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Article title:

Dynamic and subjective responses of seated subjects exposed to simultaneous vertical and fore-and-aft whole-body vibration: the effect of the phase between the two single-axis components

Authors:

Yasunao Matsumoto[a)], Katsutoshi Ohdo[b)] and Tetsuro Saito[a)]

Affiliation:

[a)]Department of Civil and Environmental Engineering, Saitama University, 255 Shimo-Ohkubo, Sakura, Saitama, 338-8570, Japan
[b)]National Institute of Industrial Safety, 1-4-6 Umezono, Kiyose, Tokyo 204-0024, Japan

Correspondence:

Dr Yasunao Matsumoto, Department of Civil and Environmental Engineering, Saitama University, 255 Shimo-Ohkubo, Sakura, Saitama, 338-8570, Japan
Telephone: +81 (0)48 858 3557.   Fax: +81 (0)48 858 7374.
e-mail: ymatsu@post.saitama-u.ac.jp

Abstract

Subjective and dynamic responses of seated subjects exposed to simultaneous vertical and fore-and-aft sinusoidal whole-body vibration were investigated. The effect of the phase difference between the vertical and the fore-and-aft vibration on the responses was of a particular interest in this study. Fifteen subjects were exposed to dual-axis vibrations at six frequencies (2.5 to 8 Hz) and at eight phases between the two single-axis components (0 to 315 degrees). The magnitude of vibration in each axis was constant at 0.7 ms^{-2} r.m.s. Discomfort caused by vibration was measured by the method of magnitude estimation. The motion of the body were measured at the head and three locations along the spine with accelerometers attached to the body surface. The most significant effect of the phase between the two single-axis components on the discomfort was observed at 5 Hz: about 40% difference in the median discomfort estimate caused by changing the phase. The transmissibilities from vertical seat vibration to vertical motions of the spine varied from 0.5 to 2.0 by changing the phase between the two single-axis components at frequencies from 2.5 to 5 Hz. The effect of the phase observed in the dynamic response was not predicted by the superposition of the responses to each single-axis vibration. The discomfort caused by the dual-axis vibration tended to be correlated better with the combinations of the dynamic responses measured in the two axes than with the dynamic responses in a single axis.

Keywords

biodynamic response, vibration discomfort, dual-axis vibration, phase difference

I. INTRODUCTION

In practical situations where people are exposed to whole-body vibration such as in various transportations, vibrations to which people are exposed usually occur in multi-axis. Many current assessment methods of whole-body vibration consider the effect of multi-axis vibrations on health and subjective responses of people (e.g., [1]). Those assessment methods have been developed based on some previous studies of the human responses to multi-axis whole-body vibration. Fairley and Griffin investigated the discomfort caused by simultaneous vertical and fore-and-aft vibration with seated subjects [2]. It was concluded that the discomfort caused by dual-axis vibration was predicted best by the root-sums-of-squares of the discomfort “caused by each of the vertical and fore-and-aft components if they had occurred separately” by comparing it with the worst component and the linear sum of the components. This finding may have been adopted in many assessment methods defined in national and international standards.

There are other factors than the magnitude of vibration that may have an effect on the human responses to multi-axis whole-body vibration. The effect of the phase difference between vibrations in different axes on the responses may be one of such factors and has been investigated in a few previous studies. Griffin and Whitham [3] investigated the discomfort caused by the combination of vertical and lateral sinusoidal vibration at 3.15 Hz with seated subjects. It was concluded that “for dual-axis motions of the type investigated the discomfort is not greatly influenced by the phase between the two single-axis components producing the motion”. Shoenberger [4, 5] investigated the perception of the intensity of dual-axis vibrations in the vertical and fore-and-aft axes and in the vertical and lateral axes with sinusoidal vibrations at 3.2, 5 and 8 Hz. It was found that there was no significant effect of the phase between the two single-axis components for the combination of the vertical and the lateral vibration, whereas there was a significant effect of the phase for the combination of the vertical and the fore-and-aft vibration.

It may be reasonable to assume that when the human body is exposed to whole-body vibration, the dynamic responses of the body influence the subjective responses. There have been few studies that investigate the relation between the dynamic and the subjective response. Some evidence of a relation between the discomfort caused by vibration and the head motion was found by Griffin *et al*. [6] and Whitham and Griffin [7] with seated subjects exposed to vertical sinusoidal vibration at frequencies below 6.3 Hz and above 16 Hz.

The dynamic response of the human body exposed to single-axis vibration was observed in, at least, two directions in many previous studies: vertical or fore-and-aft single-axis vibration resulted in the body motion in the vertical and fore-and-aft axes (e.g., [8-11]). Therefore, the dynamic response of the body measured in a single axis when exposed to dual-axis vibration will be influenced by both of the two single-axis components of the input vibration. This effect would result in the variation of the dynamic response measured in a single axis during exposure to dual-axis vibration with changes in the phase between the two single-axis components of the input vibration. This difference in the dynamic response caused by the phase between the two components of vibration might have an effect on the subjective response.

The objective of the present study was to investigate the effect of the phase between the two single-axis components of simultaneous vertical and fore-and-aft vibration on subjective and dynamic responses of seated subjects. The relation between the subjective and the dynamic response was also investigated through the effect of the phase on the responses. It was hypothesised that the subjective response was influenced by the difference in the phase between the two single-axis components of dual-axis input vibration. It was also hypothesised that the motion of the upper-body of seated subjects may be associated with the subjective response. The motion of the upper-body was represented by the motions of the head and the spine in this study because they were considered as the main transmission path of vibration in the seated body.

II. METHOD

A. Apparatus

The experiment was conducted with an electro-hydraulic shaker manufactured by Shimadzu Corp., which was capable of producing vertical and horizontal vibrations simultaneously, in a laboratory of the National Institute of Industrial Safety, Japan. The performance of the shaker was controlled and monitored by a workstation. When the shaker generated a single-axis vibration, the amount of cross-axis vibration was less than 7% of the magnitude of the single-axis vibration generated. Subjects sat on a wooden seat without a backrest mounted at the centre of the top surface of the platform of the shaker. The circular flat seat surface with a diameter of 0.3 m was set at a height of 0.5 m above the top surface of the shaker platform. There was no resonance of the seat in the frequency range used in this study. The size of the shaker platform was 2 m $\times$ 1.5 m, which was large enough to support the feet of the subject sitting on the seat mentioned above. A fall prevention fence was fixed to the edge of the shaker platform for safety reasons.

The acceleration of the seat was measured with a miniature piezo-electric accelerometer, NEC San-ei Instruments 9G111BW. The same type of miniature accelerometers were also used to measure the dynamic response of the body by mounting them on the surface of the body. For the measurement of the body motion in the vertical and the fore-and-aft axis, two accelerometers were fixed to a thin board made of polyethylene terephthalate with a size of 20 mm × 30 mm × 0.5 mm and then attached to the body surface by double-sided adhesive tape and adhesive plaster. The weight of the board, including two accelerometers and their cables, was 5 to 6 grams.

B. Subjects

Fifteen male volunteers aged from 21 to 23 yrs participated in the experiment. Their heights and weights were in the range 1.65 to 1.80 m and 52 to 75 kg, respectively. No subjects had an experience to take part in an experiment involving vibration exposures.

C. Input stimuli

The input stimuli were combinations of vertical and fore-and-aft sinusoidal vibrations. The frequencies of the sinusoidal vibrations were 2.5, 3.15, 4.0, 5.0, 6.3, and 8.0 Hz and a common frequency was used for vertical and fore-and-aft vibrations when combined. The magnitude of the input vibrations was 0.7 ms^{-2} r.m.s. for each direction. The magnitude was selected so that the input vibrations might cause moderate discomfort: the selected magnitude corresponded to values within the range of “fairly uncomfortable” in the “approximate indications of likely reactions in public transport” given in ISO 2631-1 [1]. The duration of the input vibration was 6.0 seconds with the first and the last 1.0 seconds tapered by a quarter of a sinusoidal function for each axis.

