

Latest Trend and Safety and Reliability Technology of Rolling Stock Doors

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ABSTRACT

Fuji Electric has developed and commercialized a door operating equipment (linear motor system and FCPM system) with a simplified mechanism by applying the motion direction of a motor to the linear motion of the side sliding door. The door operating equipment for the side sliding door of rolling stock is an important component that ensures the safety of passengers when they are boarding, alighting and traveling, and it may affect trains' punctuality. Consequently, the system is required to be safe, reliable, high functional, and maintenance saving. These characteristics have been achieved in a safety evaluation that was conducted at the design stage and that included failure mode effect analysis and hazard analysis, and they have also been ensured with control technologies such as triple feedback, external force suppression and push-back control.

1. Introduction

Doors for electrical rolling stock are pieces of equipment that are in direct contact with passengers with each door operating on its own independent system, and since rolling stock are often equipped with a large number of doors, they are required to have a high level of safety, reliability and functionality, while also being maintenance friendly. Fuji Electric started supplying its electrical driven doors in 1999. As of the end of 2014, our doors are being utilized in over 30,000 different door locations in Japan and overseas.

This paper describes the latest trends and safety and reliability technology of rolling stock doors.

2. Electrical Driven Door System and Components

2.1 Features of electrical driven doors

In Japan, pneumatic operating door systems have been widely adopted, but in recent years, electrical driven door systems have been quickly gaining popularity. In contrast to this, electrical driven door systems have been popular for many years overseas⁽¹⁾.

Compared to pneumatic operating doors, electrical driven doors have the benefit of not requiring air piping while also eliminating disturbances due to equipment aging. Electrical control systems are characterized as enabling the reproduction of fixed open-close patterns and open-close times, and this can contribute to reducing the initial cost and maintenance cost for the rolling stock system. Furthermore, the electrical driven system creates flexibility in the functions of the controller and enhances safety in the event that passengers or luggage are pinched by the doors. It also

makes use of data transmission technology to enable streamlined pre-operation checks and greater intelligence while providing robust self-diagnosis functions for the door unit.

Fuji Electric's electrical driven doors utilize power electronics technology and control technology, and employ a system for driving side sliding doors in the same drive direction as the motor. As a result, they have simplified the door drive mechanism and enhanced safety and reliability through improved detection of obstruction.

2.2 Linear motor door operating equipment

Fuji Electric has developed and is supplying the market with linear motor door operating equipment that makes it possible to operate the side sliding doors in the same direction as the motor. By operating the doors in the same direction as the motor movement, it is possible to eliminate the use of superfluous motion converting mechanisms. This enhancement ensures safety in the case that passengers or luggage are pinched by the doors by enabling quick detection of the danger. The linear motor adopts a permanent magnet linear synchronous motor that allocates the permanent magnet to the stator and the coil to the mover. The configuration of the linear motor (cross-section view) is shown in Fig. 1.

There are 2 types of operating systems for applications utilizing double side sliding doors. One is a system for separating the doors via 2 motors, and the other is a system that uses a mechanism for connecting and operating the left and right doors via a single motor. Determining which system to adopt depends on the safety and budget requirements of the railway operator. Fuji Electric is providing products that meet the needs of both requirements.

When operating the doors with 2 linear motors,

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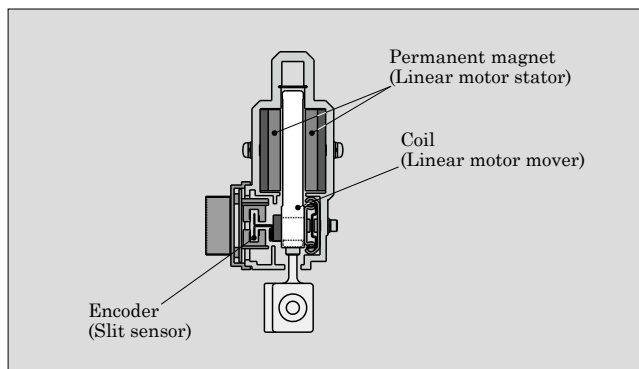


Fig.1 Configuration of linear motor (cross-section view)

a simple configuration is employed for directly opening and closing the doors via the movements of both linear motors. A configuration in which the left and right doors are opened and closed via 2 linear motors is shown in Fig. 2. This system is utilized by New York City Transit R160 trains (NYCT-R160 trains) in about 5,800 door locations (see Fig. 3).

