the determination of coefficients a_i and b_i , and the numbers M and N from the given analog filter. Different techniques exist for converting an analog filter transfer function $H(s)$ into a digital filter transfer $H(z)$. Both the *bilinear transformation method*⁷ with frequency pre-wrapping, and the *impulse invariant method*⁷ were used for this paper.

The frequency band-limiting filters defined by Eqs. (1) and (4) are 4-pole Butterworth bandpass filters that represent the combination of a 2-pole Butterworth lowpass filter and a 2-pole Butterworth highpass filter. The bilinear transformation method with frequency pre-wrapping, which is the most frequently used method for converting filters with constant gain in the passband, was employed for converting these filters. In this method, the z transform is obtained from the Laplace transform by applying the mapping (i.e., change of variables) indicated by

$$s = \frac{2\pi f_c}{\tan(\pi f_c T)} \frac{z-1}{z+1}, \quad (10)$$

where f_c is the cutoff frequency of the filter and T is the sampling interval in the time domain.

The frequency weighting filters defined by Eqs. (2), (3), and (6) have 2 poles, and the one by Eq. (5) has 4 poles. Because of the complicated properties in their frequency responses, these filters were converted into digital filters by the impulse invariant method. For this method, the Laplace transform of the filter is first expanded in the form

$$H(s) = \sum_{i=1}^N \frac{K_i}{s + s_i}, \quad (11)$$

where K_i is a constant, s_i is the i th pole, and N is the number of poles. The digital filters are then found from

$$H(z) = \sum_{i=1}^N \frac{K_i z}{z - e^{-s_i T}}, \quad (12)$$

where $H(z)$ is the transfer function of the filter in the z domain, and T is the sampling interval in the time domain.

4. IMPLEMENTATION IN SOFTWARE

Formulas for calculating the coefficients a_i and b_i of the time-domain digital filters were deduced by rearranging the transfer functions (in the z domain) in a form similar to that of Eq. (8), i.e., a rational function of two polynomials in $1/z$. The resulting coefficients of the polynomials, and consequently the formulas for calculating the coefficients a_i and b_i , are functions of the sampling interval T . The cumbersome task of rearranging transfer functions and deducing the formulas of filter coefficients was performed by means of the symbolic calculation software Maple V.⁸

Given the sampling interval T of a vibration signal, filter coefficients were calculated from the deduced formulas. Measured accelerations were then frequency weighted by applying Eq. (9), first passing the vibration signal through the band-limiting filter and then passing the resulting signal through the frequency-weighting filter. Because of the rise time in the response of the filters, it was usually necessary

to discard a small part at the beginning of filtered signals before a valid result was obtained. The lower the predominant frequency in the vibration signal, the longer the effect of the rise time of the filter. For the filters implemented in this paper, the rise time was about 1 s at 0.8 Hz.

For situations in which the number of samples of the vibration signal is too great to fit into available computer memory, the signal can be separated into as many time segments as necessary. Thus, there is no limitation on the duration of the input signal. However, a "save-and-add" scheme has to be applied in order to maintain correct initial conditions prior to the processing of each segment of the signal. That is, the last N points of the unfiltered segment and the last $M+1$ points of the weighted segment are saved and then added (i.e., appended) to the beginning of the next segment. This procedure ensures that distortions caused by the rise time of filters are restricted only to the initial part of the signal, rather than to each segment.

Computer code for a FORTRAN 77 subroutine for generating the coefficients of filters specified by the ISO and BS Standards is provided in the Appendix. The subroutine was incorporated into the program TOAP⁴ that is an interactive PC program for performing one-third-octave-band analyses of multi-channel vibration measurements. In the TOAP program, the user provides the following information: format of data files, numbers of channels to be analyzed, type of analysis (i.e., one-third-octave, frequency-weighted, or both), and the type of frequency weighting if specified. In addition, there are four other parameters specified by the user that dictate the manner in which the signals are processed. The first one is the segment length or integration time which is converted by the program to number of data points. The other three parameters are processing start time, number of time integration windows, and the number of initial time integration windows to be discarded. Other information such as sampling frequency, gains, and sensitivities of the instruments and recording equipment are read directly from header files created by the data-acquisition system. The TOAP program could access data files of signals acquired by several versions of commercially available software.