The definition of the axis for the vertical and the horizontal axis was in accordance with ISO 2631-1 [1]: *x*-axis for the fore-and-aft direction and *z*-axis for the vertical direction. With respect to the axis defined, the phase between the vertical and the fore-and-aft vibration was determined. A phase difference was defined as the delay of the vertical vibration compared to the fore-and-aft vibration in this study. Phase differences from 0 degrees to 315 degrees at an interval of 45 degrees were used in the experiment. Lissajous’ figures that illustrate the dual-axis vibrations with different phases between the two single-axis components are shown in Fig. 1. As observed in Fig. 1, the phases of 0 and 180 degrees resulted in an oblique translational motion, the phases of 45, 135, 225, and 315 degrees resulted in a oblique elliptic motion, and the phases of 90 and 270 degrees resulted in a circular motion. For the elliptic motions and the circular motions, the direction of rotation was dependent on whether the phase was greater or less than 180 degrees.

FIGURE 1 ABOUT HERE

D. Measurement

Discomfort caused by the input stimuli was measured by the method of magnitude estimation. Subjects were exposed to a series of two vibrations with an interval of 2.0 seconds. In a series of two vibrations, the vibration presented first was used as the 'reference' vibration and the vibration presented second was the 'test' vibration. The frequency of the reference vibration was the same as the frequency of the test vibration. The difference between the reference vibration and the test vibration was the phase between the vertical and the fore-and-aft component. Dual-axis vibrations with no phase difference between the two axes (i.e., the phase of 0 degrees) were selected as the reference vibration and the phase of the test vibration was altered between 0 and 315 degrees. The subjects were instructed to give a value of 100 to the discomfort caused by the reference vibration and assign a number to evaluate relative discomfort caused by the test stimulus compared to the discomfort caused by the reference vibration. For example, a subject who judged that a test stimulus was half as uncomfortable as the reference stimulus should assign it the value of 50. A subject who judged a test stimulus to be twice as uncomfortable as the reference stimulus should assign it the value of 200.

During exposure to the input vibrations, the acceleration response of the body was measured with the accelerometers attached to the surface of the body as described above. The orientations of the accelerometers were determined so that the accelerations in the vertical axis (i.e., along the body surface) and in the fore-and-aft axis (i.e., normal to the body surface) were measured. The locations of the measurement were the centre of the forehead (referred to as the head in later part of this paper) and the three locations on the back along the spine (i.e., at the first thoracic vertebra T1, the tenth thoracic vertebra T10, and the third lumber vertebra L3). The accelerations measured were digitised at 200 samples per second after anti-aliasing filtering at 25 Hz.

Additionally, the dynamic responses of the body caused by vibrations in each single axis (i.e., the vertical and the fore-and-aft axis) were measured so as to compare them with the responses caused by dual-axis vibrations. The magnitude and the duration of input stimuli for this measurement were the same as those described above. The discomfort caused by the vibrations in a single axis was not measured.

Prior to the experiment involving vibration exposures, free vibration test was conducted on each local system consisting of the miniature accelerometers and the tissue near the body surface so as to understand possible effects of the dynamic characteristics of the local system on the measurement.

E. Analysis

From the measurement of the dynamic responses of the body, the ratio between the magnitudes of accelerations measured at different measurement locations was calculated by using the r.m.s. values of the measured accelerations:

$$R_f = A_{1,rms,f} / A_{2,rms,f} \quad (1)$$

where R_f is the magnitude ratio at f Hz, $A_{1,rms,f}$ and $A_{2,rms,f}$ are the r.m.s. values of the accelerations at different locations at f Hz. The r.m.s. values were calculated by using the records without a period when the input signal was tapered: the records for the first and the last 1.0 seconds were excluded in the calculation. The time history of each acceleration record was examined before the calculation so as to eliminate effects of unwanted noise signal on the r.m.s. values. In the measurement of the response to dual-axis vibration, the motion at a measurement location in the body in an axis was caused by both vertical and horizontal components of input seat vibration. In the calculation of the magnitude ratio between seat vibration and motion of a location in the body in the present study, the ratio of the motion of the body measured in an axis to the seat vibration in the same axis was calculated. Therefore, the magnitude ratio presented in this paper does not represent an input-output relationship of the body system that the transmissibility represents as in previous studies with a single-axis vibration. However, the magnitude ratios determined with the single axis exposures in the present study corresponded to the transmissibility.

The phase between the motions at different locations was obtained by calculating the cross correlation function between two acceleration records:

$$w_{a_1 a_2,f}(p) = \frac{1}{N} \sum_{i=0}^{N-1} a_{1,f}(i) \cdot a_{2,f}(i+p) \quad (2)$$

Here, $a_{1,f}$ and $a_{2,f}$ are records of acceleration at different locations, i is an index indicating time step, and N is the number of samples in the record. The cross correlation function is the function of p that is the shift of a record with respect to another record. In the calculation, zero was assigned to $a_{2,f}(i + p)$ if the index $(i + p)$ was less than zero or greater than N-1. The phase between two records was determined based on the value of p that gave the maximum value of the cross correlation function.

Statistical analyses were applied to the data obtained by the measurement and the analysis described above so as to understand the significance of differences or associations observed in the data. Nonparametric statistics were used in this study because the assumption of normality may not be reasonable for the data obtained.

III. RESULTS

A. Relative discomfort

The medians of the magnitude estimates of the relative discomfort judged by the 15 subjects are presented for each frequency in Fig. 2. The corresponding inter-quartile ranges are also shown in the figure. The magnitude estimates of the discomfort caused by the vibrations with the phase of 0 degrees were close to 100 for almost all frequencies: this was expected because these test vibrations were the same as the reference vibration. The trend in the change in the relative discomfort with changing the phase was different depending on the frequency of the input vibration. The change in the relative discomfort caused by the change in the phase tended to be greater at frequencies of 4 and 5 Hz than at the other frequencies used in the experiment.

FIGURE 2 ABOUT HERE

The effect of the phase on the magnitude estimates of the relative discomfort was statistically significant at frequencies of 3.15, 4, 5, and 6.3 Hz (p<0.05; Friedman two-way analysis of variance) and marginally significant at 8 Hz (p<0.1, Friedman). Table 1(a) and Figure 2(b) show that, at 3.15 Hz, the relative discomfort was significantly greater for the phases of 180 and 225 degrees than for the phases of 270 and 315 degrees. At 4 Hz, the relative discomfort tended to be greater for the phases of 90, 135 and 180 degrees than for the phases of 0, 45, and 315 degrees (Table 1(b) and Fig. 2(c)). At 5 Hz, the relative discomfort was significantly greater for the phases of 90, 135, 180 and 225 degrees than for the phases of 0, 45, 270 and 315 degrees (Table 1(c) and Fig. 2(d)). At 6.3 Hz, the relative discomfort was significantly greater for the phases of 135, 180 and 225 degrees than for the phase of 45 degrees (Table 1(d) and Fig. 2(e)). At 8 Hz, the relative discomfort for the phase of 45 degrees was significantly less than the relative discomfort for 225, 270 and 315 degrees, and the relative discomfort for 270 degrees was significantly greater than that for 45, 90 and 135 degrees (Table 1(e) and Fig. 2(f)).

TABLE 1 ABOUT HERE

B. Effect of local system on surface measurement

The effect of the dynamic characteristics of the local systems, consisting of the accelerometers with the mounting and the tissue near the body surface, on the measurement of acceleration on the body surface was not found to be significant: the lowest natural frequencies of the local systems identified by free vibration tests were greater than 30 Hz for most measurement locations of the 15 subjects. For several locations that showed the lowest natural frequency less than 30 Hz, the effect of the local system on the measured data was reduced on the assumption that the local system was represented by a single degree-of-freedom system as reported in previous studies (e.g., [12]). For other measurements, any corrections were not conducted as the lowest natural frequency was high enough to avoid the effect of the local system on the surface measurement.