When operating the left and right doors with a single motor, a rack and pinion are used for the interlocking mechanism to enable door operation. A con-

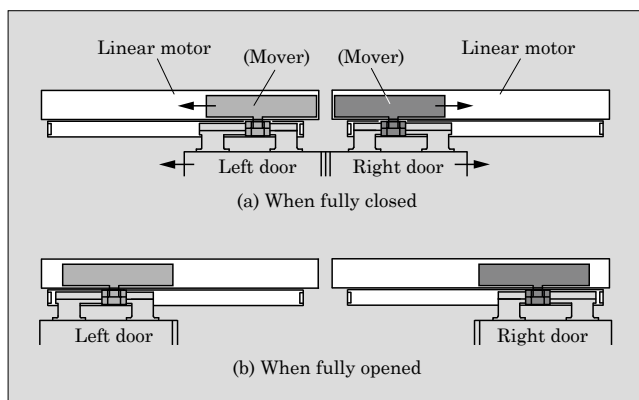


Fig.2 Configuration of linear motor (2 motors) door operating equipment



Fig.3 NYCT-R160 train and linear motor door operating equipment

figuration in which the left and right doors are opened and closed via a single linear motor is shown in Fig. 4. This system is utilized in Japan and overseas, including Series E233 trains operated by East Japan Railway Company (JR-East), at more than 20,000 door locations (see Fig. 5).

2.3 FCPM system based door operating equipment

The Flat Cup Permanent Magnet Motor (FCPM) system operates side sliding doors by rotating the pinion of the rack-and-pinion mechanism by means of the FCPM of the rotary motor. A system in which the left and right doors are opened and closed via a single rotary motor is shown in Fig. 6. The left and right doors are opened and closed by operating the upper rack and lower rack by means of rotating the pinion directly connected to the motor shaft. It is a flat-shaped FCPM since the motor needs to be stored in the narrow space inside the lintel. This FCPM system has achieved further weight reductions, while also possessing the same characteristics as a linear motor capable of using the directional motion of the motor to accommodate the movement of the side sliding doors. This system has been employed in a dozen rolling stock projects in both

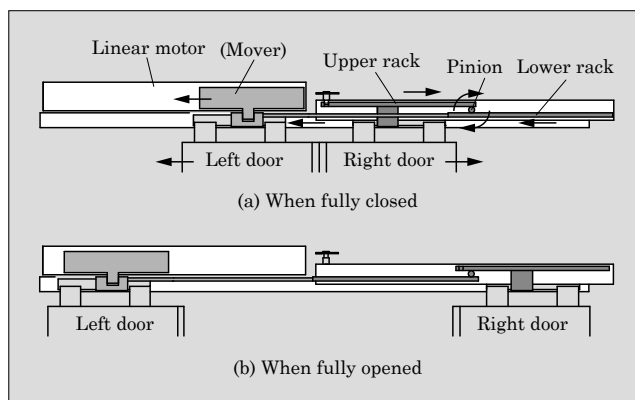


Fig.4 Configuration of linear motor (1 motor) door operating equipment



Fig.5 JR East Series E233 train and linear motor door operating equipment

the Japanese and overseas markets, and has started being utilized in transit systems such as Yurikamome (see Fig. 7).

