Experimental Measurement Design of Required Operating Torque for Hinged Door

Shih-Bin Wang, Chih-Fu Wu, Kai-Chieh Lin, and Shin-Chung Jain

***Abstract*—The lacks of operating standards and measurement methods make the universal design of the door difficult to achieve. Thus, in this study, a force measurement system for hinged door operation has been developed, and a series of operating force measurement for hinged door were carried out with and without door closer. Specially, a quarter arc guiding track was designed to confirm that the door required operating torque could be measured successfully. The results showed that as door closers were applied, the operating forces increased greatly. There were two characteristic measuring signals composed of the initial force and the maximum force existed significantly. The use of the door closer was proved to increase the required operating torque greatly, which even caused inconvenience for users. Regardless of whether use a door closer or not, the consideration of door operating torque in the universal design was proved to be decisive.**

***Index Terms*—Required operating torque, force measurement system, door closer.**

I. Introduction

Door operation composed of a series of clever actions is the most common problems confronted in our daily life. Thus, it is necessary for door designer to respect all kinds of people as the prerequisite to design; i.e. to meet the universal design (UD). With exploring questions neglected, the implementation of UD can make our life safer and more convenient. Preiser and Smith (2010) [1] had defined seven principles for Universal Design mainly based on the notion of usability to evaluate existing products and environments, guide the design process and train designers and users. Not only considering the demands of user's convenience and human factor, UD also gives overall checks of the disadvantaged and looks over a wider range of users such as the physical disabled, the elder and children. Japanese scholar Mr. Nakagawa Satoshi (2008) [2] suggested that due to different ethnicities person, operation mode of a product is also different. UD has evolved as a significant component for sustainable life and social development within the individual's own dwelling and the community as well (Kadir and Jamaludin, 2013 [3]). Especially for service facilities in public occasions, the higher, wider and heavier doors are usually adopt, so the door operability must be paid more attention. Therefore, how to design a door with versatility so that all kinds of people can live more conveniently and safely is indeed an important issue.

According to the manner of operational force, doors can be divided into force normal to door, e.g. push or pull of hinged doors, and force in plane (parallel with the door horizontally or vertically), e.g. sliding or folding doors (S.-K. Chang, C. G. Drury, 2007) [4]. Due to the function of use based on type of pressure applying on the door, the door was classified by Thompson (1972) [5] as four types of door: hinged doors, swinging doors, sliding/folding doors and revolving doors. Among all kinds of door, hinged door is one of the most frequently doors used that attract our interest to investigate.

With the progress of technology, the applications of varied kinds of door closers become popular especially for the door in public occasions. The door closer is commonly used as auxiliary device of the door, which is a mechanical device that can close a door at a controlled speed. In general, someone opens a door, after the door is automatically closed. Thus, it's a self-closing device, most commonly used on fire doors and main doors to help prevent spread of the fire and smoke in the case of fire happening.

Door exists in the environment around us; people use it every day with high frequency. However, studies have shown that doors are still causing many people injured, but analyses due to the viewpoints of human factors are still a few. Chang and Drury (2007) [4] pointed out that the main four factors of door design should be noted as the door location, door material, the type of door and door on sharp part. Norman (2012) [6] evaluated Doors and frames to review their capabilities and limitations.

There were many researchers investigated on the door design about the use of visual perception. Norman (2002) [7] revealed that the design of the door could give a successfully implication for operators to push or pull without having to rely on the symbols indicate. Su (2005) [8] further explored the affordance of push and pull in daily life to rethink the "push" and "pull operation design of the door.

As considering door operating, most of research seemed to concentrate on which way to move (Kline and Beitel, 1994 [9]; Wallace and Huffman, 1990 [10]) rather than how much the opening force would be influenced by factors. The analysis of door operational behavior (Chang and Drury, 2007 [4]) suggested that people of a shorter stature used to have a larger force to open a bigger door, and the restoring torque of the door should be less than 30 Nm. Although, specifications for door operating force have been developed

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by earlier building codes (Metric Handbook, 1999 [11]; BOCA Code, 1999 [12]; Uniform Building Code, 1997 [13]; 2000 International Building Code Handbook, 2000 [14]), still no measurement evaluation systems are further presented.

