中國機械工程學刊第四十一卷第四期第 493~501 頁(民國一百零九年)
Journal of the Chinese Society of Mechanical Engineers, Vol.41, No.4, pp 493~501 (2020)

# Quasi-Apparent Mass of Vertical Whole-Body Shock-Type Vibrations

Jun-Woo Lee*, Dong-Jun Park*, Weui-Bong Jeong** and Se-Jin Ahn***

**Keywords**： shock-type vibration, whole-body vibration, biodynamic response, Quasi-apparent mass; discomfort

## ABSTRACT

The apparent mass of a seated body exposed to vertical whole-body vibrations can be used to develop equivalent mathematical models and anthropodynamic dummies to predict and measure seat transmissibility. This experimental study investigated the biodynamic responses of 15 subjects exposed to a shock-type vibration of varying conditions. The shock-type waveforms were produced by using the response of a one-degree-of-freedom model to a half-sine force input. Shock-types according to the vibration magnitudes and decay rates were presented for each input-force frequency. “Quasi-apparent mass” defined as a biodynamic response to shock-type vibration in this study was calculated from the acceleration and force measured at the rigid seat. The results revealed significant effects of magnitude and decay rate as well as frequency of the shock-type vibration on the quasi-apparent mass, which was nonlinear as shown at the previous studies with steady state vibration input. It was found that the peak frequency of the quasi-apparent masses was between 4 and 6 Hz, and their magnitude at the peak frequency decreased with increasing decay rate.

## INTRODUCTION

The apparent mass of a body measured during a whole-body vibration provides information on human biodynamic responses and has been useful for the development of analytical models of the human body (Boileau and Rakheja, 1998). The apparent mass also provides the basis for understanding the dynamic interaction between the human body and seating. To determine the apparent mass of the body, human subjects have been exposed to various types of vibrations such as discrete sine, random, swept sine, and simulated vehicle motion, and in many studies, it was assumed that the response of the body is linear (Griffin, 1990). Idealized values for the biodynamic responses (apparent mass, mechanical impedance, and transmissibility) of a body exposed to vertical vibrations have been proposed in ISO/DIS-5982 (2000). However, some researches have demonstrated that the dynamic responses of the body are nonlinear and depend on the magnitude and waveform, as well as the frequency, of the motion input.

Most previous studies in which vibration magnitude was used as a major variable have shown nonlinearity in the body’s response (apparent mass or transmissibility) during exposure to a whole-body vertical vibration (Fairey and Griffin, 1989; Mansfield and Griffin, 2000; Matsumoto and Griffin, 2002; Rakheja et al., 2002). In these studies, the peak frequency of the body’s response was found to decrease with increasing magnitude of vibration, which means there was a “softening” of the body when the vibration magnitude increased. When Fairley and Griffin (1989) exposed eight subjects to random vibrations with four different magnitudes, the peak frequency of the apparent mass was found to decrease from 6 to 4 Hz when the vibration magnitude increased from 0.25 to 2.0 ms-2 rms. Mansfield and Griffin (2000) have also shown that the peak frequency of the apparent mass decreased from 5.4 to 4.2 Hz as the magnitude of vibration increased from 0.25 to 2.5 ms-2 rms. In a study using random vibrations in the range from 0.125 to 2.0 ms-2 rms at a frequency of 0.2 to 20 Hz, the peak frequency (6.4 to 4.75 Hz) of the apparent mass decreased when the vibration magnitude (0.25 to 2.0 ms-2 rms) increased (Matsumoto and Griffin, 2002). The research also showed that magnitude at the peak of the apparent mass does not significantly depend on the vibration magnitude. Matsumoto and Griffin (2005) employed transient (one-and-half cycle

*Paper Received February 2020. Revised May, 2020. Accepted May, 2020. Author for Correspondence: Se-Jin Ahn.*

* *Ph. D. Candidate, Department of Mechanical Engineering, Pusan National University, Busan 46241, Republic of Korea.*

** *Professor, Department of Mechanical Engineering, Pusan National University, Busan 46241, Republic of Korea.*

*** *Professor, Division of Energy & Electric Engineering, Uiduk University, Gyeongju 38004, Republic of Korea.*

sinusoidal waveform) as well as sinusoidal continuous vibrations to investigate whether the effect of magnitude causes nonlinearity in the subjective and biodynamic responses to the vibration. Magnitude effect of the stimuli happened such that the biodynamic responses were nonlinearly changed even at the same frequency of the transient and sinusoidal vibrations. The study showed that the larger the vibration magnitude, the smaller was the apparent mass. Howarth and Griffin (1991) found no large difference in the subjective response to upward and downward shocks having a nominal frequency of 1, 4, or 16 Hz.8 Ahn and Griffin (2008) and Ahn (2010), using transient shock-type vibration, found that the subjective discomfort of the shock-type vibration is significantly changed due to difference of its magnitude, decay rate (duration), and direction. Based on the results described above, the biodynamic response, such as apparent mass, to the transient shock-type vibrations requires further consideration in terms of relationship between the human response and the physical parameters of the shock-type vibration.