(1) Motor (FCPM)

The motor for the door is required to meet several conflicting requirements. For example, it needs to have a powerful closing force during rush hour, but a safe and gentle door closing force in the case of pinching, the opening and closing time and full opening stopping position must be completely identical with no variation, and size reductions are needed to meet the size limitations of the lintel, while also ensuring easy maintenance for long-term use. Based on these needs, we developed the FCPM for the dedicated door motor so that it is characterized as having a thin profile, low speed and high torque, as well as high-precision positioning detection. In order to implement the control technology described in Chapter 3, it integrates a high-precision optical encoder, and achieves a 0.01 mm position resolution and 750 μ s thrust response from 0 to 100%, as well as a door pressure of 500 N during stand still.

(2) Power transmission mechanism

Biparting doors are operated via a single motor by means of a power reversal mechanism (direction

changing device) consisting of an upper rack, lower rack and pinion mounted to the motor shaft end (see Fig. 4, Fig. 6).

This FCPM system-based door operating equipment consists of a rack-and-pinion mechanism and improves sensibility of obstruction for direct signaling to door opening and closing movements without the deceleration that is common in ball screw type systems. Furthermore, it has a simple structure that is less susceptible to failure, and it is highly reliable requiring almost no maintenance.

One of the rolling stock operated in the North American market has restricted space between the connecting doors of the train cars, and installation was not possible without reducing the length of the direction changing device. For this reason, we developed an opening and closing system achieving a reduced length by utilizing multiple racks, which have a length of about half the width of the fully opened/closed doors, and by engaging the racks with the pinions (see Fig. 8).

When the doors open and close, a force is applied to the relay rack, which is able to move horizontally, from the power supply pinion of the motor shaft. After this, the relay pinion, which is attached at the tip of the movable relay rack, rotates through engagement with the fixed rack which is mounted to the case. The