People are observed to use any available manners to increase their force production, such as application of their body weight to help their arm force, two hands instead of one hand, feet or other items, etc. Only measurements on actual operating force and time could provide direct evidence on the objective human function. Thus, it is worthy to develop a door measurement evaluation system for a further investigation.

II. Experiment

Human factors consider interactions between human and door that influence door operation deeply. The main factors included user individual capabilities, door characteristics, environmental characteristics, and social characteristics, etc. (Chang, 2004 [15]). Any study of doors as exploring these issues had to either keep unwanted issues constant or randomize their impacts (Drury, 2005[16]). To avoid the effects caused by the interactions among these factors, thus, an operating force measurement system was designed to open the door by a machine. Two conditions of hinged Door were utilized here: one with door closer and the other without door closer. There are two ways to open these manual doors: one is to push, and the other is to pull. Usually, people open a door by the help of their body weight such as leans forward to push or backward to pull. Thus, pulling a door is more laborious for most people. Thus, in this study, the operating mode of pulling a door was preferred in developing door force measurement system.

A door operating force signal processing system was firstly developed to measure the operating forces, which consisted of four parts: (1) force sensor (Load Cell), (2) signal amplifier, (3) analog to digital (A/D) signal capture card, (4) computer (with the software of WaveScan, the analysis software of MS Excel), as shown in Fig. 1.

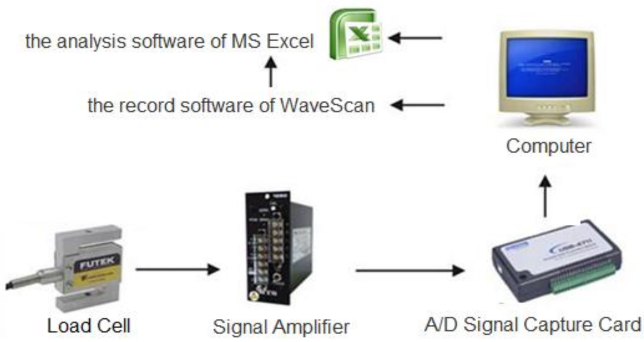

Fig. 1. The signal processing system of the door operating force.

As door was pulled to open, the pulling force was exerted on one end of the load cell, and the detected force signals through the signal line were transmitted to the signal amplifier on the other end. Then, by A/D signal capture card, analog signals were transferred into digital signals, which finally sent to the computer. The software of the WavesScan was used to read and record the data, and then the MS Excel software was applied for data processing to obtain the time-varying force diagram.

The hinged door was pulled by a servo gear motor so that the operation could be repeated. The power of the motor utilized was up to 0.75KW, where the maximum torque output transferred by a gear speed reducer was up to 26.7 KgW, a torque enough for all weights of the doors used in this experiment. Through a reel, the steel rope was droved at the speed ranging from 8cm/s to 50cm/s, speeds similar to people usually use. Accompanied by the behaviors of users' individual capabilities, the servo motor could adjust its output force according to the load imposed. In other words, as the door was heavy, the door was also pulled slowly, a condition similar to user' operate a heavy door slowly.

A hinged door with height of 2000mm and width of 900mm was applied. The hinged door was utilized in two cases: one was installed with door closer which consisted of three sizes: small (15~30Kg), medium (25~45Kg) and big (40~65Kg), as shown in Fig. 2 (http://www.ezset.com.tw) [17], and the other had no door closer applied. The position of the hinged door handle was sited at 800mm from the door hinge and 1000mm above the floor. The entire force measuring system of hinged doors was set up as shown in Fig. 3.

Fig. 2. A door closer.