C. Dynamic response to single axis vibration

The medians and inter-quartile ranges of the transmissibilities from seat vibration in a single axis to the vertical motion of the body of the 15 subjects are shown in Fig. 3. For the measurement at the head and T1, it was found that the amplitude of the acceleration responses varied with time at frequencies of 2.5, 3.15 and 4 Hz. Therefore, the transmissibilities based on the r.m.s. values were not obtained for those conditions and, therefore, they are not presented in Fig.s 3(a) and (b). In general, the transmissibilities from vertical seat vibration to vertical motions of the body presented in Fig. 3 showed similar trends that were observed in the previous experiments with various measurement methods and different types of vibrations [8, 9, 13-16]: for example, a peak in the transmissibilities was observed in a frequency region between 4 and 5 Hz in Figs. 3(c) and (d), as observed in the transmissibilities and the driving-point responses (e.g., the apparent mass) in the previous studies. Greater transmissibilities from horizontal seat vibration to vertical motions of the body observed at frequencies of 2.5 and 3.15 Hz may be associated with the resonance of the body exposed to fore-and-aft vibration as observed in the previous studies [17, 18].

FIGURE 3 ABOUT HERE

D. Dynamic response to dual-axis vibration

The median magnitude ratios between vertical seat vibration and vertical motions measured at the four locations in the body of the 15 subjects are presented for each frequency in Fig. 4. The effect of the phase between the vertical and the fore-and-aft vibration on the vertical motion of the body was clearly observed in the figure. The effect of the phase was greatest at 2.5 and 3.15 Hz and reduced with increasing frequency. At 2.5 and 3.15 Hz, the difference between the greatest magnitude ratio and the smallest magnitude ratio was about 1.1 to 1.4, while it decreased to about 0.5 to 0.6 at 8.0 Hz.

FIGURE 4 ABOUT HERE

At frequencies of 2.5 and 3.15 Hz, the vertical motions measured at the three locations along the spine showed similar characteristics, which indicated small relative motion within the spine (Figs. 4(a), (b)). Greatest vertical relative motion between the seat and the three locations along the spine was observed with the phase of 225 degrees at 2.5 Hz and 270 degrees at 3.15 Hz, compared to other phases. The vertical relative motion between the seat and the spine was relatively small with the phases separated by 180 degrees from the phases that caused greatest vertical relative motion .

There were differences observed between the vertical motions measured the three locations along the spine at frequencies from 4 to 8 Hz (Figs. 4(c) to (f)). The vertical motion measured at T1 tended to be less than those measured at the lower locations at 4 and 5 Hz, while the vertical motion at L3 tended to be less than those at the upper locations at 6.3 and 8 Hz. The trend that greater motions were seen with the phases around 225 and 270 degrees and smaller motions were observed with the phases around 90 degrees was common for all measurement locations along the spine at frequencies from 4 to 8 Hz.

The characteristics of the vertical head motion were different from the characteristics of the motions measured along the spine at all frequencies used in the experiment, particularly at lower frequencies. The effect of the phase on the vertical head motion appeared differently depending on the frequency of the input vibration, unlike the effect of the phase on the motions measured at the locations along the spine. The vertical head motion tended to be greater than the motions at the locations along the spine for all conditions used in the experiment.

In the time histories of the fore-and-aft motions of the body caused by the dual-axis input vibrations, it was found that the amplitude of the acceleration response varied with time in many measurements. It was assumed that the discomfort measured in this study might be associated more with the greatest motion of the body than with an average motion of the body. Therefore, peak acceleration was used to represent the response in the fore-and-aft direction. The medians of the peak acceleration in the fore-and-aft motion of the body of the 15 subjects exposed to the dual-axis vibrations are presented for each frequency in Fig. 5. The effect of the phase between the vertical and the fore-and-aft vibration was observed in the peak values of the fore-and-aft acceleration of the body. This effect was clearer at lower frequencies used in the experiment. For the fore-and-aft motions measured at the locations along the spine, the phases with which greater motions were observed were around 45 degrees at 2.5 Hz, 90 to 135 degrees at 3.15 and 4 Hz, and 90 to 180 degrees at 5 Hz (Figs. 5(a) to (d)). The fore-and-aft motion tended to be greatest at T1 and the head and smallest at T10 in the frequency range from 2.5 to 5 Hz, irrespective of the phase. The difference between the peak values of the fore-and-aft accelerations at different measurement locations was less at 6.3 and 8 Hz than the lower frequencies (Figs. 5(e), (f)).

FIGURE 5 ABOUT HERE

IV. DISCUSSION

A. Effect of phase on relative discomfort

The relative discomfort presented in Fig. 2 showed less inter-subject variability for the test vibrations with the phases between the vertical and the fore-and-aft vibration around 0 degrees (i.e., 315, 0 and 45 degrees). The phases for these test vibrations were close to the phase of the test vibrations, i.e., 0 degrees. The subjects might have found no significant difference between discomfort caused by those test vibrations and the discomfort caused by the reference vibrations and assigned the test vibrations the value around 100. This may result in less inter-subject variability of the relative discomfort for those test vibrations. For the dual-axis vibrations with the phases between 135 and 225 degrees, the relative discomfort tended to be greater than other phases used in the experiment. This effect tended to be more significant at frequencies 4 and 5 Hz (Fig. 2). As shown in Fig. 1, the dual-axis vibrations with the phases between 135 and 225 degrees can be generally described as a vibration from top-back of the body to bottom-front, while the dual-axis vibrations with the phase of 315, 0 and 45 degrees can be seen as a vibration from top-front to bottom-back. The difference in the relative discomfort between the vibrations in the two directions described above may be associated with the asymmetry of the body structure in the anteroposterior plane.

The effect of the phase between the vertical and the fore-and-aft vibration on the subjective response to dual-axis vibration was investigated experimentally by Shoenberger [5]. However, the results obtained in the present study may not be compared directly with his results. The subjects in the previous study sat on a seat with a backrest for a fighter aircraft and their body were fixed to the seat pan by a lap belt and to the backrest by a shoulder harness. This condition was significantly different from the experimental condition used in this study (i.e., a seat without a backrest). The difference in the support for the upper-body between the two studies may have a significant effect on subjective judgment of discomfort caused by dual-axis vibration.

B. Dynamic responses to dual-axis and single-axis vibrations

If the dynamic response of the body is linear, the dynamic responses measured with dual-axis vibrations could be predicted by the superposition of the dynamic responses measured with vibration in each single axis. The superposition of the transmissibilities (i.e., modulus and phase) measured in the body exposed to each single axis vibration, such as those shown in Fig. 3, was compared with the magnitude ratio measured with the dual-axis vibration, such as those shown in Fig. 4. The comparison for the vertical motions of the body measured at 5 Hz is shown in Fig. 6, as an example. The median values of the 15 subjects presented in Fig. 6 showed that, for the measurements at L3, the estimates of the response to dual-axis vibration obtained from the superposition of the responses to each single-axis vibration showed an agreement with the measurements with dual-axis vibration (Fig. 6(d)). The difference between the measurement and the estimate was greater at T1 and T10, although there was some agreement in the trend caused by the phase between the vertical and the fore-and-aft vibration (Figs 6(b), (c)). The motion at the head showed the greatest difference between the measurement and the estimate (Fig. 6(a)). At 6.3 and 8 Hz, a similar trend to the trend described for 5 Hz was observed, although the data are not shown in this paper. At 2.5, 3.15 and 4 Hz, the comparison between the measurement and the estimate was not made because the amplitude of the fore-and-aft response to single-axis vibration varied with time as described above.

FIGURE 6 ABOUT HERE

Mansfield and Lundström [19] compared the apparent mass of seated subjects measured in the horizontal direction at 45 degrees to the mid-sagittal plane with the "prediction" of the response from the apparent mass in the fore-and-aft axis and that in the lateral axis "by applying the principle of superposition". It was concluded that "the response of the body with direction was not linear". This finding may be consistent with the results described above: it may not be appropriate to apply the principle of superposition to predict the dynamic response of the human body exposed to multi-axis vibration based on the responses measured with single-axis vibrations.