In this study, it was hypothesized that the biodynamic response to the transient shock-type vibration would show a similar nonlinearity as shown at the previous studies employing steady-state vibration, such as sinusoidal and random vibration. Main objective of this study was to measure the dynamic response of human body exposed to the shock-type vibrations, and also to determine how it depends on the frequency, waveform, and magnitude of the shocks. Although spectral analysis method is generally used to determine the biodynamic response (eg. apparent mass), in this study, the discrete frequency method was applied to calculate the biodynamic response owing to the characteristics of the shock-type signal which has only one single major peak at a frequency (Griffin, 1990).

## METHOD

### Shock-type Vibrations

Shock vibrations are experienced when a driving vehicle is excited by an impulsive input such as a bump on the road. The mechanical system (tires, suspension system, and seat cushion) of the vehicle modifies the shock response in some way while transferring from the bump to the occupant on its seat. In this study, the bump input was represented by a Hanning-windowed half-sine input force and the shock-type vibrations were generated by the response of a one-degree-of-freedom model having mass, stiffness and damping to the half-sign input (Figure 1). Then the shock-type vibration can be described as an actual vibration on a vehicle with no discontinuity in time domain. The Hanning-windowed half-sine input is expressed theoretically as

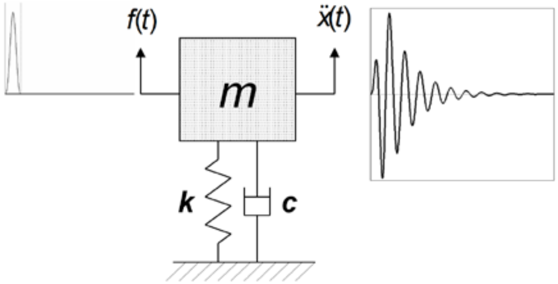



Fig. 1. One degree-of-freedom vibration model to generate shock-type acceleration signals.

$$H(t) = A\sin\left(\pi \frac{t}{t_0}\right) \times \frac{1}{2}\left[1 - \cos\left(2\pi \frac{t}{t_0}\right)\right] \qquad 0 \le t \le t_0$$
$$H(t) = 0 \qquad \text{otherwise} \qquad (1)$$

where A and t_0are the amplitude and duration of the half-sine input, respectively. The duration of the half-sine is related to main frequency of the shock-type vibration. The mass, stiffness, and damping of the one-degree-of-freedom model, as well as the duration and amplitude of the half-sine force input, were controlled to produce various kinds of shock-type waveforms having different fundamental frequencies, magnitudes, and durations. The vibration model's shock response to an impulsive input was numerically calculated by the fourth-order Runge–Kutta method (Chapra, 2006).
Shock-type signals with 16 fundamental frequencies, at the preferred one-third octave center frequencies from 0.5 to 16.0 Hz, were produced by the process described above. At each fundamental frequency, the wave of the shock signal were formed to have five magnitudes at an unweighted vibration dose values from 0.35 to 2.89 $ms^{-1.75}$ (i.e., 1.7-2, 1.7-1, 1.0, 1.7, and 1.72 $ms^{-1.75}$).

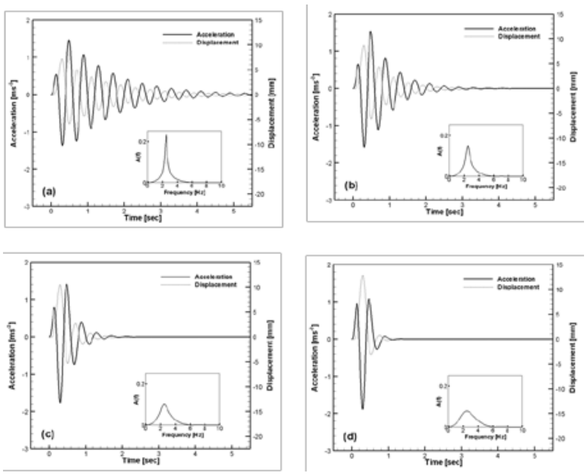


Fig. 2. Waveform and spectrum of shock-type vibrations having differenct decay rates at a frequency of 2.5 Hz and a magnitude of 1.0 ms of 1.0 $ms^{-1.75}$: (a) decay rate of 0.05, (b) decay rate of 0.1, (c) decay rate of 0.2, (d) decay rate of 0.4

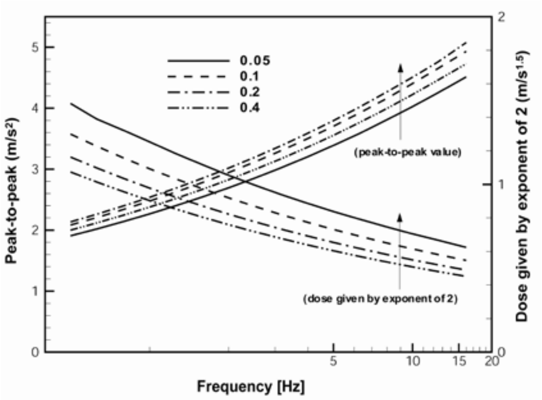



Fig. 3. Peak-to-peak values and 'dose' values given by an exponent of 2(e.g. $(\int a^2(t)\ dt)^{½}$) for shock-type vibrations having the same magnitude of 1.0 $ms^{-1.75}$