Data are processed one channel at a time for the specified number of integration time windows in a loop-like fashion. The first integration time window begins at the starting sample specified by the user. Each subsequent time window is read from the raw data starting at the time when the previous window ends.

After the filtering process is completed at the end of each segment, root-mean-square accelerations y_{rms} are calculated from

$$y_{rms} = \left[\left(\frac{1}{N} \right) \sum_{i=1}^N y_i^2 \right]^{1/2}, \quad (13)$$

where y_i is the frequency-weighted acceleration of the i th data sample in the segment and N is the number of data points in the segment. After all data segments have been processed, the greatest rms acceleration of all time segments is determined and then output to the screen of the monitor or to a file. The averaging process represented by Eq. (13) is linear, i.e., all data points have an equal influ-

Fig. 1 – Digital filter response and z-axis acceleration frequency weighting as defined in ISO 8041; 500-Hz sampling frequency.

ence on the result. This procedure is appropriate for continuous signals. For transient signals, however, exponential-time-weighted averaging is normally used to capture the effect of the transient features, in particular the signal's maximum value.

5. TOLERANCE VERIFICATION

Tolerances specified in ISO 8041 for frequency weightings of whole-body vibration in the x, y, or z directions are as follows:⁵ 0 dB at 8 Hz, ± 1 dB for the frequency range from 1.25 to 63 Hz, ± 2 dB for frequency ranges from 0.5

to 1 Hz and from 80 to 160 Hz, and $+2$ to $-\infty$ dB elsewhere.

In BS 6841, tolerances are specified⁶ as follows: *Within the nominal frequency bands and one-third of an octave in from the frequency limits, the tolerance of the combined frequency weighting and band limiting should be less than ± 1 dB. Outside this range the tolerance should be less than ± 2 dB. One octave outside the nominal frequency bands the attenuation may extend to infinity.*

For frequency weightings W_b and W_d for which nominal frequency bands are from 0.5 to 80 Hz and the corresponding lower and upper nominal frequency limits are 0.4 and

Fig. 2 – Digital filter response and x- and y-axis acceleration frequency weighting as defined in ISO 8041; 500-Hz sampling frequency.

Fig. 3 – Digital filter response and acceleration frequency weighting W_b as defined in BS 6841; 500-Hz sampling frequency.

100 Hz, the above requirements were interpreted as follows: For the frequency range from 0.4 to 100 Hz, the tolerance around the design-goal frequency weightings is ± 1 dB; from 0.25 to 0.4 Hz and from 100 to 160 Hz the tolerance is ± 2 dB; and elsewhere in the frequency range the tolerance is $+2$ to $-\infty$ dB.

The tolerances described above are relative to the design-goal frequency weightings given in Sec. 2. A tolerance of ± 2 dB, for example, was taken to mean that the calculated frequency weighting had to be within $10^{+2/20}$ and $10^{-2/20}$ of the theoretical design goal for the specified frequency range.

Rather than using Eq. (8) to determine the response of digital filters to verify the above tolerances, pure tone signals of unit amplitude were passed through the filters (one signal at a time). Pure tone signals were at the nominal midband frequencies of one-third-octave bands in the range from 0.1 Hz to the Nyquist frequency. The responses of digital filters obtained in this manner are compared with those specified by the ISO and British Standards in Figs. 1–4 for a sampling frequency of 500 Hz (i.e., a sampling time interval T of 2 ms and a Nyquist frequency of 250 Hz). The responses of the digital filters were in excellent agreement with those of the prototype analog filters.

Fig. 4 – Digital filter response and acceleration frequency weighting W_d as defined in BS 6841; 500-Hz sampling frequency.

Fig. 5 – Tolerances and deviation of digital filter response from z-axis acceleration frequency weighting as defined in ISO 8041.

To examine the effect of the sampling interval, tests were also performed with sampling frequencies ranging from 300 to 2000 Hz. Results of these tests are shown in Figs. 5–8 in terms of the deviation of the responses of the digital filters from those of the prototype filters. All digital filters realized for this paper closely satisfied the tolerances specified ISO 8041 and BS 6841, except for the 2000-Hz sampling frequency. Also, there were some minor deviations in the case of BS 6841 frequency weighting W_b as noted in the next section.