The "stiffness" of the body can be considered to be provided by passive elements of the body, such as the ligaments and the bone, and also active elements, such as the muscles. It may be reasonable to hypothesise that the contribution of the active elements of the body to the "stiffness" of the body may be greater in the fore-and-aft direction than in the vertical direction because disturbances of the surface supporting the body in the horizontal direction would directly result in the disturbance of the centre of gravity of the body that might induce muscle activities to stabilise the body by rotating and bending the upper body. The contribution of the active elements of the body to the dynamic responses in the fore-and-aft direction might be implied by the changes in the amplitude of the fore-and-aft responses when the body was exposed to a constant input motion, as described above. The effect of the active elements of the body may appear as a non-linear characteristic in the dynamic response. As observed in Fig. 5, the dynamic response of the body in the fore-and-aft direction tended to be greater at upper locations in the body. The non-linear behaviour in the dynamic responses that was clearer at upper measurement locations observed in Fig. 6 may be associated with a greater contribution of body motion that involves greater fore-and-aft motion to the responses measured.

C. Relation between subjective response and dynamic response

As observed in the comparison between the relative discomfort shown in Fig. 2 and the dynamic responses measured in a single axis shown in Figs. 4 and 5, the effect of the phase between the vertical and fore-and-aft vibration on the subjective response generally differed from those observed in the dynamic responses measured in a single axis. For example, at 5 Hz, greater relative discomfort was observed with the phases of 135 and 180 degrees than other phases as observed in Fig. 2(d), while greater motion of the body in the vertical direction was observed with the phases between 180 and 315 degrees depending on the measurement location as observed in Fig. 4(d). Correlation between the magnitude estimate of the relative discomfort and the dynamic response measured at each location in a single axis was investigated statistically. Although the detailed results of the statistical investigation are not presented in this paper, no correlations between the two responses were significant ($p > 0.05$, Spearman rank-order correlation coefficient), except the correlation between the median relative discomfort and the median peak value of fore-and-aft acceleration at T1 at 5 Hz (Spearman rank-order correlation coefficient $r_s = 0.741$, $p < 0.05$).

Correlations between the relative discomfort and the dynamic response tended to improve if the dynamic responses in both axes were combined. The dynamic responses in the vertical and the fore-and-aft axis were combined by calculating the root-sums-of-squares (r.s.s.) of the peak accelerations in the two axes. The peak acceleration was used because it was difficult to determine an appropriate "mean" magnitude of the motion in the fore-and-aft axis that showed varying amplitude as described in the preceding section. Additionally, it might be a reasonable assumption that the subjective response may be dominated by the maximum value of the dynamic response. However, there was a drawback of this method that the peak accelerations in the two axes might not occur simultaneously: the r.s.s. of the peak accelerations might, therefore, overestimate the response. At 4 Hz, the median magnitude estimate of the relative discomfort was significantly correlated with the median r.s.s. of peak accelerations in the two axes at the head ($r_s = 0.717$, $p < 0.05$) and at T1 ($r_s = 0.741$, $p < 0.05$). The correlation between the median relative discomfort and the median r.s.s. of peak accelerations in the two axes at T1 was also statistically significant at 5 Hz ($r_s = 0.964$, $p < 0.01$). The relative discomfort and the dynamic response that showed significant correlations are shown in Fig. 7.

FIGURE 7 ABOUT HERE

It may be able to hypothesise that greater relative motion within the body might cause more discomfort. The dynamic responses measured at each location showed that, during exposure to vibration, the response of each measurement location had a elliptic characteristic with the motions in the vertical and fore-and-aft axes at different magnitudes and phases. It was implied in this study that the difference in the rotational direction of the elliptic motion between two adjacent measurement locations might have an effect on the subjective response. Figure 8 shows the comparison between the median relative discomfort of subjects who showed the motion at T10 in the same rotational direction as that at L3 and the median relative discomfort of subjects who showed the motion at T10 in an opposite rotational direction of that at L3 for the input vibrations at 4 and 5 Hz. The number of subjects who showed the two motions in the same rotational direction varied depending on the frequency and the phase of input vibration: for example, all subjects showed the two motions in the same rotational direction at 4 Hz with the phase of 135 degrees and, therefore, no data for the opposite rotational direction was presented for 135 degrees in Fig. 8(a). It was observed that the relative discomfort when the rotational directions of the two motions were different tended to be greater than the relative discomfort when the rotational directions of the two motions were the same. When the rotational direction of the two motions were different, there could be greater rocking, bending and axial motions of the spine in the region between T10 and L3, compared to the same rotational direction for the two motions. Relative motions within the spine might be a cause of greater discomfort observed with subjects who showed the two motions in the opposite rotational direction, as shown in Fig. 8. This hypothesis may need further investigation including the investigation of relation between discomfort and relative motions involving the head and T1 that was not discussed in this study because the motion measured at those locations varied with time as described above.

FIGURE 8 ABOUT HERE

V. CONCLUSIONS

The effect of the phase between the two single-axis components of dual-axis whole-body vibration on the subjective and dynamic responses of seated subjects was investigated with simultaneous vertical and fore-and-aft sinusoidal vibration. It was found that the discomfort caused by the dual-axis vibration was influenced by the phase between the two single-axis components at frequencies around 4 and 5 Hz. The dynamic response of the body to the dual-axis vibration was also influenced by the phase between the two single-axis components in a way that cannot be predicted by the superposition of the responses to each single-axis vibration.

Possible relation between subjective and dynamic responses was also explored. Combinations of the dynamic responses measured at a location in the two axes tended to provide a better correlation with the discomfort than the dynamic responses in each single axis. The results obtained in the present study implied that some physical quantity that represent the severity of relative motion within the body might give a reasonable prediction of discomfort caused by vibration in the frequency range used. Further study is required to confirm the relation between relative motion within the body and discomfort.

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FIGURE CAPTIONS

Fig. 1. Lissajous' figures of dual-axis vibrations with different phases between the two axes. (a) 0°, (b) 45° and 315°, (c) 90° and 270°, (d) 135° and 225°, (e) 180°. Anticlockwise rotation for 45°, 90° and 135°, and clockwise rotation for 225°, 270° and 315°.

Fig. 2. Medians and inter-quartile ranges of the relative discomfort of 15 subjects exposed to dual-axis vibrations. (a) 2.5 Hz, (b) 3.15 Hz, (c) 4 Hz, (d) 5 Hz, (e) 6.3 Hz, and (f) 8 Hz. ◆ median, ◇ inter-quartile range.

Fig. 3. Medians and inter-quartile ranges of the transmissibilities from single axis seat vibration to vertical motions of the body of 15 subjects for each measurement location. Fore-and-aft (*x*-) axis or vertical (*z*-) axis seat vibration. (a) head, (b) T1, (c) T10 and (d) L3. ▲ median for *x*-axis, △ inter-quartile range for *x*-axis, ◆ median for *z*-axis, ◇ inter-quartile range for *z*-axis.

Fig. 4. Median magnitude ratios between vertical seat vibration and vertical motions of the body of 15 subjects exposed to dual-axis vibrations. (a) 2.5 Hz, (b) 3.15 Hz, (c) 4 Hz, (d) 5 Hz, (e) 6.3 Hz, and (f) 8 Hz. × head, ▲ T1, □ T10, ◆ L3.

Fig. 5. Median peak accelerations of fore-and-aft motion of the body of 15 subjects exposed to dual-axis vibrations. (a) 2.5 Hz, (b) 3.15 Hz, (c) 4 Hz, (d) 5 Hz, (e) 6.3 Hz, and (f) 8 Hz. × head, ▲ T1, □ T10, ◆ L3.

Fig. 6. Comparison between the magnitude ratios between vertical seat vibration and vertical motions of the body measured with the dual-axis vibration and the magnitude ratios estimated by the transmissibilities measured with the single axis vibration. Medians of 15 subjects at 5 Hz. (a) head, (b) T1, (c) T10, (d) L3. ◆ measurement, ◇ estimate.

Fig. 7. Relation between median magnitude estimates of relative discomfort and median root-sum-of-squares of peak accelerations in the two axes at a measurement location. (a) 4 Hz, (b) 5 Hz. × head, ▲ T1.

Fig. 8. Effect of the difference in rotational direction between the motion at T10 and the motion at L3 on the relative discomfort. (a) 4 Hz, (b) 5 Hz. ● same direction, □ opposite direction.

TABLE CAPTIONS

Table 1. Statistical significance of difference between the relative discomfort of dual-axis vibrations with different phase between the two single-axis components. Wilcoxon matched-pairs signed ranks tests. *: $p < 0.05$, ** $p < 0.01$.