At each fundamental frequency and at each magnitude, the shock signals were shaped to have four different decay rates for which damping ratios of the one-degree-of-freedom model were controlled to 0.05, 0.1, 0.2, and 0.4. Especially, for the highest decay rate, a reverse direction shock was additionally employed to investigate the effect of direction. The reversed direction shock had the first principal displacement in the downward direction, whereas the other 4 shocks had the first principal displacement in the upward direction. Time history of the acceleration and displacement of the shock-type vibrations used in this study, as an example, is illustrated in Figure 2, and the spectrum of each acceleration signal is also presented at the figure. The magnitude of the shock-type vibration can be expressed by several alternative measures such as an instantaneous value (e.g., the peak-to-peak value) or a cumulative value [e.g., the vibration dose value, VDV, or the dose given by an exponent of 2 (i.e., $(\int a^2(t)\ dt)^{½}$)]. Relationship between the magnitudes of the shock-type vibration employed in this study is shown in Figure 3, from which the magnitudes of any shock-type vibration can be converted with each other measurement. VDV is 1.0 $ms^{-1.75}$ on all the lines in the Figure 3, and can be proportionally calculated from the unit of the lines.

**Quasi-apparent Mass**

The apparent mass $M(f)$ is normally calculated from the force $F(f)$ and the acceleration $a(f)$ measured at the surface supporting the body as a function of frequency expressed $f$ : (Fairley et al, 1989)

$$M(f) = \frac{F(f)}{a(f)} \tag{2}$$

The shock-type vibration employed in the study has a fundamental peak on frequency spectrum as shown Figure 2. Generally, the vibration dose value (the fourth root of the integral of the fourth power of signal in time domain) is used for measuring a transient shock vibration. In the study, the ratio of the fourth root of the integral of the fourth power of the force to the acceleration was defined as the biodynamic response to the shock-type vibration, which is named as "quasi-apparent mass". The fourth power calculation can be converted to the second power calculation by referring the Figure 3. Namely, the modulus of the quasi-apparent mass of the shock-type vibration is calculated with the time histories of the acceleration and force signal on the surface as (Ahn et al, 2007)

$$M_n\ (\mathrm{kg}) = \frac{\left(\int_0^T F_n^{\,4}(t)dt\right)^{1/4}}{\left(\int_0^T a_n^{\,4}(t)dt\right)^{1/4}} \tag{3}$$

where $M_n$ is the quasi-apparent mass of a fundamental peak frequency n. $a_n(t)$ and $F_n(t)$ are the time history of the acceleration and force measured on the surface, respectively, for a shock-type vibration exposed to a subject. The integration period T means the effective duration of the shock-type vibration, which is dependent on the frequency and decay rate of the shock motion. In the study, the effective duration of each shock-type vibration was numerically calculated for the measurement time to cover a minor peak smaller than one-tenth of a major peak in the shock-type signal.

Prior to calculating the quasi-apparent mass of a measured shock-type vibration, mass cancellation is essential to subtract the force caused by the mass of the top plate of the force platform (about 30 kg) from the measured force signal. Mass cancellation was performed in time domain to obtain the force produced by only the whole-body of the subject sitting on the force platform: (Ahn et al, 2007)

$$F(t) = F_s(t) - \frac{F_o(t)}{a_o(t)} a_s(t) \tag{4}$$

where F(t) is the mass-cancelled force and $F_s(t)$, $F_o(t)$, $a_s(t)$ and $a_0(t)$ are the time histories of the measured force and acceleration with and without the subject on the platform. As an example, the mass-cancelled force calculated by a measured force and acceleration is illustrated in Figure 4. "Quasi-phase delay" is defined to present the time gap of biodynamic response from acceleration input(in-phase with exciter) to force output(in-phase with whole-body). The quasi-phase delay is calculated as (Ahn et al, 2007)

$$\text{Quasi-phase delay (radian)} = 2\pi \times \frac{T_d}{T_n} = 2\pi \times T_d \times f_n \tag{5}$$

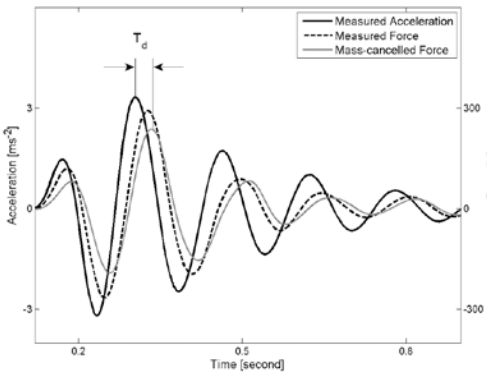



Fig. 4. Synchronized signals of acceleration and mass-cancelled force of a shock-type vibration measured (frequency: 6.3 Hz; decay rate: 0.1; magnitude: 1.7 ms$^{-1.75}$).