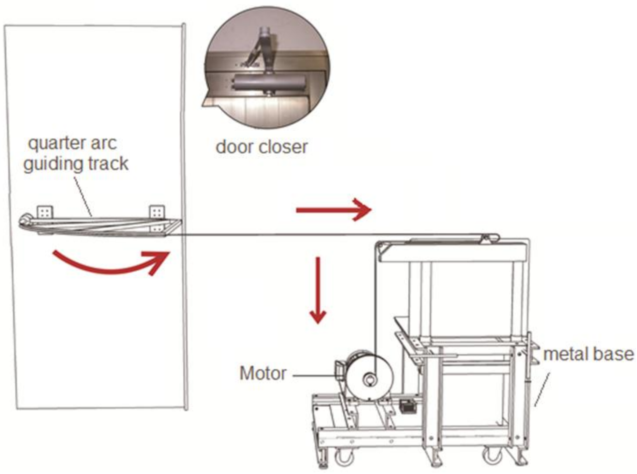

Fig. 3. The force measuring system of the hinged door.

In order to measure the operating force at the position of handle, the door handle was first removed and a hole was generated, and then a load cell was fixed into the hole. The pulling force of the door was given at one end of the load cell, which was driven by the motor through a reel to pull the steel rope directly. Also, the motor and the reel were placed on a metal base so that their heights were adjustable. In reality, the door opening speed for users differ due to their individual capabilities. Therefore, the rotary speed of the motor was designed to be controlled within 400rpm to 2400rpm, so the steel rope speed droved by the motor was within 8.37cm/s to 50.24cm/s, a condition similar to the opening speed of common users.

The size of the door pulling force directly affects whether the door open smoothly, but the key factors is the operating torque which is the cross product of torque arm and operating force, i.e. $\vec{T}=\vec{r}\times\vec{F}$, where the torque arm is the horizontal vector from the axis of the door hinge to the door handle. The intersection angle of these two vectors will affect torque size, and the largest torque output will be obtained as the intersection angle approaches 90°. Thus, if people want to operate less laboriously, the pulling force had better keep normal to the plane of the door as far as possible. Therefore, if the steel rope was directly used to pull the door handle, firstly, the pulling force would be normal to the plane of the door, but as the door opening angle increases, the rope would be finally parallel to the plane of the door.

In order to improve this situation and ensure the pulling force of the steel rope keeping normal to the door throughout the door operating process, a more similar condition that meet user' s operational behavior, a quarter arc guiding track was designed and mounted on the door at the handle position as shown in Fig. 3. The guiding track was made by aluminum alloy that had a smooth surface, so friction force could be avoided possibly when the steel rope sliding on it. Due to the application of the self-designed quarter arc guiding track, the pulling force could keep normal to the door during the whole process as the door rotatory angle changed from zero to 90°, and thus the torque arm could be fixed to the same size of 800mm in the whole measuring process. Hence, once the operating forces were measured in the experiment, the operating torque could be obtained directly by multiplication of the operating force and the torque arm. Consequently, the operating torque and the operating force with the same trend could be measured together.

Also, the weight of the doors was designed to be adjustable by the application of some packs of papers hanged on the door as counterweights. For the case of door closer applied, the hinged door was installed with small, medium and big size of door closer, respectively, according to the counterweight of the door.

III. Results

To explore how the use of door closer would impact door operating behavior, both doors considered not only the case without door close but also the case with door closer. Three different weights for the hinged door were selected: 15Kg, 30 Kg and 45Kg. The load cell in the hole of the removed door handle was pulled by the steel rope driven by the motor, and then detected the operating force. The speeds of the motor to pull the door were controlled at six speeds from 8.37cm/s to 50.24cm/s. The results were described below.

A. Operating Force of Hinged Door without Door Closer

As shown in Fig. 4, the operating force measurement of the hinged door 30 Kg was recorded at a steel rope speed of 16.75cm/s. For all the diagrams of force-time varying curves in this study, it was noted that the horizontal axis was the time (sec), and the vertical axis was the force (*N*), where force value was negative because the force was pulling force. For the hinged door, the door could rotate from zero to 90°. At the door rotatory degree of 90°, however, the device of the quarter arc guiding track would collide to the wall. In the actual door opening process, most of people will not open the hinged door completely up to 90° but to a certain degree enough for their bodies to pass. Therefore, the motor was controlled to pull the hinged door until the door rotated to about 60°, and then stopped the motor.

