# Robust and Safe Control Based on Disturbance Observer for Train Doors

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***Abstract -*** **Accidents caused by automatic doors frequently occur. Infrared sensor or force sensor is often used for automatic doors to detect the presence of a human, and ensure the safety of doors. But in the case of train doors, we can not use infrared sensor and force sensor because of several reasons. In addition, train doors should be gated exactly not to disturb the train services. This paper suggests two methods using disturbance observer. One is novel impedance control, and another is impact force suppression control. These methods are not only safe for human but also robust. Two proposed methods were implemented on train door experimental machine, and its validity was verified experimentally.**

Fig.1. Typical situations stuck between doors

## I. INTRODUCTION

Today, electrical automatic doors are in widespread use for various applications, because automatic doors are useful for temperature management, humidity management, acoustical insulation, air proof and so on. In addition, automatic doors are essential element for barrier-free design. But in late years, many serious accidents involving human life have occurred. Such a serious accident is due to lack of consideration for human force. As already mentioned, automatic doors are not only useful but also dangerous if we do not use them approximately. In the first place, we should pay enough attention on the margin of safety of electric doors, since the electric doors are one of most frequently used devices that can generate large force.

In this paper, train doors are especially studied. In the case of automatic doors for train doors, safety problems are more significant. Accidents of train doors are likely to be serious, and they could also raise various troubles on train services. What is the most problematic and frequent case of train door accidents is that humans are stuck between doors. It causes hurt on human himself, and what is more serious situation is that a human is dragged by train being stuck between doors. Under this circumstance, a human can suffer serious injuries and train services are disarranged.

As previously noted, it is important to reduce door stuck for the safety of train doors. However there are two significant problems.

1. We can not use infrared radiation sensors on train doors. General automatic doors detect the presence of human by infrared radiation sensors. But in the case of train doors, since humans could be close to doors, infrared sensors could have too much detection of human so that we can not close the doors.
2. Also we can not use force sensors. To detect door stuck, force sensors are required to be equipped with at the end of doors. Since the tips are always exposed to impacts, sensors break down quite easily.

Because of the two reasons, it is difficult to detect door stuck on train doors directly. In this paper, we use the disturbance observer. The disturbance observer has been widely used as a robust control methodology and force sensor-less power assist control [1], [2], [3], [4]. In this paper two methods using the disturbance observer are proposed. First, impedance control for the train door is proposed. In this method, we can achieve safe door control which takes consideration of human force. Since this method does not abandon response characteristic for external velocity command, doors gate appropriately when human force is not applied. This method is human-friendly, and it does not cause any undesirable effect on train service. In addition a practical example of proposed impedance control is also shown. Secondly, we implement impact force suppression control with environmental stiffness. In order to achieve impact force suppression method to ease impact force, we estimate environmental stiffness so that we can detect impacts quickly.

Some experiments were carried out with a train door experimental machine from Fuji Electric Systems Co., Ltd. An overview of the experimental machine is described in Figure 2. The experimental machine is powered by vector-controlled synchronous motor (maximum power 300[N]). An encoder is equipped with the motor. The motor and the door are connected via the rack and pinion. Figure 3 shows the scheme of train door experimental machine. We can connect force between the motor and the door through the rack and pinion structure in both directions, door opening direction and closing direction. The specifications are: height 1700[mm], breadth 2000[mm], total weight 230[kg], stroke of door 500[mm], which is two-third size of practical one. The control section is composed by microcomputer (RENESAS SH-7083). Current control is run with sampling time 250[s], and the motor is controlled with 2[ms].

Fig. 2. Train door experimental machine setup

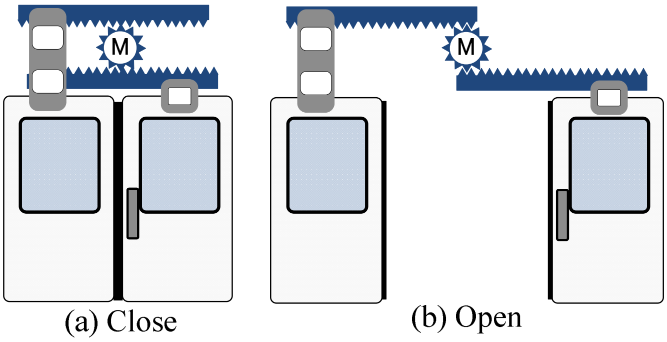



Fig. 3. Scheme of train door experimental machine

## II. IMPEDANCE CONTROL FOR TRAIN DOORS

### A. Impedance Control with External Velocity Command

A conventional impedance control is applied to only static plants [4], [5]. But train doors are not static when they contact with human. Therefore, a novel impedance control method which can be applied at opening and closing motion is required.

The novel impedance control method applied to a plant with external velocity command is proposed in this section. Figure 4 shows the block diagram of impedance control with velocity command.

The impedance control in opening or closing motion is implemented by adding $V^*$ (external velocity command) and $V_M$ (velocity command for realizing model impedance). In the proposed method, the train door opens and closes as usual when it does not contact with human. On the other hand, it becomes light or heavy virtually when it contact with human. TABLE 1 shows the definition of symbols.

