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# ISSUES IN WEIGHTING FUNCTIONS FOR THE ASSESSMENT OF EXPOSED WHOLE-BODY VIBRATION

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## Introduction

At the onset of the project that aims to develop the analysis software related to exposured whole-body vibration, it has become apparent that assessed exposure vibration levels, i.e. the vibration dose value (VDV) or the time to 15 VDV etc., can be different for a recorded vibration signal. Such difference is found to arise from the choice of different phase responses, i.e. the 'zero phase', 'linear' , or 'finite pole-zeros' phase models, for each frequency weighting function corresponding to each measurement axis. To examine this issue, an FFT-based filtering technique is used in this paper, which plays a key role in estimating frequency weighted time series. Assessed results of the whole-body vibrations exposed from the body contact area are presented. Finally, the preference of phase characteristics surveyed from Korean automotive engineers is briefly introduced.

## FFT-Based Frequency Weighting Scheme

A precision vibration measurement system, similar to the Griffin model[1], is considered, which enables us to measure 12 vibration signals at the body contact area, i.e. the back, hip and feet of the body, as shown in Fig. 1. The first difficulty in assessing those exposed whole-body vibrations arises from the fact that 12-axis raw vibration signal levels monitored from accelerometers are not directly related to the human perception-based, subjective quantity. This aspect is not well recognised in the automotive fields, but previous results by the Griffin's group[1] for last three decades reveal that 'equi-perceptive' vibration level to human body is different for each measurement axis of the body contact area and, furthermore, its frequency components. The frequency dependence, referred to the frequency weighting function, and the relative significance of each measurement axis, referred to the measurement axis multiplying factor, are comprehensively listed in the standard code of BS 6841 (1987). In the standard, six kinds of finite pole-zero models in the Laplace domain and their linearly asymptotic approximations over the segmented frequency ranges are proposed. The pole-zero models present the amplitude and phase responses, i.e., $W_k(f) = |W_k(f)| \cdot e^{j\theta_k(f)}$ (k = b, ... , g), as shown in Fig. 2. But, the asymptotic approximations specify only their amplitude responses, i.e. $|W_k(f)|$, without any comment on the phase characteristics.

To obtain frequency weighted acceleration signals, the choice of their practical implementation schemes is inevitable. Let $\{x_n, n = 0, 1, \cdots, N-1\}$ be the time series of sampled signals and $\{X(i), i = 0, 1, \cdots, N-1\}$ the discrete Fourier transform of $\{x_n\}$. Then, the weighted vibration signal $X_{w,k}(i)$ in the frequency domain becomes $X_{w,k}(i) = W_k(i) \cdot X(i)$. By letting either $W_k(f) = |W_k(f)| \cdot e^{j\theta_k(f)}$ or $W_k(f) = |W_k(f)|$, one of the two possible weighting models can be selected. A time domain, weighted signal $\{x_{w,n}\}$ is readily obtained by implementing the discrete inverse Fourier transform of $X_{w,k}(i)$. As well known in digital signal processing[2], the forward and inverse Fourier transforms can be very efficiently implemented using the FFT algorithm. This FFT-based filtering scheme is chosen in this work. A size of record length N is chosen as a large value of $N = 2^{18}$ to $2^{22}$ that is enough to cover a full record length. According to authors' experience, the FFT-based scheme is felt to be much compact in the code size and more faster than the digital filter-based computation scheme in the personal computer with the memory size of 32 Mbytes.

## Simulation Results and Discussions

As introduced above, any choice of possible phase responses, such as zero phase, linear phase or designer chosen types, can be made by choosing the adequate description of phase function $\theta(f)$. This work considers the identical amplitude response to the finite pole-zero weighting functions proposed in BS 6841, but two different phase responses are different: the standard phase model, $W_k(f) = |W_k(f)| \cdot e^{j\theta(f)}$, and the zero-phase, $W_k(f) = |W_k(f)|$. To examine their effects on the assessed values of whole-body vibration signals, a square wave of periodicity T, which may be observed from the elevator moving up and down at the constant acceleration, is considered

$$a(t) = \begin{cases} 2.5\ \text{m/s}^2 & \text{for } n \cdot T \le t < n \cdot T + 0.5T \\ -2.5\ \text{m/s}^2 & \text{for } n \cdot T + 0.5T \le t < (n+1) \cdot T. \end{cases}$$

This acceleration signal is assumed to be exposed in the direction of each measurement axis. Its frequency weighted time signal is obtained by the FFT-based filtering scheme introduced in the previous section. Table 1 shows the assessed vibration values for each measurement axis, whose computation was made according to the definitions[1].

The vibration severity, which is normally defined by the root mean squared value $V_{rms}$, is shown to be identical each other. As expected, the difference in the phase response does not affect its signal power due to the same amplitude response. Thus, the estimated vibration dose values $V_{EVDV}$ that is computed only from the rms value are also identical. But, all the peak vibration levels $V_{peak}$ for the non-zero phase weighting function are shown be larger than those for the zero phase model. This trend is also observed from the crest factors $V_{cf}$. Furthermore, the vibration dose values $V_{DVD}$ for both cases, which are estimated for the total measuring time interval, are shown to be more noticeable difference in their comparison. The time the vibration dose value reaches to the upper limit of normal activity ($V_{DVD}$ =15 m/s$^{1.75}$), denoted by $T_{15}$, becomes shorter.