The Fig. 4 showed that the signals of measuring force were characterized by a vibrating phenomenon, and a maximum pulling force happened. The operating force had the same trend with the operating torque, i.e. the cross product of arm and operating force ($\vec{T}=\vec{r}\times\vec{F}$), which could be elucidated below.

To open the door successfully, the operating torque must overcome the moment of inertia generated by the weight of the door and the friction torque caused by the door hinges. If the operating torque exceeded the total resistant torques combined by the door inertia moment of and hinge friction torque, the door would instantly rotate and its speed might be even higher than the speed of the steel rope. Thus, the tightened steel rope would be relaxed, and then the door lost the driven force instantly. Until the movement of the steel rope caught up with the movement of the door, the steel rope would be tightened and the measuring force would lift again. Thus, the vibrating phenomenon happened.

Also, the door ought to overcome the maximum static friction from a standstill to rotate, so a maximum force arose firstly, and then decayed gradually due to the fact that the operating force just need to conquer the dynamic friction force. As shown in Fig. 4, a maximum pulling force occurred at the top value of the first peak as 6N.

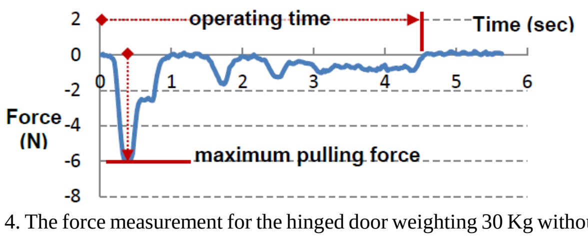

Fig. 4. The force measurement for the hinged door weighting 30 Kg without a door closer at steel rope speed of 16.75cm/s.

TABLE I: Force Measurement for Hinged Door with Different Weights

steel rope speed (cm/s)	15 Kg		30Kg		45 Kg	
	maximum force(N)	operating time(sec)	maximum force(N)	operating time(sec)	maximum force(N)	operating time(sec)
8.37	2.7	7.86	6.7	8.36	9.7	9.74
16.75	3.0	4.08	6.0	4.54	8.0	5.68
25.12	2.3	2.84	8.0	3.08	8.6	4.08
33.49	2.9	2.78	7.2	2.62	6.6	3.62
41.87	4.4	1.94	7.6	2.3	7.1	3.16
50.24	4.4	1.56	7.5	1.82	8.2	2.96

As shown in Table I, the operating forces of 3 weights of the hinged door (15Kg, 30Kg and 45Kg) for door operating process at varied steel rope speeds was measured. The results revealed a common trend that as the door was heavier, the measured force was greater. Also, a quicker steel rope speed caused a larger measured force in a shorter operating time. These results elucidated that a larger operating force is required to open a heavier door. Furthermore, a quicker steel rope speed, a condition similar to the case of user with superior capabilities, led to a shorter operating time to open a door.

B. Operating Force of Hinged Door with Door Closer

The hinged door here was installed with three sizes of door closers: small, medium and big, in accordance with the adjustment of three weights of the doors: 15Kg, 30Kg and 45Kg, respectively. The speeds of the motor to pull the door were controlled at six speeds. A measuring result of the hinged door with a big size of door closer at steel rope speed of 8.37cm/s was shown in Fig. 5.

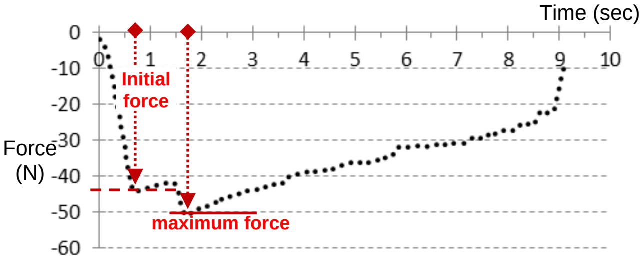

Fig. 5. The force measurements for the hinged door with a big size of door closer at steel rope speed of 8.37cm/s.