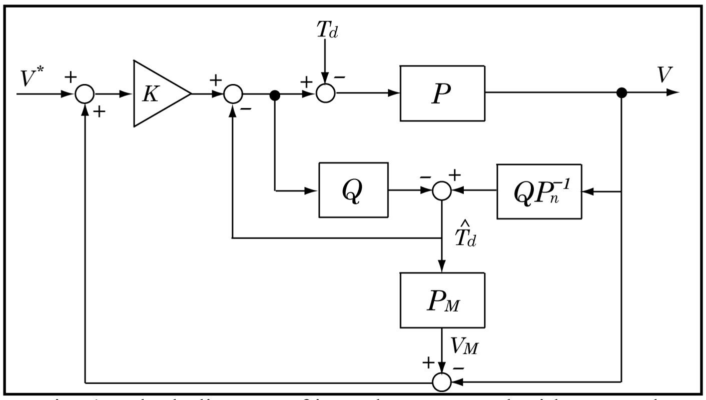



Fig. 4. Block diagram of impedance control with external velocity command

TABLE 1
**DEFINITION OF SYMBOLS**

| | |
|---|---|
| V | Velocity of the door |
| $V^*$ | External velocity command |
| $V_M$ | Velocity for model impedance |
| Q | Low pass filter |
| $P_n$ | Nominal plant model |
| $P_M$ | Model impedance |
| K | Velocity feedback gain |
| $T_d$ | Disturbance (Human force) |
| Td | Estimated disturbance by DOB |
| $F$ | impact force |
| $K$ | environmental stiffness |
| $x_{off}$ | impact start position |
| $x_{max}$ | impact end position |
| $v_0$ | velocity of the door when the impact starts |
| $a$ | acceleration of the door |

### B. Experimental Results

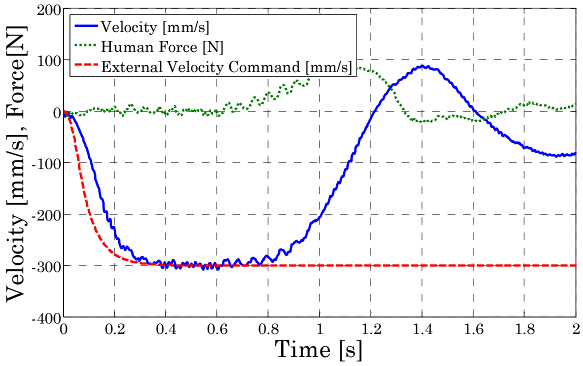
Some experiments are carried out with the train door experimental machine. In these experiments, we apply a step external velocity command (-300[mm/s]) from the open position to close the door, and external force (human force) is added in the opening direction. The experiments are set up with some model impedance. External force is estimated by disturbance observer. Figure 5 shows the results. In the graphs, we set the door closing direction to negative. The experimental parameters are shown in TABLE 2.

TABLE 2
**EXPERIMENTAL PARAMETERS**

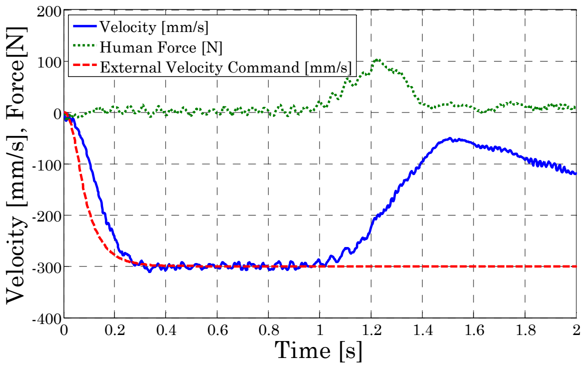
| | | | |
|---|---|---|---|
| $Q$ | 1/(0.025s+1) | $V^*$ | -300[mm/s] |
| $P_n$ | $1/(J_n s+B_n)$ =1/(59.7s+60.5) | $K$ | 2.5 |

By comparison among Figure 5 (a) ~ (c), we see that the impedance model of the train door against human force enlarges gradually as we set model impedance large. The door velocity changes rapidly in (a) But in (b) and (c) the velocity of the door does not change compared with (a) for the reason that the model impedance of friction is large, which shows that the response characteristic for human force can be determined arbitrary.

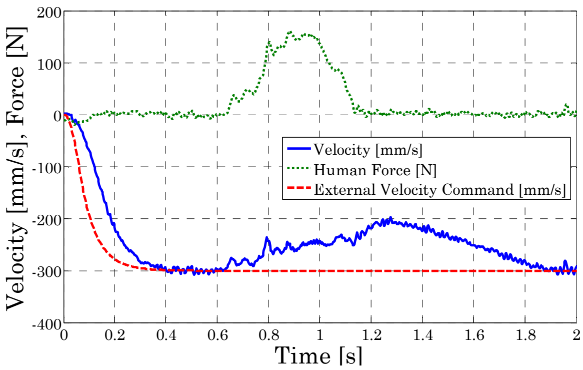
It should be also emphasized that the proposed method does not change the tracking performance for external velocity while it changes the impedance characteristic against human force. As shown in Figure 5, the response for the velocity command does not change in spite of the changes in the response to human force.