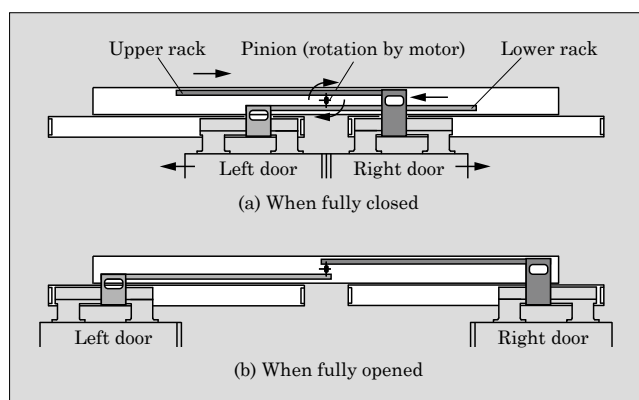


Fig.6 Configuration of FCPM system based door operating equipment



Fig.7 Yurikamome rolling stock and FCPM system based door operating equipment

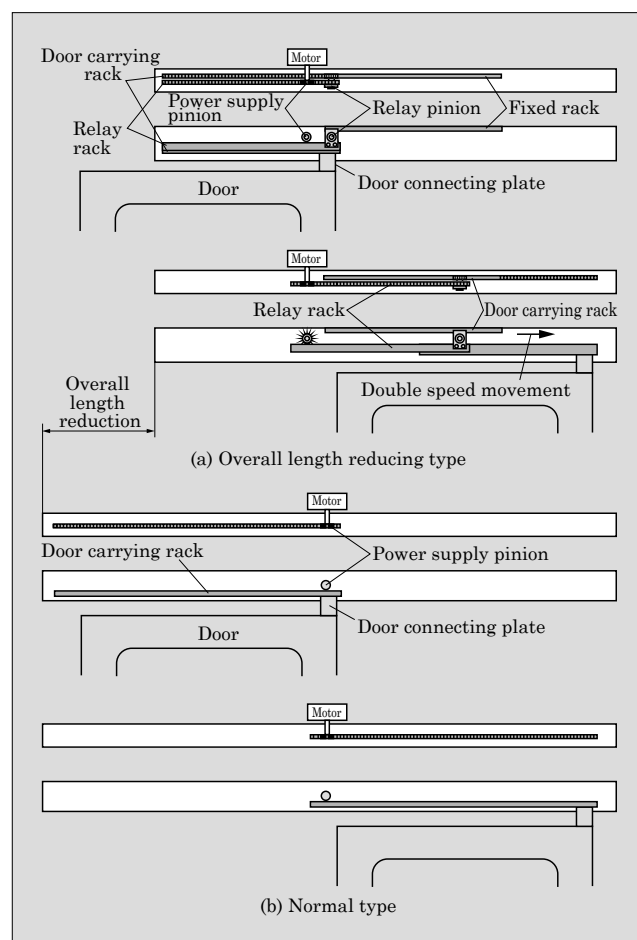


Fig.8 Direction changing device

relay pinion, which moves in the advancing direction and rotates in the advancing direction, moves the horizontally movable door carrying rack to open and close the doors.

By making the length of the relay rack, fixed rack and door carrying rack each approximately half the width of the door opening, the total length of the door opening and closing system has been reduced to about three-quarters of the size of conventional systems.

2.4 Locking and unlocking unit

The locking unit ensures that the door is in the closed position, and it is one of the most important components for ensuring the safety of the door. Fuji Electric has employed a mechanism that utilizes a lock pin for the locking unit. The unit also incorporates a mechanism for releasing the locked state when the doors move to open. The mechanism offers two systems: the self-unlocking system via the thrust in the door opening direction generated by the motor (see Fig. 9) and the solenoid unlocking system via a solenoid whose power supply is not shared with the motor (see Fig. 10). Both systems allow for manual door unlocking during times of emergency when there is no control power.

Furthermore, some customers require that the locking and unlocking mechanism be independent from the door opening and closing system, which is differ-

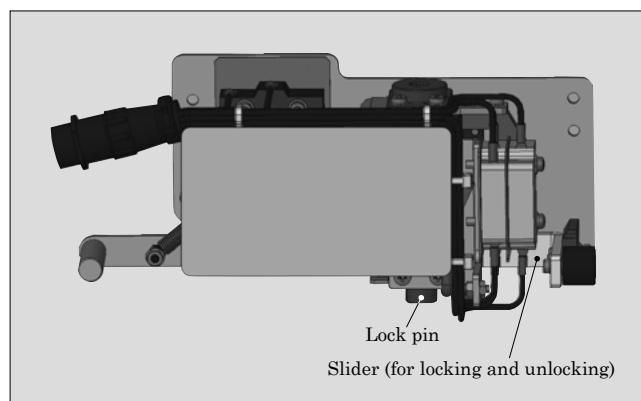


Fig.9 Locking and unlocking unit (self unlocking type)

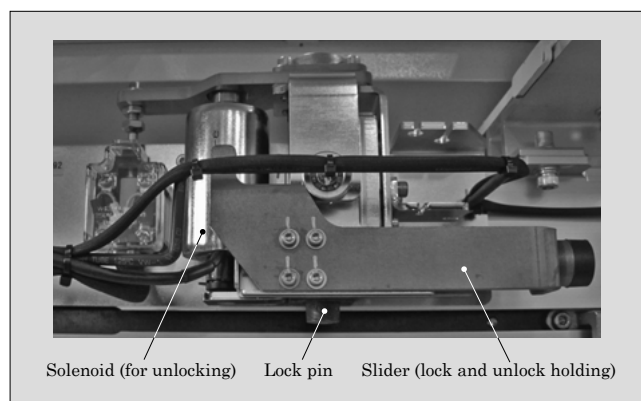


Fig.10 Locking and unlocking unit (solenoid unlocking type)