In practice, Korean automotive engineers are very sensitive to such difference observed from these simulation results, and, moreover, do not try to give much confidence to the results if any improvement of fundamental causes to those effects is not made. A majority of Korean automotive engineers are felt to prefer the zero-phase weighting function models that are described by the asymptotically linearised approximations. It is the reason that the zero-phase models do not cause any more rapidly rising or falling peaks than the model with the non-zero phase responses and, furthermore, those phase responses do not consider obvious human effects. A common comment of Korean automotive engineers is related to the significance of human perception-based phase responses in vibration reduction since fundamentals in vibration reduction come from the understanding of phase information rather than its amplitude.

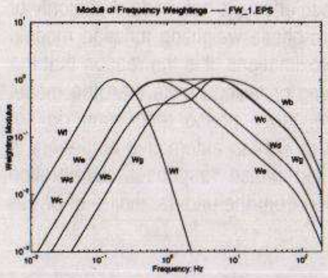
## Concluding Remarks

This paper addresses the issues encountered in assessing exposed whole-body vibration in a perception-based, subjective way. They are shown to arise from the choice of the frequency weighting functions, more specifically from their phase responses. Simulation results reveal that the zero phase weight function yields the less assessment values, that is the less crest factor, the less vibration dose value and the longer time to 15 VDV, in comparison to those of the finite pole-zero models proposed in BS 6841. Those results should be very sensitive to Korean automotive engineers. They prefer the zero-phase weighting function models that do not cause any more rapidly rising or falling peaks. Furthermore, they are emphasising the significance of the perception-based phase response that is not well understood. Finally, the authors are very regretful that due to the protection agreement of industrial cofidentials any experimental results that were made only for a new car under development is not presented in this paper. But, another experiment, which is independent of the agreement, is progress now so that its results will be presented in the conference session.

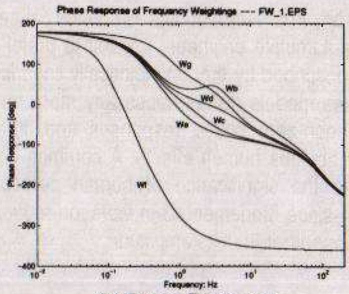
## References

[1] M.J. Griffin, Handbook of Human Vibration (Academic Press, London, 1990)
[2] J.K. Hammond, Lecture Notes on Time Series Analysis (ISVR, England, 1991)

Fig. 1. 12-axis whole-body vibration measurement system




(a) Magnitude Response




(b) Phase Response

Fig.2. Frequency Characteristics of weighting functions proposed in BS 6841..

Table 1. Assessment results for 9 measurement axes.

(a) The case of zero-Phase filter response

| Position | Axis | Weighting Function | $V_{rms}$ $m \cdot s^{-2}$ | $V_{rmq}$ $m \cdot s^{-2}$ | $V_{cf}$ | $V_{FVDV}$ $m \cdot s^{-1.75}$ | $V_{FDV}$ $m \cdot s^{-1.75}$ | $T_{15}$ s |
|---|---|---|---|---|---|---|---|---|
| Seat | $s_x, s_y$ | Wd × 1.0 | 4.67 | 5.33 | 1.14 | 15.63 | 11.57 | 93 |
| | $s_z$ | Wb × 1.0 | 2.40 | 4.36 | 1.82 | 8.03 | 6.55 | 901 |
| Back | $b_x$ | Wc × 0.8 | 3.89 | 4.22 | 1.09 | 13.01 | 9.39 | 214 |
| | $b_y$ | Wd × 0.5 | 2.33 | 2.66 | 1.14 | 7.82 | 5.78 | 1,481 |
| | $b_z$ | Wd × 0.4 | 1.87 | 2.13 | 1.14 | 6.25 | 4.63 | 3,618 |
| Foot | $f_x, f_y$ | Wb × 0.25 | 0.60 | 1.09 | 1.82 | 2.01 | 1.64 | 230,530 |
| | $f_z$ | Wb × 0.4 | 0.96 | 1.74 | 1.82 | 3.21 | 2.62 | 35,176 |

(b) The finite pole-zero based-filter model recommended in BS 6841

| Position | Axis | Weighting Function | $V_{rms}$ $m \cdot s^{-2}$ | $V_{rmq}$ $m \cdot s^{-2}$ | $V_{cf}$ | $V_{FVDV}$ $m \cdot s^{-1.75}$ | $V_{FDV}$ $m \cdot s^{-1.75}$ | $T_{15}$ s |
|---|---|---|---|---|---|---|---|---|
| Seat | $s_x, s_y$ | Wd × 1.0 | 4.67 | 7.23 | 1.55 | 15.63 | 12.68 | 64 |
| | $s_z$ | Wb × 1.0 | 2.40 | 7.79 | 3.25 | 8.03 | 8.97 | 256 |
| Back | $b_x$ | Wc × 0.8 | 3.89 | 7.31 | 1.88 | 13.01 | 11.14 | 108 |
| | $b_y$ | Wd × 0.5 | 2.89 | 3.16 | 1.55 | 7.82 | 6.34 | 1,025 |
| | $b_z$ | Wd × 0.4 | 1.87 | 2.89 | 1.55 | 6.25 | 5.07 | 2,505 |
| Foot | $f_x, f_y$ | Wb × 0.25 | 0.60 | 1.95 | 5.25 | 2.01 | 2.24 | 65,646 |
| | $f_z$ | Wb × 0.4 | 0.96 | 3.12 | 3.25 | 3.21 | 3.59 | 10,017 |