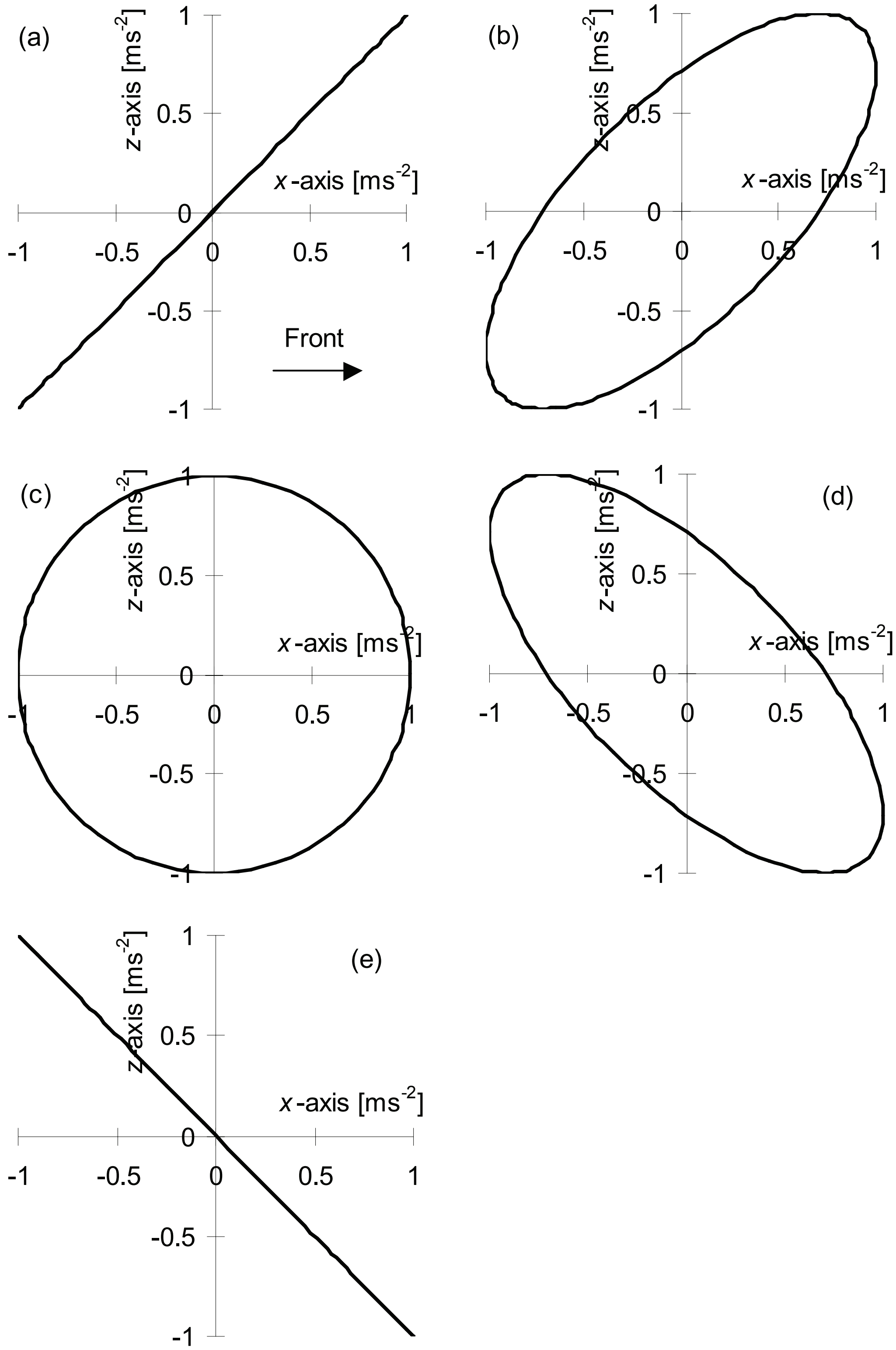

Fig. 1. Lissajous' figures of dual-axis vibrations with different phases between the two axes. (a) 0°, (b) 45° and 315°, (c) 90° and 270°, (d) 135° and 225°, (e) 180°. Anticlockwise rotation for 45°, 90° and 135°, and clockwise rotation for 225°, 270° and 315°.

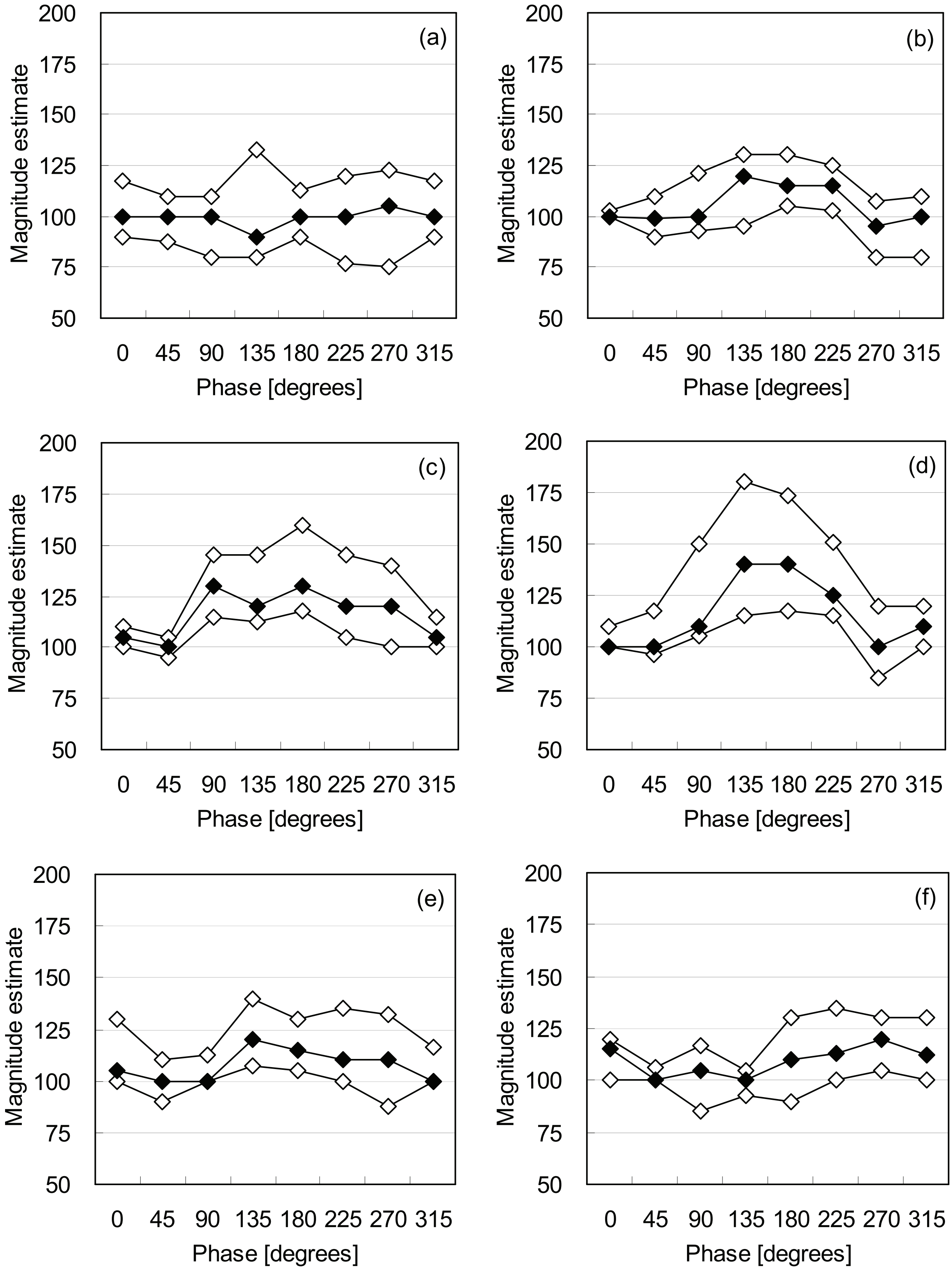

Fig. 2. Medians and inter-quartile ranges of the relative discomfort of 15 subjects exposed to dual-axis vibrations. (a) 2.5 Hz, (b) 3.15 Hz, (c) 4 Hz, (d) 5 Hz, (e) 6.3 Hz, and (f) 8 Hz. ◆ median, ◇ inter-quartile range.