where $T_n$ and $f_n$ are the period and frequency of the shock-type vibration input, respectively, at the fundamental frequency n. $T_d$ is the time gap between the major acceleration peak and the major force peak which are from measurements (Figure 4)

**Apparatus and subjects**

The shock-type vibrations were produced on a 1 m stroke vertical hydraulic vibrator located at the Institute of Sound and Vibration Research (ISVR) of Southampton University. An HVLab system of the ISVR was used to control the shock motion and measure its acceleration and force at 400 samples/s.

Each subject sat on the rigid flat surface (600 × 400 mm) of a force plate (Kistler 9281 B) secured to a rigid seat, and the vertical force applied in the region of his ischial tuberosities was measured. The electrical signals from the force plate were amplified using an amplifier (Kistler 5007). The acceleration on the platform was simultaneously measured by an accelerometer (Setra, 141A). These signals of not only acceleration but also force were digitized at 400 samples/s via a 135 Hz antialiasing filter. The peak-to-peak values (the difference between the maximum positive peak value and maximum negative trough) and the fourth root of fourth power of each shock-type signal were calculated after a 40 Hz low-pass filter.

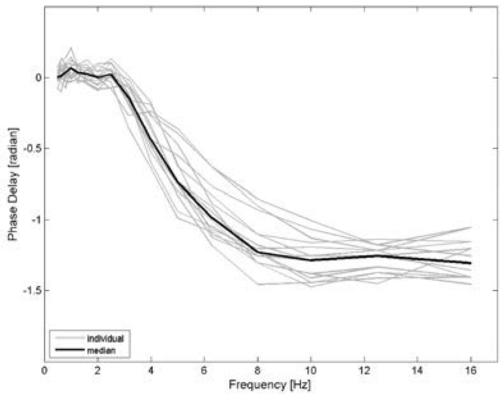
Fifteen male subjects aged 22 to 39 years (average: 30.2, standard deviation: 5.2), with weight 54 to 105 kg (average: 75, standard deviation: 12.5) and stature 168 to 186 cm (average: 175.8, standard deviation: 5.3), participated in the experiment. The subjects were asked to sit without a backrest in a comfortable upright posture, with their thighs horizontal and lower legs vertical (achieved by adjusting the height of a footrest that was moved in phase with the rigid seat). The experiment was approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research.

## RESULTS

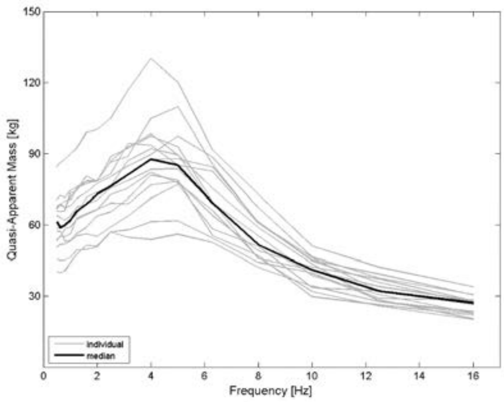
The quasi-apparent mass of the 15 subjects exposed to an example shock-type vibration of an intermediate magnitude (a VDV of 1.0 ms$^{-1.75}$) and a decay rate of 0.1 was found as Figure 5, which is a similar result as the apparent mass that Fairley and Griffin (1989) and Mansfield and Griffin (2000) observed using random vibrations. The peak frequencies of the quasi-apparent mass of the human whole-body exposed to the shock-type vibrations were in the range of 4 to 6 Hz, in which the time delay between acceleration and force increased with increasing frequency. The range of peak frequencies of the apparent mass has been determined by previous studies using random or sinusoidal vibrations, not by using the shock-type vibration with a fundamental frequency, decay rate, and direction as performed in this study. Fairley and Griffin (1989) employed 60 subjects (24 men, 24 women, and 12 children) and found that their mean apparent mass has a main peak at about 5 Hz (range 4 to 6 Hz), in which the phase of the apparent mass was reduced from 0° to -90°. Wang et.al (2004) also found that the biodynamic response was partly affected by body posture (e.g., normal, erect, backrest, and tense). In another study, the peak frequency of the apparent mass ranged from 4.75 to 6.4 Hz, dependent on magnitude of the vibration, and the phase delay was also obvious (Matsumoto and Griffin, 2002). When Matsumoto and Griffin (2005) used sinusoidal and transient vibrations having five different frequencies (3.15, 4.0, 5.0, 6.3, and 8.0 Hz), the apparent mass for sinusoidal vibrations had a peak at 4.0 Hz, although there is no evident peak in the case of transient vibrations. The result of the quasi-apparent mass in this study indicates that shock-type vibration with a single fundamental frequency can excite the body resonance over a similar frequency range as in the case of continuous vibrations used in the previous studies.