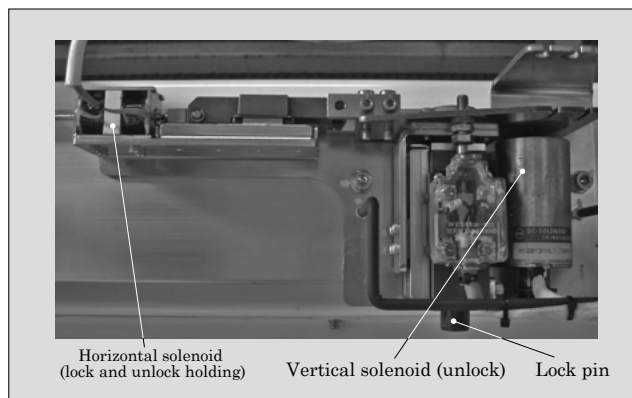


Fig.11 Locking and unlocking unit (door opening/closing and locking/unlocking independent type)

ent from conventional systems that linked the locking and movement mechanism with door opening and closing movements. In order to meet these needs, we have developed a mechanism for locking and unlocking that is independent of the door opening and closing system (see Fig. 11).

2.5 Emergency unlocking and isolation unit

It is also required that, in addition to the opening and closing function itself, there be a function allowing for forced manual unlocking and releasing of the doors during times of emergency when there is no control power, as well as function for temporarily isolating specified faulty doors, while still enabling the rolling stock to operate normally.

The emergency door unlocking unit, as shown in Fig. 12, has conventionally taken the form of a handle, which is installed on both the inside and outside. The locking and unlocking unit mounted to the door operating equipment is mechanically connected by means of a metal wire, and unlocking can be done by operating the handle. Some specified units, depending on a specification, are operated by crew members with keys instead of a handle. Furthermore, there are also other various requirements such as allowing passengers access to the unlocking mechanism, but only allowing crew members to restore the unit to its default state

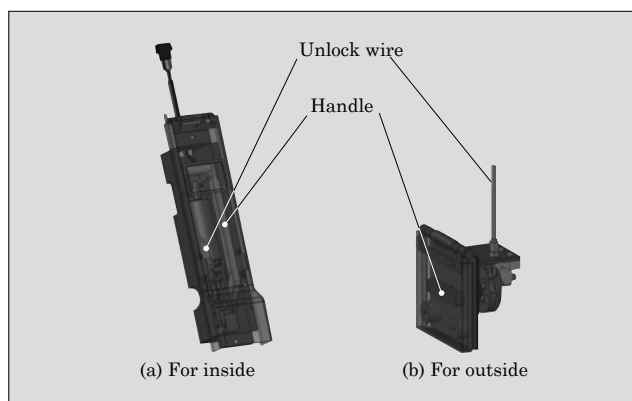


Fig.12 Emergency door unlocking unit

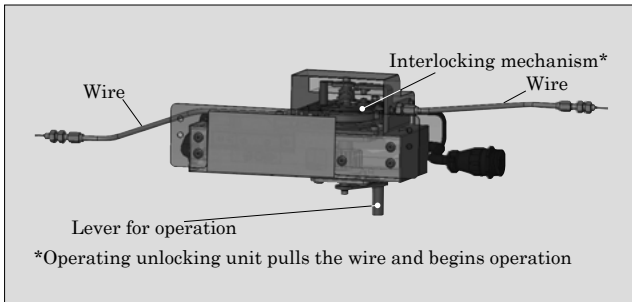


Fig.13 Isolation unit (with interlocking mechanism)

using a dedicated key. Also, specifications related to the operating force of the handle differ according to customer requirements. When designing the unit, it is necessary to consider the laying route (length, number of bends, etc.) of the frame of the release wire, while also calculating the operation force needed to satisfy the specifications.

