Postural Movements in Standing Human Induced by Ship's Rolling and Pitching—I.

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船体運動による直立時の身体動揺—I.

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動揺する船舶の甲板上で開脚，閉脚，マンの姿勢，片足などの直立姿勢を取っている人の身体動揺を実測した。測定結果を頭部および重心のパワースペクトル，重心の動揺軌跡，動揺速度の分布，船の揺れと身体の揺れの間の位相差などによって解析し，船体の動きに対する人体の動的応答を調べた。

Abstract

The subjects who were standing aboard rolling ship with several foot positions, such as open stance, close stance, the Mann's posture, and one foot were observed. Power spectra of the head and the body center of gravity (CG), velocity distribution of CG, sway paths of CG of the body, and phase angle between rolling of ship and the CG of the body were analysed, and the dynamic response of the body due to the ship's motion was discussed.

1. Introduction

In the author's last paper⁽¹⁾, postural movements and developments of nystagmus in standing human on the rotating table were investigated. This paper deals with observations and analyses of the postural movement of a subject standing with several postures aboard a rolling ship.

The ship's motion was relatively small throughout the field measurements of this time, so that authors are considering actual measurement of postural responses related to seasickness on board a ship in heavy rolling on the basis of the present fundamental research.

2. Methods

The center of gravity (CG) of the subjects on board a tug boat (grt 86.77 tons, overall length 21.15m, breadth 6.50m) afloat freely were measured by means of a statokinesimeter settled on the ship's deck. Sway of the subject's head was also measured by means of an accelerometer attached to the helmet. The experimental methods are mostly the same as described in the previous paper⁽¹⁾. The (anterior-posterior and left-right) sway of the head and the CG of the subject's body were recorded electro-magnetically by use of a data recorder. Figure 1 (A) shows the case of a human standing toward the ship's stern aboard a tug boat, and Fig. 1 (B) the case of a human standing toward starboard on deck. The phase angle between the ship's

Fig. 1 Arrangement of Instrument.

S: Statokinesimeter y: Posterior→Anterior
V: Video-camera x: Left→Right

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roll and the sway motion of the head, and between the ship's roll and the motion of CG of the body were calculated by use of a signal processor. The subjects examined are 4 males (2 in fifties, 2 in twenties) and 3 females (all in twenties) in good health.

3. Experimental results and consideration

3.1 Ship's sway and measured responses of the postural movement

Table 1 shows the resonance frequency and the significant angle of the ship's roll and pitch. Figure 2 indicates the dynamic behaviors of the head and the CG of the body of a subject standing in close stance with eyes closed, under the conditions of roll and pitch depicted below. This experiment was performed on board a tug boat loosely tied to the shore, and rolling was prevalent compared to pitching. The postural movement proved to be affected mainly by the rolling motion.

Table 1 The resonance frequency and the significant angle of ship's roll and pitch.

	Significant angle	Resonance frequency
Roll	1.5~2.5°	0.22 Hz
Pitch	0.5~1.0°	0.30 Hz

Fig. 2 Dynamic behaviors of several characteristics in upright standing (close stance) with eyes closed.

3.2 The Lissajous's figures of the sway of CG of a subject's body

Figure 3 shows the Lissajous's figures of the sway of CG of a subject's body as shown in Fig. 1 (A). It is natural that the sway area indicating the spread of the sway path when open stanced is smaller than that when close stanced, and the sway area when eyes open is also less than that when eyes closed.

Figure 4 shows the dynamic behaviors of a subject when a ferry boat passed near by. The sway of the CG of the body was small at the times A and B when the ship's roll was as much as 0.5 degree, while the sway was increased when a ferry passed by, and the roll angle was 2 degrees at the time C.

3.3 Power spectra of the sways of the head and the CG of the subject's body

Roll was prevalent compared to pitch throughout the experiment of this time, so that the subject experiences roll, i.e. sway of lateral directions, when he stands upright facing toward the ship's stern, shown in Fig. 1-(A). When a subject stands toward ship's side, he experiences the anterior-posterior (A-P) motion of the body, as shown in Fig. 1-(B), Figures 5 and 6 show the power spectra of the lateral motions of the head and the CG of a subject, in the case of Fig. 1-(A). The power spectra of the ship's roll and pitch were also depicted.