TABLE II: OPERATING FORCE FOR HINGED DOOR WITH DOOR CLOSER

size of door closer	steel rope speed(cm/s)	initial force(N)	maximum force(N)	operating time(sec)
small	8.37	22.7	23.7	9.08
	16.75	26.9	26.9	4.94
	25.12	28.4	28.4	3.32
	33.49	25.9	25.9	2.76
	41.87	25.7	25.7	2.88
	50.24	26.8	26.8	2.52
medium	8.37	37.6	45.5	9.20
	16.75	42.0	45.8	4.68
	25.12	42.6	47.9	3.20
	33.49	48.7	48.7	2.56
	41.87	48.2	48.2	2.96
	50.24	47.7	47.7	2.80
big	8.37	44.4	50.9	9.08
	16.75	49.7	50.0	4.8
	25.12	50.7	51.0	3.42
	33.49	51.0	51.0	2.72
	41.87	49.2	54.6	2.30
	50.24	49.2	53.3	1.70

The results showed that, with a door closer, a phenomenon of fluctuated force signal was less obvious, as compared to the conditions without a door closer. This could be explained as the damping effects of the door closer reduced the vibrating phenomenon of the force signal. Also, the experimental results showed that usually a smaller peak of the initial force occurred first, and then a higher peak of the maximum force arose. The initial forces and the maximum forces at varied steel rope speeds were collated as shown in Table II.

Since the door ought to overcome the maximum static friction from a standstill to rotate, an initial force generated firstly. The required maximum force was the force necessary to overcome both the hydraulic damping force and the dynamic friction force. It was reasonable that the operating force should decrease subsequently because the dynamic friction force was always smaller than the maximum static force. However, the hydraulic damping force caused by the door closer became greater with the increasing door rotatory angle, so the door operating force increased to the maximum force. Moreover, the phenomenon of two peaks of forces was more obvious for a bigger size of door closer at a slower steel rope speed. As shown in Fig. 5, at the steel rope speed of 8.37cm/s, the initial force was obtained at the value of 44.4N, and the maximum force was obtained at the value of 50.9N. It was noted that the phenomenon of two peaks of the operating force, i.e. the initial force and the maximum force, were less obvious when the steel rope became faster and only one peak occurred clearly, where the initial force overlapped the maximum force together.

The results showed that a larger operating force was required to open the hinged door with a bigger size of door closer. Also, a quicker speed of the steel rope, i.e. a faster velocity to open the door, resulted in a larger operating force so that the door could be opened in a shorter operating time.

IV. DISCUSSIONS

This research developed appropriate measuring systems and methods to perform the measurement of door operating force. The experiments were set up and performed in controllable laboratory due to the fact that strength measurements are difficult to carry out for doors used in daily life environment. Also, the strength of opening a door was driven by the motor, so it didn't need to consider the human factors such as gender, age, stature, physical state, etc. The experiments were designed and performed only for the most common doors including hinged door and sliding door, where the weight of the doors were adjustable by utilizing counterweights hanging on the door. Therefore, the experiments of door operating force without door closer applied were conducted first, and followed by the installation of the door closer, and then compared their results to assess the effect of the door closer on the door operation.

A. Use of Door Closers

The results showed that as a door closer was applied, no matter hinged door or sliding door, the operating force was enhanced significantly. A heavier hinged door required a greater operating force to open. Also, a quicker speed of the steel rope, i.e. a faster velocity to open the door, resulted in a larger operating force so that the door could be opened in a shorter operating time. As compared with the case of no door closer used, taken the hinged door at the steel rope speed of 16.75cm/s for an example, the operating forces of the 15Kg door increased from 3N to 26.9N, and those of 45Kg door increased from 8N to 50N.