6. DISCUSSION

Theoretically, the greater the sampling rate, the smaller the error between a digital filter and its analog prototype. However, care must be taken in practice when the sampling rate is very high. More accurate results do not necessarily follow with greater sampling rates. The deviation of the responses of the digital filters implemented for this paper from those of their prototype analog counterparts is shown in Figs. 5–8 for various sampling rates. From these figures,

Fig. 6 – Tolerances and deviation of digital filter response from x and y-axis acceleration frequency weighting as defined in ISO 8041.

Fig. 7 – Tolerances and deviation of digital filter response from acceleration frequency weighting W_b as defined in BS 6841.

it can be seen that results obtained with a sampling rate of 2000 Hz were not as good as the results obtained at lower sampling rates. The effect of the sampling rate is believed to be caused by an accumulated numerical error resulting from the finite length of binary words in the computer.

Calculations reported in this paper were performed in double-precision floating-point arithmetic using an IBM-compatible personal computer with an Intel 486DX microprocessor and the Microsoft FORTRAN compiler version 5.1. Further tests showed that the sampling frequency effect appeared, for the case of the filters implemented here, when the sampling rate was greater than 1200 Hz. The response of the filters, however, stayed within the tolerances for

sampling rates up to 1500 Hz. The above numerical error is hardly a limitation for the digital filters implemented here as a sampling rate of 1000 Hz is most likely the greatest rate to be used in practice. If vibration signals are acquired at sampling rates greater than 1000 Hz, accuracy can be improved by decimating the digital signals, e.g., by halving the sampling rate. Before decimation, however, the signals must be digitally lowpass filtered to prevent frequency aliasing.

Some difficulty was encountered in meeting the low-frequency tolerances for frequency weighting W_b of BS 6841 for sampling rates equal to or less than 600 Hz. The errors at frequencies less than 1.6 Hz for a sampling rate of

Fig. 8 – Tolerances and deviation of digital filter response from acceleration frequency weighting W_d as defined in BS 6841.

600 Hz were slightly larger than 1 dB. This error made the filter exceed the ± 1 dB tolerances in the frequency range from 0.4 to 1.6 Hz. If predominant frequencies of vibration fall in this range, the tolerances of BS 6841 in this range could be fulfilled, if necessary, by applying a factor of 0.905 to the filter response. This factor decreases the positive errors at low frequencies and shifts the errors in the middle frequency range to negative. If the above adjustment was applied, the response of the digital filter up to 80 Hz satisfied the tolerances even for sampling frequencies as low as 300 Hz. Deviation from the specified tolerances for frequencies greater than 80 Hz was considered to be inconsequential as significant vibrations at these frequencies are unlikely to be encountered in buildings.

Finally, when the Q_1 selectivity of 0.71 in Eq. (1) was used as specified in BS 6841 for the band-limiting filter, it was not possible to obtain the exact values of the frequency weightings as they were listed in the British Standard. The frequency weightings were obtained, however, when a

value of 0.707 was used for Q_1 . This suggested that it would have been better if additional significant digits had been provided in BS 6841 to specify the selectivities, resonance frequencies, and constant gains.

7. CONCLUSIONS

Prototype frequency-weighting functions specified by the ISO 8041 and BS 6841 Standards for evaluation of the annoyance response to building vibrations were successfully simulated as time-domain digital filters. The digital filters satisfied the tolerances specified in the International and British Standards with minor exceptions. Situations in which the tolerances were exceeded occurred when the sampling frequency was greater than 1500 Hz or when the sampling frequency was less than 600 Hz in the case of the W_b weighting of BS 6841. Simple remedies were suggested to ensure that the digital filters satisfy the specified tolerances for those situations.