The isolation unit mechanically maintains the closed position for specified faulty doors, while bypassing door closure detection conditions and lock detection conditions to forcibly establish a state that satisfies conditions allowing the entire train to set off on its course. In North America, the American Public Transportation Association (APTA) standard creates a dependency between the emergency door unlocking unit and the isolation unit. In other words, it stipulates that operating the emergency door unlocking unit in the isolation state will force the doors to be unlocked if the isolation state is automatically canceled. An example of an interlocking mechanism is shown in Fig. 13.

2.6 Controller

The controller of the electrical driven doors implements high-precision and stable door opening and closing control through utilizing the features of the FCPM. In recent years, lots of information is measured and recorded in order to monitor not only control activity for opening and closing the doors, but also to confirm the state of the doors and analyze trouble during failures. The unit comes equipped with an automatic testing function for understanding the health of the doors, which are susceptible to daily changes, by means of self diagnostics. It is also compatible with communication protocols such as RS-485 based high-level data link control (HDL) and Ethernet*1 in order to transmit information to conductors and train drivers through use of a monitor. The controller utilizes a single 32-bit high-performance CPU chip capable of simultaneously processing door control, communication functions and automatic testing functions. The software comes with a self-update function, and it can quickly perform specification and parameter changes

*1: Ethernet is a trademark or registered trademark of Fuji Xerox Co., Ltd.

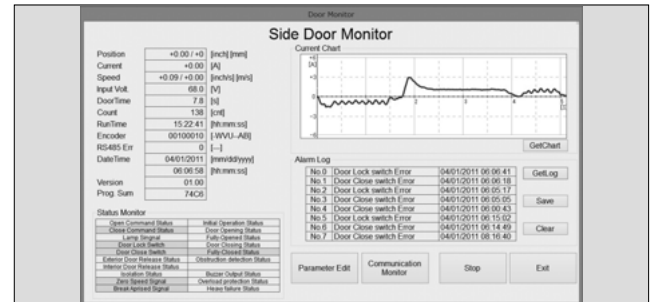


Fig.14 PTU screen example

as well as carry out version upgrades via the communication function and batch updating for the software by means of the portable test unit (PTU) described in Section 2.7.

2.7 PTU

There are many moving components incorporated into rolling stock doors, and since the doors directly interact with passengers, they determine whether a train can continue operation when a failure occurs. Therefore, determination needs to be made quickly regarding whether operations can continue by utilizing self diagnostics and displays that detail the cause of failures. The PTU is a dedicated piece of software used during failures that allows crew members to connect a PC to the door unit in order to display the details of the failure, perform monitoring and implement self diagnostics (see Fig. 14).

Expertise is required when making determination about failures, and ultimately, this is something that should be done by the manufacturer. However, since a quick determination needs to be made on site, we have prepared the PTU for use by our customers in order to contribute to smooth operations by supporting maintenance work on site.

3. Safety and Reliability Technology

3.1 Safety assessment during the design stage

Doors for rolling stock are required to operate with a high degree of safety and reliability since they are important pieces of equipment related to the boarding and alighting of passengers and they ensure the safety of passengers during train traveling. Therefore, the safety design concept must be closely examined during the design review process by means of techniques including failure modes effects and criticality analysis (FMECA) and hazard analysis, and the design must be revised when it does not fulfill the needed requirements. In addition, the doors need to be vandalism resistant to ensure that the door system does not suffer from any impact due to aggressive operation and mischievous acts. This is especially true of doors developed for the overseas market.