Figure 5 shows CG of the body sways mainly in harmony with the roll frequency. The component of the power spectra corresponding to the roll frequency when close stanced is larger than that when open stanced, and the component when eyes closed is also more than that when eyes open. Thus, a subject proves to be swayed in harmony with the ship's motion when open stanced with eyes closed, whereas the subject controls his own posture in response to the impulses through eyes when close stanced with eyes open, so that the component of power spectra other than the frequency of roll appears. The power spectra when subject was close stanced with eyes close indicate the augmentation of spectral component of 1.0 Hz compared to when open stanced with eyes closed. Since the Mann's posture and one foot are both unstable foot steps and the subject

Fig. 3 Sway paths of the body center of gravity in case of several foot positions.

Fig. 4 Sway paths of the body center of gravity.

Fig. 5 Power spectra of posture movements of the body center of gravity (lateral directions).

Fig. 6 Power spectra of posture movements of head movements (lateral directions).

Fig. 8 Power spectra of Mann's posture (lateral directions).

Fig. 7 Power spectra of posture movements of the body center of gravity (A and B) and of the head movements (C and D), (antero-posterior directions).

Fig. 9 Power spectra of posture movements of one foot (lateral directions).

is hard to keep upright standing, the spread of spectral components gets wider. When a subject is standing on one foot as shown in Fig. 1-(A), he faces toward the stern, and the power spectra for one foot (Fig. 5) consist of the same component as the ship's pitch. (The resonance frequency of roll and pitch are 0.22 Hz and 0.30 Hz, respectively.) The power spectra of the sway of the head (Fig. 6) is alike to that of the CG of the body (Fig. 5), whereas the spectra of the Mann's posture and one foot consist of higher component of frequency. If we enlarge the frequency range of the latter spectra, Fig. 8 and Fig. 9 were obtained. The figures indicate the frequency spectra of sway of the CG of the body was less than 2 Hz, whereas the spectra of sway of the head extend up to the 7 Hz region. Figure 7 shows the power spectra of antero-posterior sway of the CG of the body in the case of rolling motion of the ship, shown in Fig. 1-(B). The figure (antero-posterior directions) shows almost the same behavior as Fig. 5 and Fig. 6 (lateral directions), but the higher component of the power spectra are relatively prevalent. Since the subject respond to the ship's sway and has the freedom of taking up the postures by bending knees and hip, the frequency range of power spectra seems to get wider.

3.4 Phase lag of sway of the head and CG of the body in response to the ship's roll, and velocity distribution at every small intervals of sway path

Gains, phases, and coherencies were calculated for subjects standing in various posture, where the input was ship's roll, and the output is the lateral sway of the CG of the body. Figure 10 is an example. We will take the gain as unit when the CG of the body displaces 1 cm in response to the ship's roll of one degree. Figures 11 and 12 show the mean and the S.D. of the phase lag of the head and the CG of the body in response to the ship's roll. The number of the subjects are four males and three females in health. Those figures were prepared by regarding the phase angle of body sway nearly at the resonance frequency of ship's roll as a representation of the phase lag. Figure 11 depicts the phase lag of lateral sway of the body corresponding to Fig. 1-(A), Figure 12 also shows the phase lag of A-P sway of the body corresponding to Fig. 1-(B).

Figure 13 (middle) shows the sway spreads of the CG of the body, Figure 13 (below) and (left) depict mean velocity distribution at 5mm intervals of lateral and A-P displacements of sway respectively. The figure explains that the postural balance is maintained by maximizing the back-taking speed at the extremes of the A-P sway.

Figure 14 shows the case of a subject standing on one foot with eyes open, and indicates the wider spread of sway and the speeds of lateral and A-P sway gets higher. (Note: the scale of the figure is different from the one in Fig. 13). The back-taking speed at the extreme of the posterior tilt is approximately 160 cm/sec.

Periodic motion of posture inherent to human has two components; one, whose period is approximately 50 seconds, is said to have causal relation to the periodic motion of leg's joints, and the other, whose

Fig. 10 Relations between ship's rolling and lateral postural movements of the body center of gravity.

Fig. 11 Phase lag of the head and the body center of gravity to rolling (Fig. 1-(A)).

Fig. 12 Phase lag of the head and the body center of gravity to rolling (Fig. 1 (B)).

Fig. 13 Sway spreads of body center of gravity and mean velocity distribution for every 0.5 cm displacement.
case: open stance, eyes closed

Fig. 14 Sway spreads of body center of gravity and mean velocity distribution for every 0.5 cm displacement.
case: one foot, eyes open

period is as small as 1-2 seconds, is caused by the proprioceptive reflex of skeletal muscles⁽²⁾. In this experiment, postural motion due to bend of leg's joint was mainly synchronized to the ship's proper rolling period. When a subject's posture such as the Mann's posture or one foot gets unstable, and he is nearly falling down, postural balance is thought to be maintained by two ways; one is relatively fast proprioceptive reflex of skeletal muscles, and the other is relatively slow visual and vestibular reflexes⁽³⁾.