8. APPENDIX

Disclaimer of Warranty

The National Research Council of Canada and the Institute of Noise Control Engineering make no warranties, expressed or implied, that this computer code is free of error, or is consistent with the ISO 8041:1990 and BS 6841:1987 Standards or any other Standard, or that it will meet the user's requirements for any application. The user should not rely on this computer code for solving problems for which incorrect solutions could result in injury to a person or loss of property. If the user does use this computer code in such a manner, it is at his or her own risk. The National Research Council of Canada, the authors of this paper, and the Institute of Noise Control Engineering disclaim all liability for direct or consequential damages resulting from the use of this computer code.

```

c      The following FORTRAN computer code was written by Wei Guan.
c      Subroutine HUMANCDEF(iwtype,fs,ibpfiw,coefa,coefb,m,n)
c      Generates the coefficients of time-domain digital filters (Eq. 9) for band-limiting and frequency-weighting of
c      acceleration signals as per ISO 8041:1990 and BS 6841:1987.
c      input parameters:
c      iwtype = weighting type
c              = 2 (weighting  $W_b$ , BS 6841)
c              = 4 (weighting  $W_d$ , BS 6841)
c              = 11 (weighting for x- and y-axis vibration, ISO 8041)
c              = 12 (weighting for z-axis vibration, ISO 8041)
c      fs = sampling frequency in hertz
c      ibpfiw = filter type (band-limiting or frequency-weighting)
c              = 1 (band-limiting filter)
c              = 2 (frequency-weighting filter)
c
c      output parameters:
c      m = number of zeros
c      n = number of poles
c      coefa = array containing  $a_i$  coefficients ( $i = 1$  to  $n$ )
c      coefb = array containing  $b_i$  coefficients ( $i = 0$  to  $m$ )
c
c      .....
c      integer*2 iwtype, ibpfiw, n, m
c      real*4 coefa(1:4), coefb(0:4)
c      real*4 fs
c      real*8 PI
c      parameter (PI=3.1415926)
c      real*8 u1,u2,u3,u4,u5,u6,u7,u8,u9,u10,u11,u12, a0
c      real*8 v1,v2,v3,ve91,ve13,ve182,ve26
c      real*8 w1,w2,w3,w4,w5,w6,w7,w8,w9,w10,w11,w12,w13,w14,w15,w16
c      real*8 w1413,w76,w21,w22,w23,w24