**Effect of Magnitude**

It was shown, in this study, that there is an magnitude effect on the median of the quasi-apparent mass and the quasi-phase delay of the shock-type vibration at all the four decay rates and the reversed direction (Figure 6). Especially at the peak frequency around 4Hz, the magnitude effect seems to be more evident in the figure. The statistical test results of the magnitude effect are as Table 1. At each frequency higher than 4Hz, the quasi-apparent mass is bigger, and the quasi-phase delay is smaller when the magnitude of the shock-type vibration is smaller ($p < 0.001$; Spearman). The peak frequency of the quasi-apparent mass decreased with increasing magnitude at all the decay rates (Table 4). The peak magnitudes of the quasi-apparent mass were




(a)




(b)

Fig. 5. 'Quasi-apparent-mass' of fifteen subjects to a shock-type vibration at a magnitude (1.0 ms-1.75) and at a decay rate of 0.1; (a) Modulus (b) Phase delay

summarized in Table 5 where they are significantly diminished with greater shock-type even not at the highest magnitude ($p < 0.001$; Spearman).

In the present study, the peak frequency and peak magnitude of the quasi-apparent mass were shown to depend on the magnitude of the shock-type vibration, which means the biodynamic response to shock is nonlinear, as for the continuous vibration (sinusoidal or random vibration). The peak frequency and the peak magnitude of quasi-apparent mass decreased with increasing shock magnitude. These results were consistent with the previous studies that showed a reduction in the peak frequency owing to an increase in the magnitude of vibration (e.g., Fairley and Griffin, 1989; Mansfield and Griffin, 2000; Matsumoto and Griffin, 2002). A softening phenomenon at the locations along the spine was found in the transmissibility from the seat cushion to some locations of the body, which might validate the assumption that high intra-abdominal pressure owing to a high magnitude of vibration functions as a relief from loading on the spine (Sandover, 1988). In consequence, it was concluded that the reduction of the peak frequency and the nonlinearity of the apparent mass might be caused by the softening phenomenon. The reduction in the peak magnitude of the quasi-apparent mass with increasing shock magnitude was a somewhat different situation from the previous studies that showed either an increase or no increase with increasing magnitude of vibration (Matsumoto and Griffin, 2002; Matsumoto and Griffin, 2005; Mansfield and Griffin, 2000). Without concrete validation, it can be assumed that the decay rate of the shock-type vibrations might make the magnitude effect on the peak on the peak.

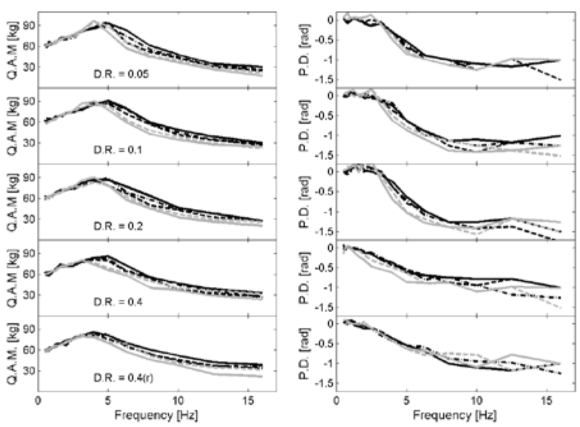



Fig. 6. Effect of magnitude on 'quasi-apparent-mass' and 'phase delay' (median curves of 15 subjects of 4 decay rates and a reversed direction). ——: $0.346ms^{-1.75}$, – • –: $0.588ms^{-1.75}$, – – –: $1.0ms^{-1.75}$, – – –: $1.7ms^{-1.75}$, —— $2.89ms^{-1.75}$

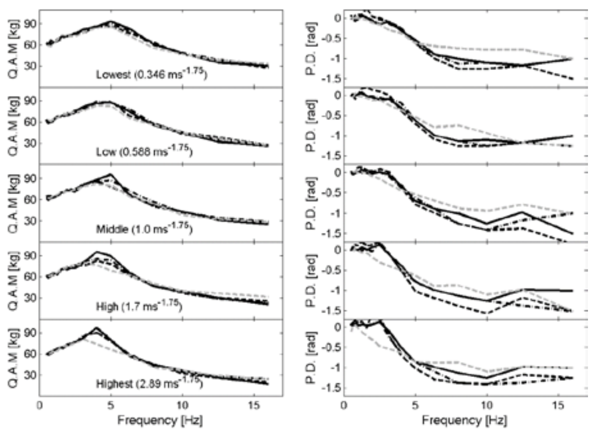



Fig. 7. Effect of decay rate and reversed direction on 'quasi-apparent-mass' and 'phase delay' (median curves of 15 subjects of 5 magnitudes). ——: 0.05, – • –: 0.1, – – –: 0.2, – – –: 0.4