Conclusions

Postural motion of a subject who is standing upright on deck in open stance, close stance, the Mann's posture or one foot was measured on board a rolling ship.

Experimental results obtained are as follows:

(A) Postural sway due to the ship's motion of lateral directions

- (1) The area covered by the sway paths of CG of a subject's body in close stance gets larger than that in open stance, and the area of that with eyes closed is larger than that with eyes open, thus the former posture is unstable to the sway.
- (2) The power spectra of the sway of CG of the subject's body has the prevailing frequency component corresponding to the proper period of the ship's roll. That is, posture response follows after the ship's roll, and is explained mainly as the periodic motion of leg's joints. When eyes are closed, power spectra in close stance has higher frequency component than that in open stance. When a subject takes the Mann's posture or standing on one foot, power spectra compose much higher frequency components, and postural balance is maintained by the servo-mechanism of antigravity muscles.
- (3) The phase lag of the head and the CG of the body behind the ship's roll when eyes closed is smaller than that when eyes open, and that in open stance is less than that in close stance. Since the positions of two foot steps and the hip structures a triangle when open stanced, postural stability is maintained. When open stanced, a subject maintains his posture by simply moving hip laterally in response to the ship's roll. Thus, the phase lag of postural movement in response to the ship's motion when open stanced is considerably small.

When close stanced, posture is unstable due to the inverse-pendulum motion of the body, and the phase lag of the body behind the ship's roll gets longer, and the sway angle of the inverse-pendulum motion of the body is also larger.

The phase lag of the postural movement behind the ship's roll when eyes open is larger than that when eyes closed, but the sway angle of the body is small. Thus, postural response is thought to be delayed and made less by visual control.

- (4) Power spectra of the sway of CG of the body is not more than 2 Hz, whereas that of the head extends up to the 7 Hz region.
- (5) The mean velocity at every small intervals of sway path gets maximum at the extremes of A-P motions or lateral motions, thus postural balance is maintained.

(B) Postural sway due to the ship's motion of anterior-posterior (A-P) directions

- (6) The dynamic behaviors of postural movements in response to the ship's motion of A-P directions is similar to that for the ship's motion of lateral directions explained in (1) through (5). However, since human has the freedom of taking up postures by bending ankles, knees and hip in response to the ship's motion of A-P directions, thus that frequency range of power spectra gets wider.

References

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質 疑 応 答

川島利兵衛: 1. 頭の動揺とは何ですか。

2. コヒーレンスを求めた時の入出力は何ですか。

3. “自己受容反射” とは一言でいえばどう説明したらよいでしょうか。

今枝彬郎: 1. 被験者が着用しているヘルメットの上部に取りつけた加速度計により前後と左右の方向の頭部の

傾きを測定しました。そしてその時間的変化が頭部の動揺です。

2. 入力 は船体のローリングの角度、出力 は頭部の傾斜角度または重心の移動距離です。

3. 人が直立姿勢をとっている時、倒れそうになり骨格筋が伸びると筋からの信号が脊髄を通じて求心性神経に伝えられ反射的に再びその筋が収縮して身体のバランスを保ちます。これを伸張反射といいます。この反射は倒れそうになって筋が伸張すると反射的にその筋が直ちに収縮するので自己受容反射 proprioceptive reflex といいます。

井上篤次郎：片足で立った場合、静止面でもふらつくが、揺れている船上での実験を検討する時にはその差について考える必要があると思います。もう一つ片足で立つとすぐ倒れそうになり足をつくこともあると思いますが、スペクトル推定をするときサンプル数が少なくなる懸念はありませんか。

今枝彬郎：御説のように片足の場合は非常に不安定ですので閉眼では身体の動揺が大きく倒れてしまって実験できないので、開眼の場合で船の揺れの小さい時に実測しました。倒れずにバランスを保ちつづけた時間内でのデータでスペクトルを推定しました。静止面でのふらつきと船上でのふらつきを比較するのは大切で次の機会に詳しく調べたいと思っています。スペクトルを見たら分りますように片足の場合は殆んど船体運動に同期するスペクトル成分はなく、船体運動に関係なく自分自身が不安定で倒れそうになりバランスをとっていることが分ります。ただ Fig. 1 (A) の片足の時、足先が船首尾方向を向いているので足底が前後方向のピッチングの影響を受けてピッチングのスペクトル成分が少し出ております(図5参照)。