The RAMS analysis items required of rolling stock in North America are given below. An example (im-

Item Name / Functional Identification	Function	Failure Mode	Failure Cause	Failure Effects	Safety Class (SIL)	Failure Detection Means	Available Contingency/Compensating Measures	Design Actual/Recommendation
Slider Horizontal Direction	To pull Lock Pin (for locking operation) / To pull Lock Pin (for unlatching operation)	Unlatched fails to latch.	Failure of lock pin / Failure of power supply / Bad or loose connection.	Unable to pull up the lock pin. (Unable to lock or unlatch). Driver cannot open the door after opening. Possible delay. Passengers cannot board/alight a car by the door opening. Possible delay.	NA	III	Controller will send a "Close Door" signal to the door drive unit. In addition, "Open Door" signal is displayed in the cab. Controller will continue to function.	High reliable release adopted. / NA
Slider Vertical Direction	To lift Lock Pin (for locking operation) / To pull Lock Pin (for unlatching operation)	Unlatched fails to latch.	Failure of lock pin / Failure of power supply / Bad or loose connection.	Unable to pull up the lock pin. (Unable to lock or unlatch). Train cannot start. Possible delay.	NA	III	Function check of subunit.	High reliable release adopted. / NA
Slider Horizontal Direction	To lock and unlock when door is closed and opening and closing operation.	Failure of lock pin / Failure of power supply / Bad or loose connection.	Unable to lock and unlock.	Door cannot be opened. Possible delay. Passengers cannot board/alight a car by the door opening. Possible delay.	NA	III	Visual check.	Slider is designed to maintain the door in the closed position. / Periodical inspection of door lock device.
Slider	To move smoothly the Lock Pin.	Failure of roller / Failure of power supply / Bad or loose connection.	Unable to keep lock/unlock condition. (Keep the condition of door lock).	Door can be opened but door cannot be closed. Possible delay. Emergency brake applied. Train will be delayed.	NA	III	Visual check.	Slider is designed to maintain the door in the closed position. / Periodical inspection of door lock device.

Fig.15 FMECA example (image)

age) of FMECA is shown in Fig. 15.

- (1) Reliability Prediction Report
- (2) Availability Prediction Report
- (3) Maintainability Analysis
- (4) Preliminary Hazard Analysis
- (5) FMECA (failure modes effects and criticality analysis)

3.2 Control technology

In order to further enhance safety and stability in the opening and closing control of doors, we are researching and developing a new control technology.

We have made use of our servo technology in the basic control of the doors, and we are utilizing triple feedback control which includes feedback for the thrust (current), speed and position in order to ensure delicate and smooth door operation (see Fig. 16).

The door closing delay during rush hour is one problem peculiar to doors that is often taken up for discussion. This problem occurs when the control pattern cannot follow up properly as a result of the need of a drive force during crowded rush hour operation that is more than 10 times the force required during normal operation. Therefore, we have adopted “external force suppression control” to carry out stable operation by measuring and negating external force. We have utilized an experiment for simulating a rush hour scenario in which 8 people are forcibly leaning on the doors. Under such a condition a delay of 10.0 seconds or more would be generated using a conventional control method, but we have achieved stable operations while significantly reducing delay to just 0.2 seconds (see Fig. 17, Table 1).

Electrical driven doors utilizing a lock unit for maintaining a firm closed door position are faced with

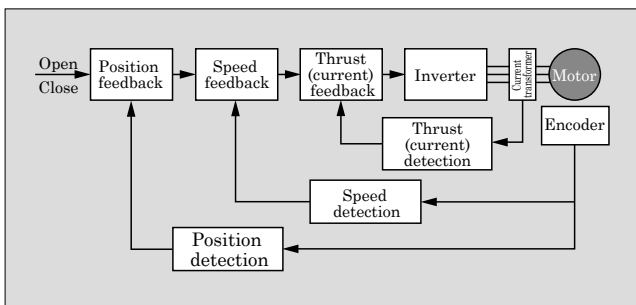


Fig.16 Triple feedback control

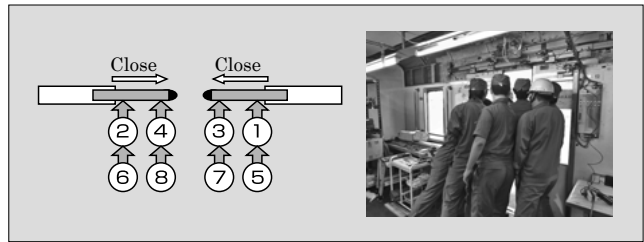


Fig.17 External force suppression control experiment

Table 1 Closing time based on rush-hour scenario

No. of people	Proposed model		Conventional model	
	Closing time (s)	Delay (s)	Closing time (s)	Delay (s)
0	3.33	—	3.15	—
1	3.36	+0.04	4.09	+0.94
2	3.41	+0.08	9.38	+6.23
4	3.51	+0.18	14.03	+10.88
8	3.55	+0.22	15.05	+11.90

