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An experimental study on individual walking speed during ship evacuation with the combined effect of heeling and trim

Jinlu Sun [a,b], Yafei Guo [a], Changhai Li [a], Siuming Lo [b], Shouxiang Lu [a,*]

[a] Skate Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, China
[b] Department of Architecture and Civil Engineering, City University of Hong Kong, Hong Kong, China

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ABSTRACT

Ship listing and motion is one significant factor that affects safety evacuation in passenger ship by reducing individual walking speed. A ship corridor simulator was developed to investigate the combined effect of heeling and trim on individual walking speed when freely and fast walking circumstances were considered. The value of the heeling angle α considered in the experiment is 0, ±5, ±10, ±15°, and the value of the trim angle β is 0, ±5, ±10, ±15, ±20°. It is found that average individual walking speed could be greatly attenuated, when the heeling and/or trim angles are considered. Compared to trim angles, heeling angles show less impact on average individual walking speed. When trim angle $\beta > 0°$, the gradient of average individual walking speed along with the increasing heeling or trim angle is larger compared to that when trim angle $\beta < 0°$. The maximum value for average individual speed could be achieved at the heeling angle α of 0°, with trim angle β ranging from −15° to −5°, since the average individual walking speed increases obviously under gravity effect during trim-down conditions ($\alpha = 0°$) as the trim-down slope increases from 0° to 10°. The results will provide fundamental guidance to the practical ship evacuation.

1. Introduction

Passenger ship, especially the cruise ship, as one of the most reliable means for marine transportation, has gained increasing attention in recent years (Fowler and Sørgård, 2000). Although the possibility for the occurrence of serious accidents is rather low, the consequences could be destructive, e.g. the capsize of Chinese passenger ship-Oriental Star in 2015 has caused 442 life casualties (Meng et al., 2016). In the event of such a catastrophe, an efficient evacuation could be the promising means to minimize its consequence (Hystad et al., 2016).

In 1995, passenger ship St. malo wrecked on the rocks and took in water. Despite that the weather conditions for evacuation on that occasion were favorable, the ship was subject to listing and motion. This, however, had extended the evacuation time for the 308 passengers aboard to 77 min, after the initial alert notification for emergency (Hystad et al., 2016; Lee et al., 2003, 2004; Lockey et al., 1997). Nevertheless, the evacuation time in the exercise under static conditions was only 8 min. This indicates that evacuation simulation exhibits certain limitation in that the practical scenarios of rolling, pitching and listing have not been taken into account in model design.

Individual walking speed is an important parameter for evaluating the personnel evacuation performance. Generally, individual walking speed will be affected by several factors including: the complexity of the evacuation environment, and the particular of individuals (gender, height, weight, age, etc.). The cerebellum also plays an important role in the control and adaptation of gait (Vinueza Veloz et al., 2015). When the environment is inclined, experimental subjects tend to feel dizzy, and their gait would alter as well, all of which results in the loss of individual walking speed. Furthermore, the changes of fraction between planta and the floor would also have a quite considerable impact (Chen et al., 2016; Park et al., 2004).

There are numerous publications highlighting human behaviors in evacuation with ship listing and in motion. National Maritime Research Institute of Japan (NMRI) reported that the average walking speed of the experimental subjects (70–120 students with an average age of 20) in ship corridor was 1.4 m/s (Katsuhara et al., 1999; Katuhara et al., 1997, 1999). Australian Maritime Engineering Cooperative Research Centre (AME CRC), and Korea Maritime University conducted several observations in ship corridors and on stairs and correlated the basic experimental data such as gender distribution and age distribution to walking speed

* Corresponding author.
E-mail address: sxlu@ustc.edu.cn (S. Lu).

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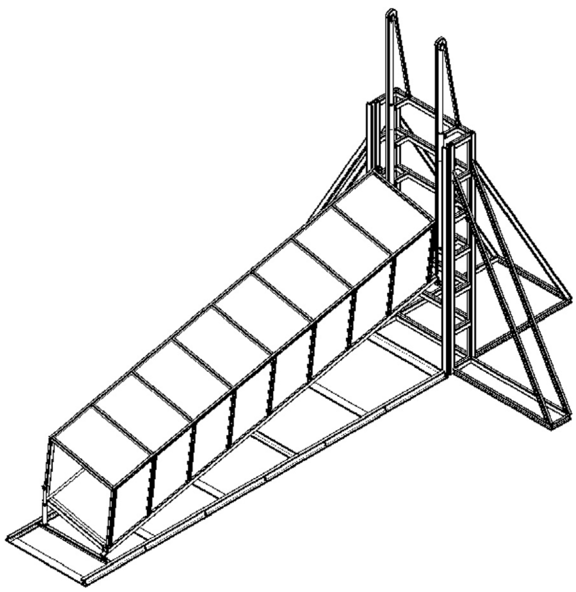

Fig. 1. A schematic of the developed ship corridor simulator.