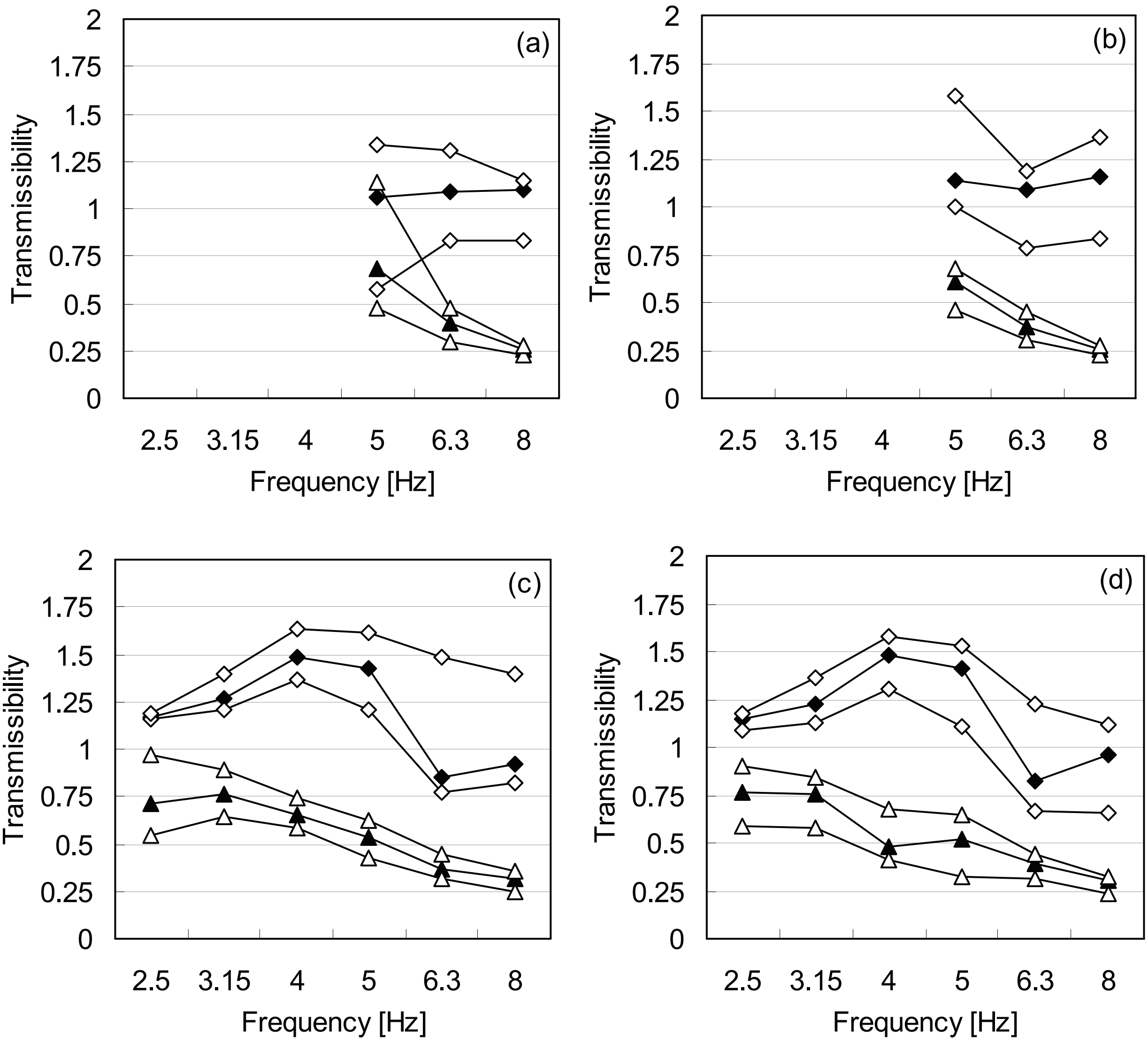

Fig. 3. Medians and inter-quartile ranges of the transmissibilities from single axis seat vibration to vertical motions of the body of 15 subjects for each measurement location. Fore-and-aft (*x*-) axis or vertical (*z*-) axis seat vibration. (a) head, (b) T1, (c) T10 and (d) L3. ▲ median for *x*-axis, △ inter-quartile range for *x*-axis, ◆ median for *z*-axis, ◇ inter-quartile range for *z*-axis.

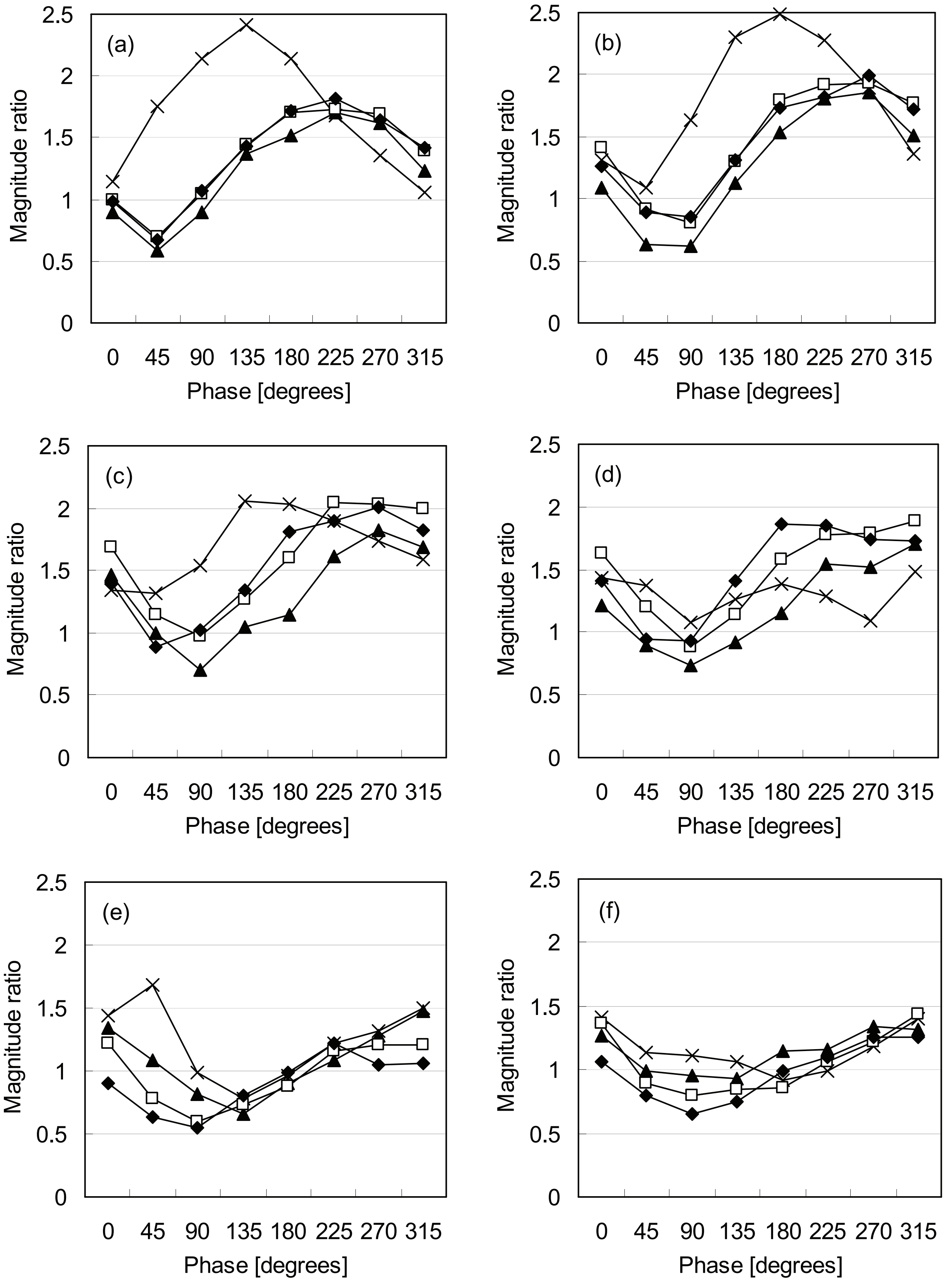

Fig. 4. Median magnitude ratios between vertical seat vibration and vertical motions of the body of 15 subjects exposed to dual-axis vibrations. (a) 2.5 Hz, (b) 3.15 Hz, (c) 4 Hz, (d) 5 Hz, (e) 6.3 Hz, and (f) 8 Hz. × head, ▲ T1, □ T10, ◆ L3.