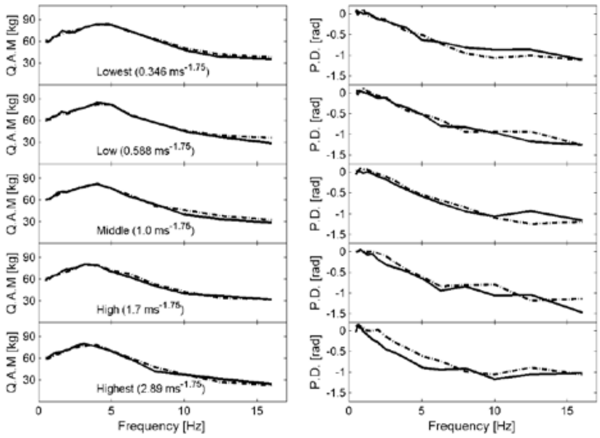



Fig. 8. Effect of direction on ‘quasi-apparent-mass’ and ‘phase delay’ (median curves of 15 subjects of 5 magnitudes). ——: upward, – • –: downward

**Effect of Decay Rate**

Median curves of the quasi-apparent mass and the quasi-phase delay at the four decay rates are shown in Figure 7. The decay rate effect on the quasi-apparent mass was found to be evident at the frequencies from 3.15 to 6.3 Hz, and the effect becomes greater at a higher magnitude of the shock-type vibration (Figure 7). The decay rate of the shock affects the quasi-phase delay at most magnitudes and at most frequencies as well. Statistical analysis of the decay rate effect was performed to be seen in the Table 2 where significance of the effect was highly found at the higher frequencies of the quasi-phase delay. Both the peak frequency and the peak magnitude of the quasi-apparent mass decreased with increasing decay rate at all five magnitudes (Tables 4 and 5).

The effect of decay rate on the apparent mass has rarely been considered because most previous studies used stationary vibrations (random or sinusoidal) to obtain the human response. In this study, it was hypothesized that with a high decay rate, the shock-type vibrations employed would not effectively excite the body resonance because there were not enough cycles of the shock type vibration to make the human body resonant. Nevertheless, the shock-type vibrations with a single fundamental frequency, even those with the highest decay rate (few cycles of vibration), had a peak quasi-apparent mass at around 4 to 5 Hz, although the peak magnitude was quite lower than that about continuous vibrations in the previous studies. It was also found that the peak magnitude and the peak frequency of the quasi-apparent mass decreased with higher decay rates (i.e., fewer cycles of the shock-type vibration). It means that the decay rate of the shock-type vibration at near the peak frequency does not allow the body resonance to be effectively activated.

**Effect of Decay Rate**

For the reversed shock-type vibration (at the highest decay rate of 0.4), the median values of the quasi-apparent mass and the quasi-phase delay at each frequency are shown in Figure 8 for the two directions (upward and downward displacements). Although the effect of direction on the quasi-apparent mass was statistically significant at a few frequencies in Table 3, depending on the magnitude, the difference of the median values on each frequency seems to be minor in the figure. At frequencies over 10 Hz, the quasi-apparent mass of downward motion was found to be slightly greater than that of the upward motion and vice versa in the case of the higher shock magnitude. At frequencies between 1.0 and 3.15 Hz, the quasi-phase delays were significantly affected by the shock direction such that the phase delay of the upward vibration was larger at three of the five magnitudes at each frequency, and the difference became greater with increasing shock magnitude.

At most shock frequencies, even though there was no significant difference in the quasi-apparent mass after a change in the direction of the shock (i.e., upward or downward), the phase delay was shown to be significantly affected owing to the direction at larger magnitudes. Blüthner et al. (1993) performed an electromyography(EMG) test using five subjects exposed to a transient vibration (nearly sinusoidal or half-sinusoidal waveform) and predicted that health risk would be higher when there was an initial phase of a sudden upward displacement without motion in the preceding history. A sudden stop during the interval in which the back muscles were relaxed was also expected to be a health risk which was dependent on the direction and duration before the stop. In a subjective experiment using the same stimuli as the shock-type vibration in this study, upward shock was estimated to be more uncomfortable than downward shock-type vibration (Ahn and Griffin, 2008).

Table 1 Magnitude effect of shock-type vibration on the ‘quasi-apparent-mass’ and ‘phase delay’ (Friedman; **: *p*<0.01, *: *p*<0.05, -: not significant)