```

```

real*8 g0dB, ag, g8HzA, g8HzD
c
if (ibpfw.eq.1) then
c
    if (iwttype.eq.2.or.iwttype.eq.4) then
c .....
c Coefficients of band-limiting filter of BS 6841, Eq. (4)
c .....
n = 4
m = 4
v1 = tan(100*PI/fs)
u1 = tan(100*PI/fs)
u2 = tan(0.4*PI/fs)
a0 = 0.4946781854*(u2*u1) +
+ 0.3512215116*(u1 + u2 + u2*u1*u1 + u2*u2*u1) +
+ 0.2493672732*(u2*u2 + u1*u1 + u2*u2*u1*u1 + 1)
coefb(0) = 0.2493672732 * v1 * v1 / a0
coefb(1) = 0.0
coefb(2) = -0.4987345464 * v1 * v1 / a0
coefb(3) = 0.0
coefb(4) = 0.2493672732 * v1 * v1 / a0
coefa(1) = ( 0.001e-7*(u2*u2) - 0.002e-7*(u1*u1) +
+ 0.9974690931*(u2*u2*u1*u1 - 1) +
+ 0.7024430232*(u2*u1*u1 - u2 - u1 +
+ u2*u2*u1)) / a0
coefa(2) = ( -0.4987345464*(u2*u2 + u1*u1) +
+ 1.496203640*(u2*u2*u1*u1 + 1) -
+ 0.9893563708*(u2*u1)) / a0
coefa(3) = ( 0.001e-7*(u2*u2) - 0.002e-7*(u1*u1) +
+ 0.9974690931*(u2*u2*u1*u1 - 1) -
+ 0.7024430232*(u2*u1*u1 - u2 - u1 +
+ u2*u2*u1)) / a0
coefa(4) = ( 0.4946781854*(u2*u1) -
+ 0.3512215116*(u1+u2 + u2*u1*u1 + u2*u2*u1) +
+ 0.2493672732*(u2*u2 + u1*u1 +
+ u2*u2*u1*u1+1)) / a0
else if (iwttype.eq.11.or.iwttype.eq.12) then
c .....
c Coefficients of band-limiting filter of ISO 8031, Eq. (1)
c .....
n = 4
m = 4
v1 = tan(100.0*PI/fs)
u1 = tan(2.49536704474637/fs)
u2 = tan(100.0*PI/fs)
a0 = 0.983305794766386*(u2*u2 + u1*u1*u2*u2 + u1*u1 + 1) +
+ 1.390604390918679*(u1*u1*u2 + u1*u2*u2 + u1 + u2) +
+ 1.966611589532773*(u1*u2)
coefb(0) = 0.983305794766386 * v1 * v1 / a0
coefb(1) = 0.0
coefb(2) = -1.966611589532773 * v1 * v1 / a0
coefb(3) = 0.0
coefb(4) = 0.983305794766386 * v1 * v1 / a0
coefa(1) = ( 2.781208781837358*(u1+u2)*(-1+u1*u2) +
+ 3.933223179065546*(-1+(u1*u2)*(u1*u2))) / a0
coefa(2) = ( -1.966611589532773*(u2*u2 + u1*u1) +
+ 5.899834768598319*(u2*u2*u1*u1 + 1) -
+ 3.933223179065546*(u2*u1)) / a0
coefa(3) = ( 2.781208781837358*(u1+u2)*(1-u1*u2) +
+ 3.933223179065546*(-1+(u1*u2)*(u1*u2))) / a0
coefa(4) = ( 1.96661158953277*u1*u2 +
+ 0.983305794766386
+ (1 + u2*u2 + u1*u1*u2*u2 + u1*u1) -

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+         1.390604390918679*
+         (u1*u1*u2 + u1*u2*u2 + u1 + u2)) / a0
    else
        write(*,'(a)') 'wrong code for weighting type !'
    end if
else if (ibpfw.eq.2) then
c
    if (iwtype.eq.2) then
c
c         .....
c         Coefficients of frequency-weighting filter  $W_b$  of BS 6841, Eq. (5)
c         .....
        n = 4
        m = 3
        w1 = sinh(13.22775854/fs)
        w2 = cos(21.37009794/fs)
        w3 = sin(56.67646735/fs)
        w4 = cosh(13.22775854/fs)
        w5 = cos(56.67646735/fs)
        w6 = -2.0*w5*w3 + 2.0*w3*w2*w4 - 2.0*w3*w2*w1
        w7 = w5*w5 - w3*w3 - 2.0*w5*w2*w4 + 2.0*w5*w2*w1 +
+         cosh(26.45551708/fs) - sinh(26.45551708/fs)
        w8 = sin(21.37009794/fs)
        w9 = 0.1026812916e9*(w5 + w2*w1 - w2*w4) +
+         0.2165387003e9*(w8*w4 - w8*w1)
        w10 = sinh(91.39178632/fs)
        w11 = cos(41.88097775/fs)
        w12 = cosh(91.39178632/fs)