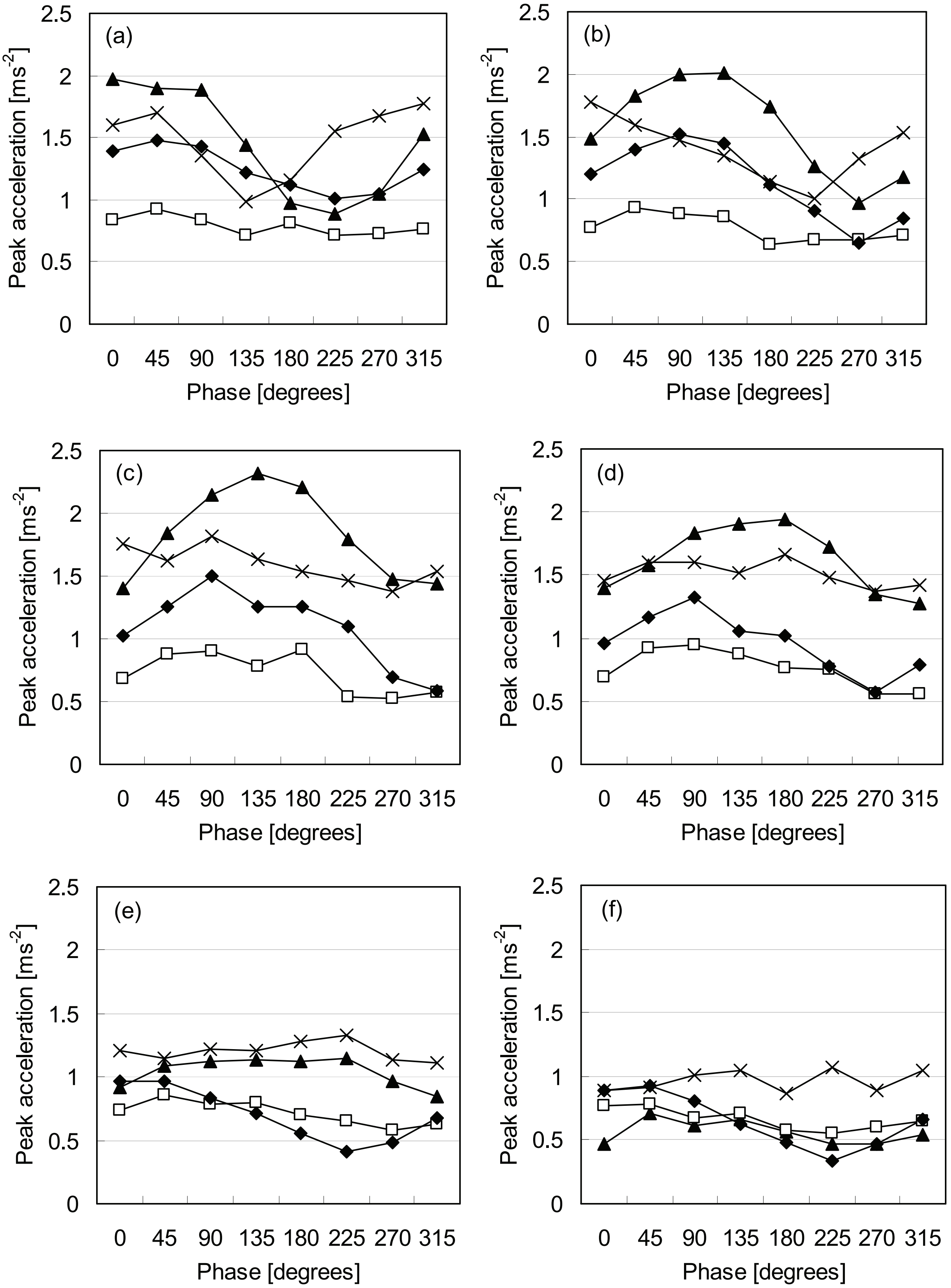

Fig. 5. Median peak accelerations of fore-and-aft motion of the body of 15 subjects exposed to dual-axis vibrations. (a) 2.5 Hz, (b) 3.15 Hz, (c) 4 Hz, (d) 5 Hz, (e) 6.3 Hz, and (f) 8 Hz. × head, ▲ T1, □ T10, ◆ L3.

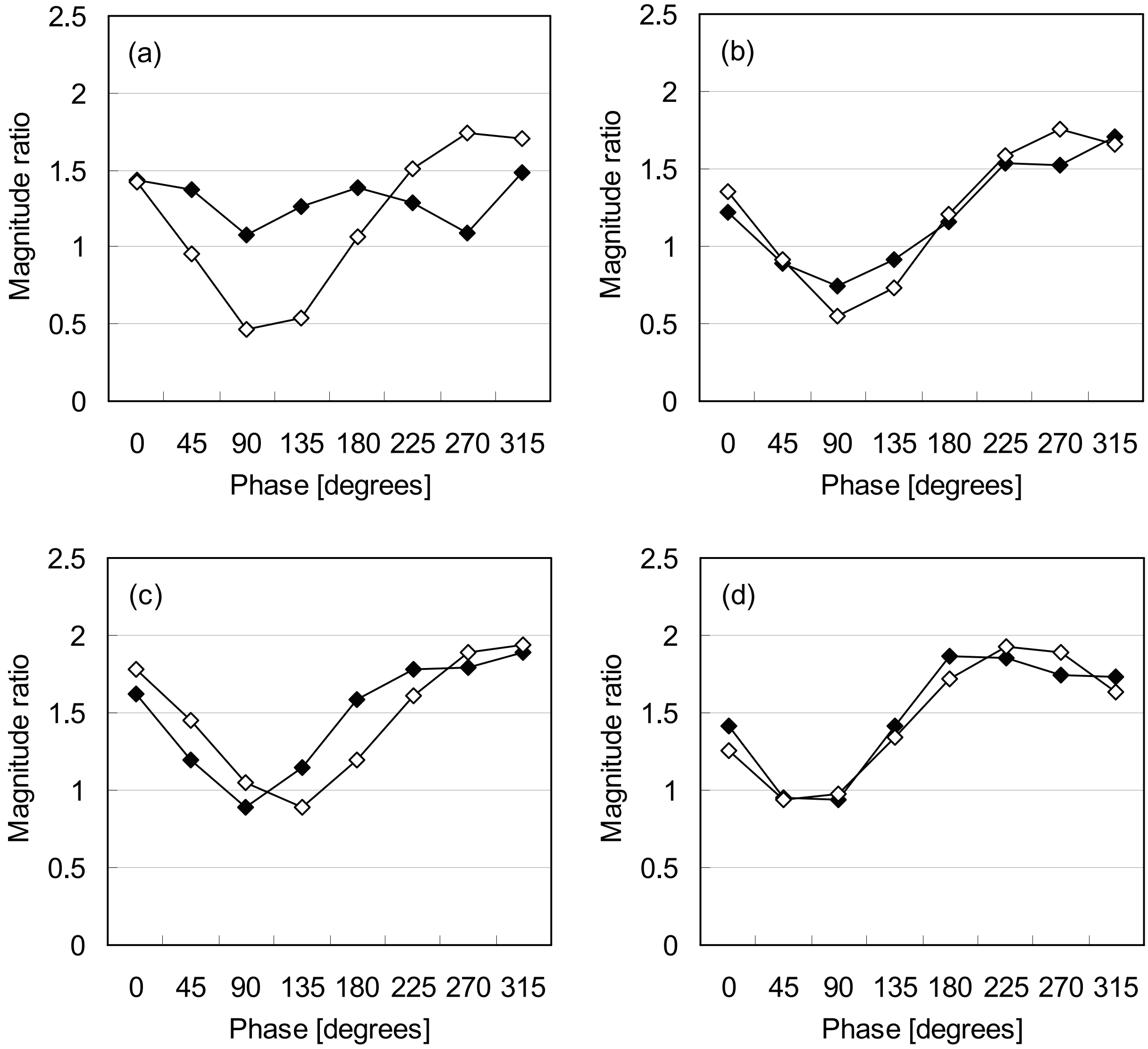

Fig. 6. Comparison between the magnitude ratios between vertical seat vibration and vertical motions of the body measured with the dual-axis vibration and the magnitude ratios estimated by the transmissibilities measured with the single axis vibration. Medians of 15 subjects at 5 Hz. (a) head, (b) T1, (c) T10, (d) L3. ◆ measurement, ◇ estimate.