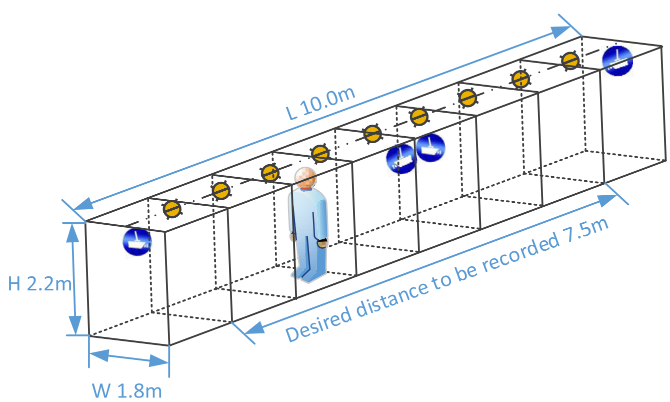

Fig. 2. The internal structure of the developed ship corridor simulator and the instrument arrangement therein.

(Brumley and Koss, 2000; Hwang, 2013). NMRI and Research Institute of Marine Engineering of Japan (RIME) constructed a walkway model with a fixed length of 6.0 m and changing width as 1.2, 0.9, and 0.6 m for static inclination tests (Murayama et al., 2000; Yoshida et al., 2001). The normal walking speed of the experimental subjects (19 male and 2 female adults) was 1.23–1.25 m/s. Under heeling conditions, no significant changes in walking speed of the experimental subjects could be observed, as the heeling angle increased to 20°. By contrast, the walking speed decreased from 1.38 m/s to 0.82 m/s, with the increasing trim angle from −20° to +20°. Fleet Technology Limited (FTL) and Fire Safety Engineering Group (FSEG) in University of Greenwich devoted joint efforts to establish the Ship Evacuation Behavior Assessment Facility (SHEBA). The SHEBA featured a 7 m (L) × 4 m (W) sized cabin, a 10 m (L) × 2 m (W) sized corridor, and a flight of stairs, in which a series of experiments were conducted (Galea et al., 2012; Glen, 2004; Glen et al., 2001; Nicholls et al., 2012; Valanto, 2006). Moreover, similar investigations has also been reported by AME CRC (67 adult males and females between 18 and 25 years of age), the Dutch research institute TNO Human Factors (150 people between the ages of 18 and 83), and Korea Research Institute of Ships and Ocean Engineering (KRISO) (18 male students and 3 female students) (Bles et al., 2002; Boer and Skjong, 2001; Kim et al., 2004; Koss et al., 1997; Lee et al., 2004; Valanto, 2006; Vanem and Skjong, 2006). Based on the experimental results above, Germanischer Lloyd proposed a model for describing the change of speed reduction (defined as the ratio of individual walking speed in inclined conditions to that in normal conditions) with different trim or heeling angle. The proposed model had been applied in AENEAS, a ship evacuation software widely used in ship design (Valanto, 2006).

Despite that individual walking speed tested under single heeling and trim conditions have been reported, the available statistic for quantitative analysis is limited. Besides, the effects of heeling and trim experimental conditions on individual walking speed deserve further understandings. Hitherto, the combined effect of both heeling and trim on individual walking speed has been rarely reported, which is more likely to happen than single heeling or trim conditions when ship accidents occur. Therefore, this work mainly focuses on the quantitative analysis of the combined effects of heeling and trim conditions on individual walking speed. And the experimental results will provide fundamental guidance to the practical evacuation in ship accidents.

2. Experimental section

2.1. Experimental setup

To investigate the factors affecting human walking speed, a dead-end ship corridor simulator with a size of 10.0 m (L) × 1.8 m (W) × 2.2 m (H) was developed, as presented in Fig. 1. Two sets of hydraulic systems were equipped within the perpendicular tracks respectively, along which the ship corridor simulator could slide. One set of the equipped hydraulic systems is responsible for raising one side of the ship corridor simulator, and the other one is responsible for raising one end of the ship corridor simulator. The maximum tilt angle of the ship corridor simulator is 30° in both directions, which could be measured by two inclinometers equipped on the ship corridor simulator respectively.

Fig. 2 shows the internal structure of the developed ship corridor simulator and the instrument arrangement therein. A total of 9 lamps is located in the centerline of the ceiling with an interval of 1 m. A 4-channel electrical monitoring device with 4 cameras is arranged to record the behaviors of experimental subjects within the desired distance during the experiment. Moreover, experimental subjects in the ship corridor simulator would lose sight of the external environment, which could promote the reality of walking in the inclined corridor.

2.2. Experimental design

It has been proposed that ship would capsize as the heeling angle exceeds 30° (Valanto, 2006). However, our preliminary experiment results indicated that experimental subjects would slip and fall, when the heeling angle exceeded 15° or the trim angle was greater than 20°. Considering the safety of the experimental subjects, the designed experimental conditions in the inclined corridor simulator are shown in Fig. 3. The value of the heeling angle α is 0, ±5, ±10, ±15°, and the value of the trim angle β is 0, ±5, ±10, ±15, ±20°. A total of 17 students (24.6 ± 1.45 years old, 167.7 ± 6.4 cm, and 60.5 ± 9.1 kg) was involved as the selected experimental subjects, and their particulars are listed in Table 1. In each inclined conditions, experimental subjects were required to walk in the ship corridor simulator one by one in freely and fast walking modes in order to investigate the relationship between fast walking speed and freely walking speed. Freely walking mode refers to the normal walking state, while fast walking mode is to walk as fast as possible rather than run up.

2.3. Experimental procedure

Operating instructions including walking freely, walking fast, start walking and stop walking were issued by the experimental commander using wireless walkie-talkie devices for communication. Once the experimental subjects received the instruction, they completed the