        w13 = -2.0*w5*w3 + 2.0*w3*w11*w12 - 2.0*w3*w11*w10
        w14 = w5*w5 - w3*w3 - 2.0*w5*w11*w12 + 2.0*w5*w11*w10 +
+         cosh(182.7835726/fs) - sinh(182.7835726/fs)
        w15 = sin(41.88097775/fs)
        w16 = 0.2966362766e10*(-w5 + w11*w12 - w11*w10) +
+         0.601151618e9*(w15*w10 - w15*w12)
        w1413 = w14*w14 + w13*w13
        w76 = w7*w7 + w6*w6
        w21 = 0.3722926540e-7
        w22 = 0.7296167000e-7
        w23 = 0.2966362766e10
        w24 = 0.1026812916e9
        g0dB = sqrt(
+         (-w21*w5*(w16*w14/w1413 + w23*w3*w13/w1413)
+         -w21*w3*(-w16*w13/w1413 + w23*w3*w14/w1413)
+         -w22*w5*(w9*w7/w76 - w24*w3*w6/w76)
+         -w22*w3*(-w9*w6/w76 - w24*w3*w7/w76))**2 +
+         (-w21*w5*(-w16*w13/w1413 + w23*w3*w14/w1413)
+         +w21*w3*(w16*w14/w1413 + w23*w3*w13/w1413)
+         -w22*w5*(-w9*w6/w76 - w24*w3*w7/w76)
+         -w22*w3*(w9*w7/w76 - w24*w3*w6/w76))**2)
        v1 = cos(41.88097775/fs)
        v2 = cos(21.37009794/fs)
        ve91 = exp(-91.39178632/fs)
        ve13 = exp(-13.22775854/fs)
        ve182 = exp(-182.7835726/fs)
        ve26 = exp(-26.45551708/fs)
        coefa(1) = -2.0*v1*ve91 - 2.0*v2*ve13
        coefa(2) = ve182 + (-2.0*v1*ve91)*(-2.0*v2*ve13) + ve26
        coefa(3) = ve182 * (-2.0*v2*ve13) - 2.0*v1*ve91 * ve26
        coefa(4) = ve182 * ve26
        u1 = sinh(182.7835726/fs)
        u2 = sinh(13.22775854/fs)
        u3 = sin(21.37009794/fs)
        u4 = cosh(13.22775854/fs)
        u5 = cos(21.37009794/fs)

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u6 = sinh(26.45551708/fs)
u7 = cosh(91.39178632/fs)
u8 = cos(41.88097775/fs)
u9 = cosh(26.45551708/fs)
u10 = cosh(182.7835726/fs)
u11 = sin(41.88097775/fs)
u12 = sinh(91.39178632/fs)
coefb(0) = 102.9437082
coefb(1) = -15.79902519*u3*u4 + 15.79902519*u3*u2 -
+ 213.3792149*u5*u4 - 22.38043313*u11*u12 -
+ 95.45190967*u8*u7 + 22.38043313*u11*u7 +
+ 213.3792149*u5*u2 + 95.45190967*u8*u12
coefb(2) = 44.76086626*u11*u12*u5*u4 -
+ 44.76086626*u11*u12*u5*u2 -
+ 110.4355067*u6 - 31.59805039*u3*u4*u8*u12 +
+ 7.491798513*u1 - 44.76086626*u11*u7*u5*u4 +
+ 31.59805039*u3*u4*u8*u7 + 110.4355067*u9 -
+ 31.59805039*u3*u2*u8*u7 -
+ 205.8874164*u8*u12*u5*(u4-u2) +
+ 44.76086626*u11*u7*u5*u2 - 7.491798513*u10 +
+ 31.59805039*u3*u2*u8*u12 +
+ 205.8874164*u8*u7*u5*(u4-u2)
coefb(3) = 7.491798513*u5*u4*(u10-u1) +
+ 110.4355067*u8*u12*(u9-u6) -
+ 22.38043313*u11*u12*(u9-u6) +
+ 22.38043313*u11*u7*(u9-u6) -
+ 7.491798513*u5*u2*(u10-u1) -
+ 15.79902519*u3*u4*(u10-u1) +
+ 15.79902519*u3*u2*(u10-u1) -
+ 110.4355067*u8*u7*(u9-u6)
coefb(0) = coefb(0) / g0dB
coefb(1) = coefb(1) / g0dB
coefb(2) = coefb(2) / g0dB
coefb(3) = coefb(3) / g0dB
else if (iwtype.eq.4) then
c .....
c Coefficients of frequency-weighting filter  $W_d$  of BS 6841, Eq. (6)
c .....
n = 2
m = 1
v1 = exp(-9.973310011/fs)
v2 = cos(7.645047930/fs)
v3 = sin(7.645047930/fs)
u1 = exp(-19.94662002/fs)
a0 = 1.0