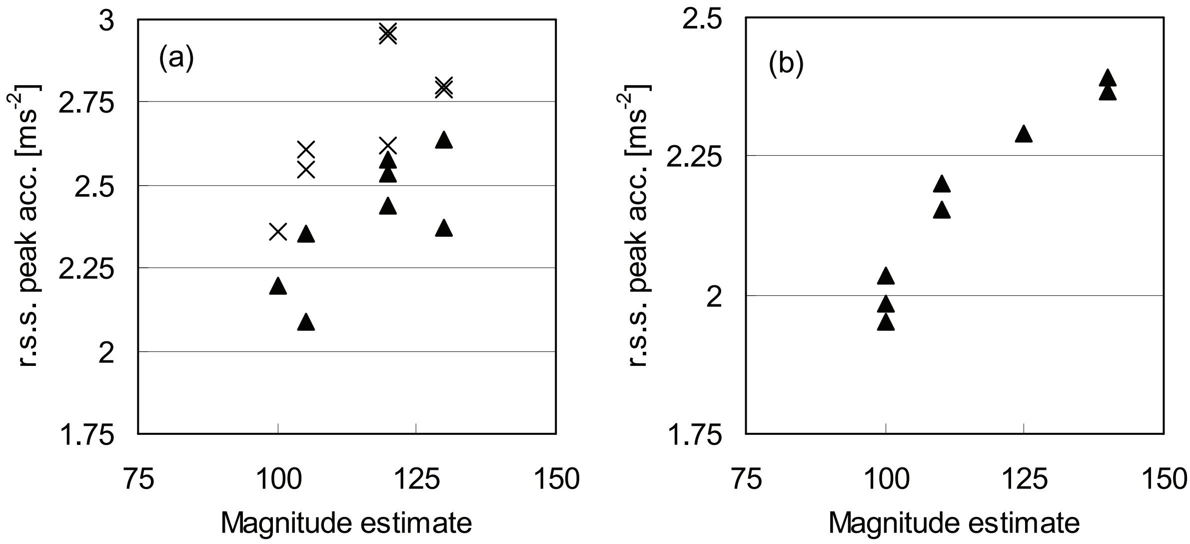

Fig. 7. Relation between median magnitude estimates of relative discomfort and median root-sum-of-squares of peak accelerations in the two axes at a measurement location. (a) 4 Hz, (b) 5 Hz. × head, ▲ T1.

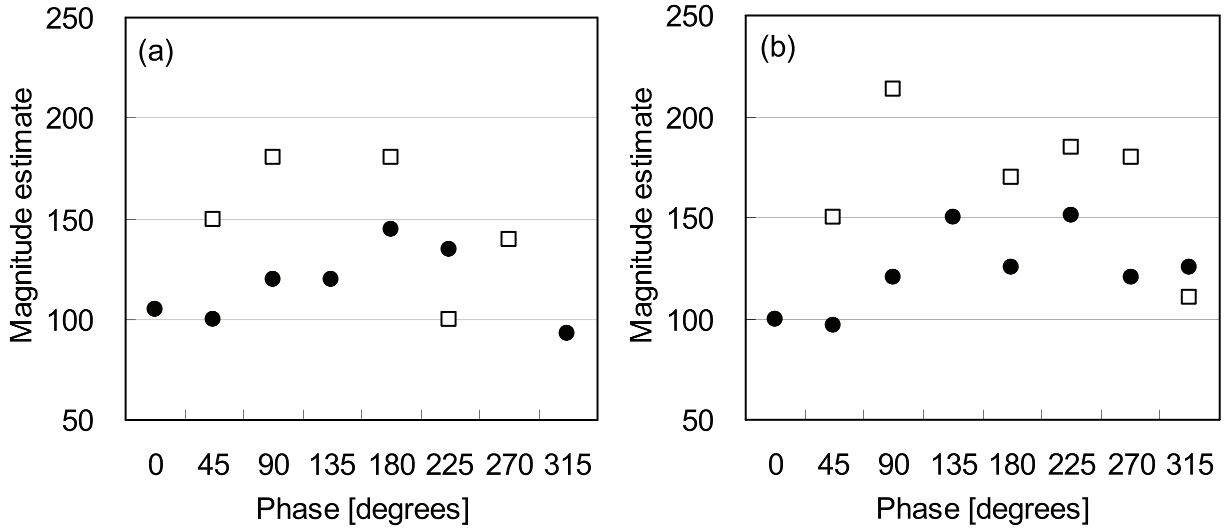

Fig. 8. Effect of the difference in rotational direction between the motion at T10 and the motion at L3 on the relative discomfort. (a) 4 Hz, (b) 5 Hz. ● same direction, □ opposite direction.

Table 1. Statistical significance of difference between the relative discomfort of dual-axis vibrations with different phase between the two single-axis components. Wilcoxon matched-pairs signed ranks tests. *: $p < 0.05$, ** $p < 0.01$.

(a) 3.15 Hz

Phase [degrees]	45	90	135	180	225	270	315
0	0.581	0.119	0.165	0.078	0.157	0.588	0.659
45		0.330	0.171	0.590	0.147	0.393	0.659
90			0.660	0.401	0.480	0.388	0.313
135				0.344	0.905	0.130	0.200
180					0.636	0.017*	0.003**
225						0.015*	0.003**
270							0.944

(b) 4 Hz

Phase [degrees]	45	90	135	180	225	270	315
0	0.503	0.024*	0.025*	0.011*	0.108	0.238	0.877
45		0.045*	0.063	0.035*	0.255	0.310	0.592
90			0.900	0.310	0.705	0.105	0.021*
135				0.401	0.532	0.256	0.084
180					0.220	0.131	0.023*
225						0.397	0.880
270							0.329

(c) 5 Hz

Phase [degrees]	45	90	135	180	225	270	315
0	0.579	0.022*	0.009**	0.003**	0.016*	0.850	0.574
45		0.005**	0.002**	0.002**	0.015*	0.950	0.476
90			0.607	0.285	0.472	0.043*	0.068
135				0.450	0.528	0.017*	0.010*
180					0.062	0.011*	0.004**
225						0.017*	0.002**
270							0.697

Table 1. (contd.) Statistical significance of difference between the relative discomfort of dual-axis vibrations with different phase between the two single-axis components. Wilcoxon matched-pairs signed ranks tests. *: $p < 0.05$, ** $p < 0.01$.

(d) 6.3 Hz

Phase [degrees]	45	90	135	180	225	270	315
0	0.047*	0.201	0.874	0.36	0.783	0.409	0.448
45		0.484	0.013*	0.009**	0.032*	0.144	0.244
90			0.108	0.105	0.420	0.506	0.844
135				0.656	0.504	0.223	0.293
180					0.628	0.172	0.363
225						0.307	0.813
270							0.965

(e) 8 Hz

Phase [degrees]	45	90	135	180	225	270	315
0	0.146	0.374	0.394	0.806	0.311	0.156	0.326
45		0.532	0.726	0.165	0.038*	0.026*	0.027*
90			0.806	0.783	0.234	0.018*	0.068
135				0.392	0.083	0.020*	0.108
180					0.573	0.183	0.529
225						0.571	0.975
270							0.844