The results also indicated that, without a door closer, the signal of the operating force fluctuated more intensely. Furthermore, the maximum force happened in the first peak where the static friction in the beginning was overcome. After the operating force exceeded this maximum force, door could be opened successfully. However, with door closer applied, the phenomenon of fluctuated force signal was less obvious. This could be explained as the damping effects of the hydraulic door closer reduced the vibrating phenomenon of the force signal. The experimental results also showed that often a smaller peak of the initial force occurred at first, and finally a highest peak of the maximum force arose. The first peak of the initial force occurred when the static friction was overcome. However, with the increasing door opening rotatory degree, the hydraulic damping force became greater, so the maximum force was the required force to overcome the hydraulic damping force and dynamic friction force. Furthermore, a smaller difference between these two forces generated as the steel rope speed was quicker; whereas an obvious difference existed as the steel rope speed was slower. The experiments showed that, especially for the sliding door, the increasing hydraulic resistance caused a longer time to open the door.

As mentioned above, only the maximum force was the key force to open the door without a door closer. However, both the initial force and the maximum force were the key force to open the door as using a door closer. The fact that the difference of the initial force and the maximum force was unobvious and became a same value at quicker steel rope speed illustrate that users with excellent body force could open the door smoothly. For users with the smaller body force, such as children, women, the elderly, wheelchair users, it would be more difficult to open the door because a large gap between the initial force and the maximum force. First, they had to overcome the initial force due to the static friction force of the door, and then they must surmount the maximum force due to the damping force of the door closer. Therefore, it needs to especially consider the damping effect as applying a door closer to design a universal door.

B. Required Operating Torque of the Hinged Door

A lot of specifications of door operating force have been set in the world. The building codes consulted earlier [11]-[14] had specified maximum forces ranging from 22 to 132N depending on door type. These specifications do provide a reference of the design of the door operating force. For a sliding door, it is adequate. However, for a hinged door, not only the operating force, but the operating torque is the key to decide whether door opens smoothly and successfully and a valid measure for suggestion of the major determinant of human adaptation to open the door. Chang (2007) [4] suggested that the restoring torque of the door should not be greater than 30 Nm. But they did not propose the assessment factors considered and how to measure. So far, the specification of door operating torque had not yet been presented.

As shown in Fig. 3, the idea of the large torque output could be reached by a self-designed quarter arc guiding track mounted on the door to ensure the pulling force of the steel rope maintained perpendicular to the door throughout the door operating process. Since the torque arm of the operating force in the measuring process was maintained at the same size of 800mm, the operating torque could be obtained directly by multiplication of the operating force with the torque arm. Due to these special experimental designs, the operating forces and torques had the same trend. Therefore, the time when the maximum torque occurred was also the time when the maximum force produced in the whole operating process, and thus this time could be characterized as the transcending time when the door was identified to be opened successfully. Also, the maximum torque occurred could be regarded as the required operating torque.

The required operating torque for three weights of hinged doors without closer were summarized as listed in Table III. The results showed that variation of required torque was not obvious for different door opening speeds at the same door counterweight. When the door was heavier, the maximum torque was greater, which range was only about 2 ~ 8Nm. This value was far less than the minimum restoring torque of 30Nm recommended by Chang (2007) [4]. It illustrated that the door was easy to be opened in the case of no door closer. Furthermore, the transcending time could be shortened at a fast door opening speed; however, a heavy door would increase the transcending time.

Moreover, the required operating torque for hinged door with three sizes of door closers were summarized as listed in Table IV. The results showed that the required operating torque did not vary obviously as door opening speed increased for the same door closer applied. It seemed that the main factors affecting the operating torque were the door itself characteristics such as the weight and the applied door closer. Among these three cases of door closer applied, only 15Kg door installed with small size of door closer, whose required operating torque was less than the recommended value of 30Nm by Chang (2007) [4], which was less laborious to be opened. Compared with the cases without door closer used, it indicated that the use of the door closer would greatly increase the required door operating torque, even caused the inconvenience to operate.