| | Damping ratio | Frequency [Hz] | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0.5 | 0.63 | 0.8 | 1.0 | 1.25 | 1.6 | 2.0 | 2.5 | 3.15 | 4.0 | 5.0 | 6.3 | 8.0 | 10.0 | 12.5 | 16.0 |
| A.P. | 0.05 | ** | - | - | ** | - | * | * | ** | - | ** | - | ** | ** | ** | ** | ** |
| | 0.1 | * | ** | ** | - | ** | - | * | ** | ** | - | ** | ** | ** | ** | ** | ** |
| | 0.2 | - | * | - | ** | * | ** | - | ** | - | - | ** | ** | ** | ** | ** | ** |
| | 0.4 | * | - | - | - | - | ** | ** | - | - | ** | ** | ** | ** | ** | ** | ** |
| | 0.4(r) | ** | ** | - | - | - | ** | * | - | * | ** | ** | ** | ** | ** | ** | ** |
| Phase | 0.05 | * | ** | ** | - | - | ** | ** | ** | * | ** | ** | ** | ** | ** | * | ** |
| | 0.1 | - | ** | - | - | ** | - | ** | ** | ** | ** | ** | ** | ** | ** | ** | ** |
| | 0.2 | ** | ** | * | - | * | ** | ** | ** | ** | ** | ** | ** | ** | ** | * | ** |
| | 0.4 | * | ** | - | - | ** | ** | ** | ** | ** | ** | ** | ** | * | ** | ** | ** |
| | 0.4(r) | ** | - | - | ** | ** | ** | ** | - | * | - | ** | ** | ** | ** | ** | - |

Table 2 Decay rate effect of shock-type vibration on the ‘quasi-apparent-mass’ and ‘phase delay’ (Friedman; **: *p*<0.01, *: *p*<0.05, -: not significant)

| | Magnitude | Frequency [Hz] | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0.5 | 0.63 | 0.8 | 1.0 | 1.25 | 1.6 | 2.0 | 2.5 | 3.15 | 4.0 | 5.0 | 6.3 | 8.0 | 10.0 | 12.5 | 16.0 |
| A.P. | Lowest | * | - | - | - | - | ** | - | * | - | - | ** | * | - | - | - | ** |
| | Low | - | - | - | ** | * | - | * | - | - | - | - | ** | - | - | - | * |
| | Middle | ** | ** | - | * | - | - | - | - | - | - | ** | ** | * | ** | - | * |
| | High | ** | - | * | ** | - | - | ** | ** | - | ** | ** | - | - | - | ** | ** |
| | Highest | ** | - | - | ** | - | * | - | - | ** | ** | ** | - | ** | ** | ** | ** |
| Phase | Lowest | - | - | - | - | ** | ** | ** | ** | ** | - | - | ** | ** | ** | ** | ** |
| | Low | - | - | - | - | ** | ** | ** | ** | ** | * | ** | ** | ** | ** | - | ** |
| | Middle | - | ** | - | ** | ** | * | ** | ** | ** | - | ** | ** | ** | ** | ** | ** |
| | High | ** | ** | - | * | ** | ** | ** | ** | ** | * | ** | ** | ** | ** | ** | ** |
| | Highest | * | * | - | ** | ** | ** | ** | ** | ** | * | ** | ** | ** | ** | ** | ** |

Table 3 Direction effect of shock-type vibration on the ‘quasi-apparent-mass’ and ‘phase delay’ (Wilcoxon; **: *p*<0.01, *: *p*<0.05, -: not significant)

| | Magnitude | Frequency [Hz] | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0.5 | 0.63 | 0.8 | 1.0 | 1.25 | 1.6 | 2.0 | 2.5 | 3.15 | 4.0 | 5.0 | 6.3 | 8.0 | 10.0 | 12.5 | 16.0 |
| A.P. | Lowest | * | - | - | - | - | ** | - | - | - | - | - | - | - | - | - | - |
| | Low | - | - | ** | - | - | ** | - | - | - | - | - | - | - | - | - | * |
| | Middle | - | - | - | - | - | - | - | - | - | - | - | - | - | ** | * | * |
| | High | * | - | - | - | - | ** | ** | - | - | - | - | * | * | - | * | - |
| | Highest | * | - | - | * | - | ** | - | - | - | - | - | - | ** | - | ** | - |
| Phase | Lowest | - | * | - | ** | * | - | - | - | - | - | * | - | ** | ** | * | - |
| | Low | - | ** | - | * | - | * | ** | - | - | ** | - | ** | * | - | ** | - |
| | Middle | * | - | ** | ** | ** | - | ** | * | ** | - | - | - | - | - | ** | - |
| | High | - | - | - | - | ** | * | ** | ** | ** | - | - | - | - | ** | - | ** |
| | Highest | * | - | - | ** | ** | ** | ** | ** | ** | ** | ** | ** | - | - | * | - |

Table 4 Peak frequency of quasi-apparent mass in Figure 6 and 7 (unit: Hz)

| | | Magnitude | | | | | |
|---|---|---|---|---|---|---|---|
| | | lowest | low | middle | high | highest | Avg. |
| Damping ratio | 0.05 | 5 | 5 | 5 | 4 | 4 | 4.6 |
| | 0.1 | 5 | 5 | 5 | 4 | 4 | 4.6 |
| | 0.2 | 5 | 5 | 4 | 4 | 4 | 4.4 |
| | 0.4 | 4 | 4 | 4 | 3.15 | 3.15 | 3.66 |
| | Avg. | 4.75 | 4.75 | 4.5 | 3.79 | 3.79 | 4.32 |