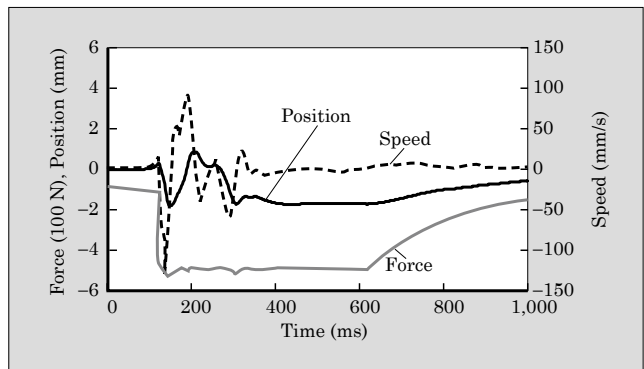


Fig.18 Push-back control experiment

challenges such as outfitting adjustment difficulties and failures. Therefore, we have been researching “push-back control” in order to achieve a firm closed door position that utilizes the motor. By maintaining the closed door position via motor control, we are aiming to ensure safety through the use of a simplified lock unit without the need to implement detailed adjustments during outfitting. Instant determination is made regarding doors that are opened as a result of external forces, such as passengers trying to force open doors, and prevention of these types of scenarios is made through a strong push back (see Fig. 18).

Verification has been made with the control system mounted to rolling stock currently in use. The results showed that for 150,000 door opening and closing events, approximately 300 instances of forced door opening events occurred, but the doors were never opened more than 1.0 mm, thus demonstrating the safe control of the system.

3.3 Standby redundant system controller

There are many doors in a train, and if one of the doors were to fail, this could cause an impact on not only the rolling stock, but also the entire route.

Therefore, the doors must be highly reliable. If a failure were to occur using a conventional door unit at an intermediate station, passengers would have to move to an alternate train, and this would cause a huge delay to occur. Fuji Electric has duplicated the internal structure by adopting a standby redundant configuration, and as a result, high reliability can be maintained during failures by utilizing the controller on the stand-

by side for carrying out control (see Fig. 19).

4. Postscript

Fuji Electric's doors for electrical rolling stock, configured with either a linear motor system or FCPM system, are being used by customers in Japan and overseas. In the future, we plan to further enhance the safety and reliability of our doors for electrical rolling stock in order to satisfy the expectations of our customers, while being continuously conscious of the doors' intimate proximity to passengers and extremely important role in the stable operation of the rolling stock.

References

- (1) Umezawa, K. Power Electronic Devices for Railway Vehicles. FUJI ELECTRIC REVIEW. 2012, vol.58, no.4, p.175-181.

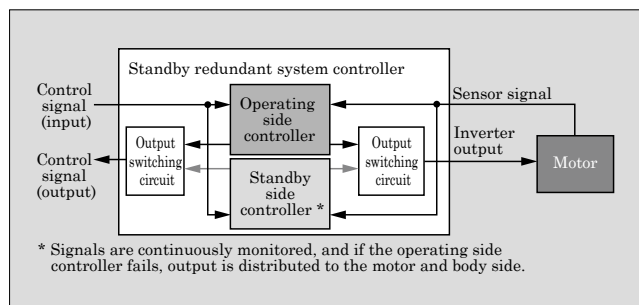


Fig.19 Standby redundant system controller





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