w1 = sin(8.710531638/fs)
w2 = cos(8.710531638/fs)
w3 = cos(7.645047930/fs)
w4 = exp(-9.973310011/fs)
w5 = -2.0*w1*w4*w3 + 2.0*w2*w1
+ w6 = -2.0*w2*w4*w3 + w2*w2 - 1.0*w1*w1 +
+ exp(-19.94662002/fs)
w7 = sin(7.645047930/fs)
w8 = w6*w6 + w5*w5
w9 = 20.0*(-0.628318531*w4*w3 + 0.628318531*w2 +
+ 0.213114168*w7*w4)
g0dB = sqrt( (w9*(w2*w6+w1*w5)/w8 -
+ 12.56637062*w1*(-w2*w5+w1*w6)/w8)**2 +
+ (w9*(-w2*w5+w1*w6)/w8 +
+ 12.56637062*w1*(w2*w6+w1*w5)/w8)**2)
ag = a0 * g0dB
coefb(0) = 12.56637062 / ag
coefb(1) = (-12.56637062*v1*v2 + 4.262283360*v3*v1) / ag

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coefa(1) = -2.0*v1*v2 / a0
coefa(2) = u1 / a0
else if (iwtype.eq.11) then
c .....
c Coeff. of x and y-axis frequency-weighting filter, ISO 8041, Eq. (3)
c .....
n = 2
m = 1
a0 = 1.0
w1 = 49.9073408949275/fs
w2 = 7.80272826384304/fs
w3 = exp(-9.765625/fs)
w4 = -2.0*sin(w1)*w3*cos(w2) + 2.0*cos(w1)*sin(w1)
w5 = -2.0*cos(w1)*w3*cos(w2) + 2.0*cos(w1)*cos(w1) - 1.0
+   + exp(-19.53125/fs)
w6 = -125.0*w3*cos(w2) + 125.0*cos(w1)
+   + 43.8047902531539*sin(w2)*w3
g8HzD = 0.1 * sqrt(
+   ( (cos(w1)*w6 - 125.0*sin(w1)*sin(w1))*w5 +
+     (sin(w1)*w6 + 125.0*cos(w1)*sin(w1))*w4)**2 +
+   ( (sin(w1)*w6 + 125.0*cos(w1)*sin(w1))*w5 -
+     (cos(w1)*w6 - 125.0*sin(w1)*sin(w1))*w4)**2)
g8HzD = g8HzD / (w5*w5 + w4*w4)
g8HzA = 0.254212224196366
ag = (g8HzA / g8HzD) / a0
coefb(0) = ag * 12.5
coefb(1) = ag * (-12.5*exp(-9.765625/fs)*
+   cos(7.80272826384304/fs) +
+   4.38047902531539*exp(-9.765625/fs)*
+   sin(7.80272826384304/fs))
coefa(1) = -2.0 * exp(-9.765625/fs)*
+   cos(7.80272826384304/fs) / a0
coefa(2) = exp(-19.53125/fs) / a0
c .....
c else if (iwtype.eq.12) then
c .....
c Coeff. of z-axis frequency-weighting filter, ISO 8041, Eq. (2)
c .....
n = 2
m = 1
a0 = 1.0
w1 = 49.9073408949275/fs
w2 = exp(-24.44444444444444/fs)
w3 = 22.6623089493013/fs
w4 = -2.0*sin(w1)*w2*cos(w3) + 2.0*cos(w1)*sin(w1)
w5 = -2.0*cos(w1)*w2*cos(w3) + 2.0*cos(w1)*cos(w1) - 1.0
+   + exp(-48.88888888888889/fs)
w6 = -250.0*w2*cos(w3) + 250.0*cos(w1)
+   - 166.698714867456*sin(w3)*w2
g8HzD = 0.2 * sqrt(
+   ( (cos(w1)*w6 - 250.0*sin(w1)*sin(w1))*w5 +
+     (sin(w1)*w6 + 250.0*cos(w1)*sin(w1))*w4)**2 +
+   ( (sin(w1)*w6 + 250.0*cos(w1)*sin(w1))*w5 -
+     (cos(w1)*w6 - 250.0*sin(w1)*sin(w1))*w4)**2)
g8HzD = g8HzD / (w5*w5 + w4*w4)
g8HzA = 0.905633362802681
ag = (g8HzA / g8HzD) / a0
coefb(0) = ag * 50.0
coefb(1) = ag * (-33.3397429734913*
+   exp(-24.44444444444444/fs)*
+   sin(22.6623089493013/fs) -
+   50.0 * exp(-24.44444444444444/fs)*
+   cos(22.6623089493013/fs))

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```

+      coefa(1) = -2.0 * exp(-24.444444444444/fs)*
        cos(22.6623089493013/fs) / a0
c      coefa(2) = exp(-48.8888888888889/fs) / a0
      else
      write(*, '(a)') 'wrong code for weighting type'
      end if
      end if
      return
    end
  c

```

9. REFERENCES

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