The results also showed that the faster door opening speed and larger size of door closer were adopted, the higher the required operating torque was obtained. Furthermore, as the door opening speed was slower and the larger size of door closer was applied, the transcending time increased. The results demonstrated that better individual capability was necessary to open the door at a bigger size of door closer and at a faster door opening speed.

As experimental results mentioned above, two peaks of initial force and maximum force appeared as a door closer was utilized. A large gap between these two forces meant that the task of the door was completed segmentally and inappropriately. This condition usually occurred especially for the users with poor individual capability, such as children, women, the elderly, wheelchair users. On the contrary, as the value of the initial force approached to the maximum force even to the same value, the door operating behavior could be confirmed to complete smoothly.

Compared Table III with Table IV, the results showed that after the installation of the door closer, the required operating torques for the three counterweights of door increased significantly: from 2.3 Nm to 20.7Nm for the 15Kg door, from 5.8 Nm to 39.0Nm for the 30 Kg door, and from 6.4 Nm to 40.8Nm for the 45 Kg door, respectively. As door closer was applied, these results manifested that the user's individual capability should be substantially improved in order to open the door successfully. Thus, it needs to carefully consider the application of door closer to accomplish a door with universal design.

TABLE III: REQUIRED OPERATING TORQUES FOR HINGED DOOR WITHOUT CLOSER

door opening speed(cm/s)	15 Kg			30Kg			45 Kg		
	maximum force(N)	transcending time(sec)	required operating torque(Nm)	maximum force(N)	transcending time(sec)	required operating torque(Nm)	maximum force(N)	transcending time(sec)	required operating torque(Nm)
8.37	2.7	0.38	2.2	6.7	0.42	5.4	9.7	0.48	7.8
16.75	3	0.34	2.4	6	0.36	4.8	8	0.36	6.4
25.12	2.3	0.22	1.8	7	0.32	5.6	8.6	0.34	6.9
33.49	**2.9**	**0.24**	**2.3**	**7.2**	**0.28**	**5.8**	**8**	**0.3**	**6.4**
41.87	4.4	0.22	3.5	7.6	0.28	6.1	8.1	0.28	6.5
50.24	4.4	0.2	3.5	7.5	0.26	6.0	8.2	0.26	6.6

TABLE IV: REQUIRED OPERATING TORQUES FOR HINGED DOOR WITH CLOSER

Size of door closer	steel rope speed(cm/s)	initial force(N)	maximum force(N)	transcending time(sec)	required operating torque(Nm)
small	8.37	22.7	23.7	0.72	19.0
	16.75	26.9	26.9	0.52	21.5
	25.12	28.4	28.4	0.56	22.7
	33.49	**25.9**	**25.9**	**0.52**	**20.7**
	41.87	25.7	25.7	0.44	20.6
	50.24	26.8	26.8	0.46	21.4
medium	8.37	37.6	45.5	1.12	36.4
	16.75	42.0	45.8	0.86	36.6
	25.12	42.6	47.9	0.88	38.3
	33.49	**48.7**	**48.7**	**0.8**	**39.0**
	41.87	48.2	48.2	0.74	38.6
	50.24	47.7	47.7	0.7	38.2
big	8.37	44.4	50.9	1.9	40.7
	16.75	49.7	50	1.3	40.0
	25.12	50.7	51	1.02	40.8
	33.49	**51**	**51**	**0.78**	**40.8**
	41.87	49.2	54.6	0.78	43.7
	50.24	49.2	53.3	0.74	42.6

V. CONCLUSIONS

In this study, an appropriate measurement systems and methods of operating force for hinged door has been established, especially considering the use of a door closer. Due to a self-designed quarter arc guiding track mounted on the door, the operating torque for the hinged door could be measured simultaneously.

The results revealed that as door closer was applied, the fluctuated phenomenon of force signals obviously reduced, but the operating force substantially increased. As a bigger size of door close was applied, the required operating torque became greater. The required operating torque would apparently increase as the door opening speed increased. The results demonstrated that the use of the door closer made the operational behavior more complex also caused a substantial increase in physical load. Thus, the universal design of the door with closer was very crucial.

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