Table 5 Peak magnitude of quasi-apparent mass in Figure 6 and 7 (unit: kg)

| | | Magnitude | | | | | |
|---|---|---|---|---|---|---|---|
| | | lowest | low | middle | high | highest | Avg. |
| Damping ratio | 0.05 | 90.2 | 86.4 | 91.5 | 88.7 | 92.4 | 89.8 |
| | 0. | 89.8 | 87.7 | 85.9 | 87.4 | 87.9 | 87.8 |
| | 0.2 | 85.5 | 86.4 | 83.7 | 82.9 | 85.9 | 84.9 |
| | 0.4 | 83.2 | 84.1 | 81.3 | 80.2 | 79.9 | 81.8 |
| | Avg. | 87.2 | 86.1 | 85.6 | 84.8 | 86.6 | 86.0 |

## CONCLUSIONS

The quasi-apparent mass as a biodynamic response of the seated whole-body exposed to a shock-type vibration was nonlinear in terms of its magnitude, decay rate, and direction. At all decay rates in the study, the greater was the magnitude of the shock-type vibration that the subjects were exposed to, the lower was the peak frequency of the whole-body quasi-apparent mass. The decay rate of the shock-type vibration at the same magnitudes also consistently affected to the peak frequency such that the higher the decay rate, the lower the peak frequency. The magnitude of the peak of the quasi-apparent mass was also dependent on the decay rate and the magnitude of the shock-type stimuli. Upward vibrations of high magnitude at a low frequency range had a larger phase delay of the quasi-apparent mass than downward vibrations.

## ACKNOWLEDGEMENT

This research was supported by Basic Science Research Program through the National Research Foundation of Korea(NRF) funded by the Ministry of Education(NRF-2017R1D1A1B03028674).

## REFERENCES

Ahn, S. J., Griffin, M. J., Effects of frequency, magnitude, damping, and direction on the discomfort of vertical whole-body mechanical shocks. Journal of Sound and Vibration. 311, 485-497, (2008).

Ahn, S. J., Discomfort of vertical whole-body shock-type vibration in the frequency range of 0.5 to 16Hz. International Journal of Automotive Technology. 11, 909-916, (2010).

Blüthner R., Hinz B., Monzel G., Seidel H., Back muscle response to transient whole-body vibration. International Journal of Industrial Ergonomics. 12, 49-59, (1993).

Boileau P., Rakheja S., Whole-body vertical biodynamic response characteristics of the seated vehicle driver measurement and model development. International Journal of Industrial Ergonomics. 22, 449-472, (1998).

Chapra S. C., Applied Numerical Methods for Engineers and Scientists. Published: McGraw-Hill. ISBN: 007-124429-8, (2006).

Fairley T. E., Griffin M. J., The apparent mass of the seated human body: vertical vibration. Journal of Biomechanics. 22, 81-94, (1989).

Griffin M.J., Handbook of human vibration. Published: Academic Press. London, ISBN: 0-12-303040-4, (1990).

Howarth H. V. C., Griffin M. J., Subjective reaction to vertical mechanical shocks of various waveforms. Journal of Sound and Vibration. 147, 395 – 408, (1991).

International Organization for Standardization, Mechanical vibration and shock-range of idealized values to characterize seated-body biodynamic response under vertical vibration. Draft International Standard, ISO/DIS-5982, (2000).

Mansfield N. J., Griffin M. J., 2000, Non-linearities in apparent mass transmissibility during exposure to whole-body vertical vibration. Journal of Biomechanics. 33, 933-941, (2000).

Matsumoto Y., Griffin M. J., Nonlinear characteristics in the dynamic responses of seated subjects exposed to vertical whole-body vibration. Journal of Biomechanical Engineering. 124, 527-532, (2002).

Matsumoto Y., Griffin M. J., Nonlinear subjective and biodynamic response to continuous and transient whole-body vibration in the vertical direction. Journal of Sound and Vibration. 287, 919-937, (2005).

Nawayseh N., Griffin M.J., Non-linear dual-axis biodynamic response to vertical whole-body vibration. Journal of Sound and Vibration. 268, 503-523, (2003).

Nawayseh N., Griffin M. J., Effect of seat surface angle on forces at the seat surface during whole-body vertical vibration. Journal of Sound and Vibration. 284, 613-634, (2005).

Rakheja S., Stiharu I., Boileau P., Seated occupant apparent mass characteristics under automotive postures and vertical vibration. Journal of Sound and Vibration. 253, 57-75, (2002).

Sandover J., Behaviour of the spine under shock and vibration: a review. Clinical Biomechanics. 3, 249-256, (1988).

Wang W., Rakheja S., Boileau P., Effects of sitting postures on biodynamic response of seated occupants under vertical vibration. International Journal of Industrial Ergonomics. 34, 289-306, (2004).

Ahn, S. J., Griffin M J., Yoo, W. S., Jeong, W. B., Nonlinearity of biodynamic response to shock-type vertical whole-body vibration. Trans. Of KSME (A), 31.2, 145~151, (2007).