(a) $J_M=J_n$, $B_M=1/2B_n$




(b) $J_M=J_n$, $B_M=B_n$




(c) $J_M=4J_n$, $B_M=B_n$

Fig. 5. Results of proposed impedance control

Figure 6 shows the external velocity commands $V^*$, $V_M$ (velocity command for model impedance) and the sum these velocity commands. Note that the proposed method is implemented by making the door velocity follow the sum of external velocity command and velocity command for model impedance.

It is emphasized that making door light virtually by proposal method is different from low-gain feedback control in velocity control loop. In the case of low gain feedback control, we cannot control the velocity quickly. On the other hand, by the proposal method, it is possible to achieve model impedance without abandoning response characteristic for external velocity command.

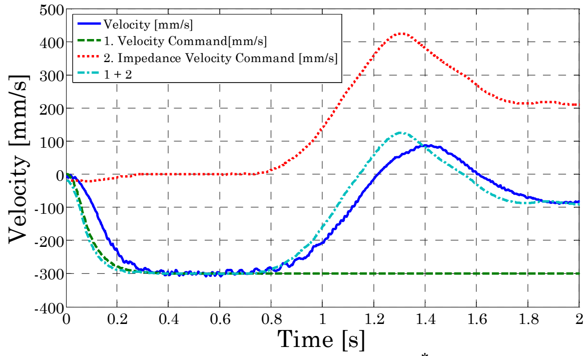



Fig. 6. Relationship between $V^*$ and $V_M$

### C. A practical Use of Impedance Control for Doors

In the former section, impedance control with the external velocity command is proposed. But what is the more important is how to apply the method to practical use for doors. As a practical matter, if the train doors are too human-friendly, many people will try to rush into the train opening the door with their force which causes other problems on the train system. One of the examples of application for practical train doors is shown in this section.

In this example, we change the model impedance. Now we adopt the model impedance like Figure 7.

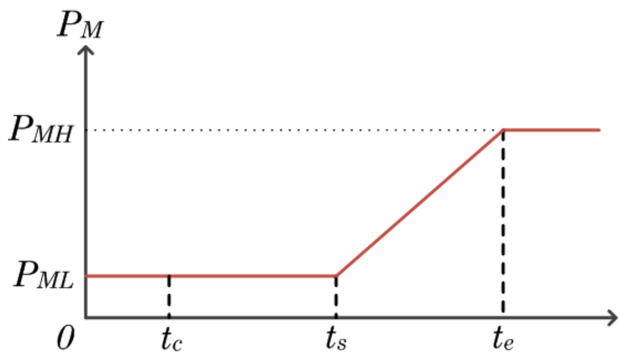



Fig. 7. Impedance value in respect to time

$t_c$ is the time when the door starts touching human. That can be detected by measuring the decrease of the door velocity. $t_s$ is the impedance change time. From this time, we gradually enlarge the model impedance. Therefore during the period $t_c$ ~ $t_s$, the motor assists the human force and it is easy for the human to open the door. In the period $t_s$ ~ $t_e$, the model impedance increases linearly since a step change of the model impedance causes undesired effects on door motion. After the time, the door will more in the closing direction with large suppressing force against human, since the model impedance becomes heavier.

An experiment of impedance changing is carried out. In the experiment we set $t_s$ as the time when the door is pushed back more than 100[mm]. $t_s$ ~ $t_e$ is set 500[ms], $P_{ML}$ is set to $(J_n, 0.5B_n)$ and $P_{MH}$ is set to $(4J_n, B_n)$. Figure 8 shows the experimental result.

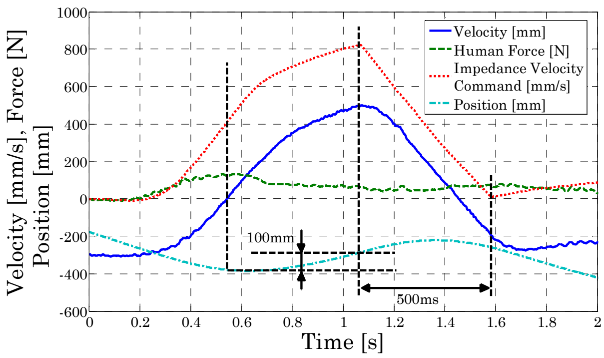


Fig. 8. Impedance varying result

In Figure 8, human force is applied to the door at time 0.2[s], simulating a human is stuck between doors, and he applies force to push back the door. In the period $t_c$ ~ $t_s$, the door velocity changes significantly since the model impedance is light. After $t_s$, the model impedance becomes heavier gradually and the door closes against human force.

### *D. Summary*

As an extended impedance control theory, a new method with external velocity command is proposed. In this method we set the door impedance for human force arbitrary without abandoning the response characteristic. In addition, one of the practical uses of proposed method is suggested. The example is implemented by model impedance changing. By changing model impedance according to the circumstances, we can achieve a good balance between human-friendly door motion and the robustness of door closing.

## III. IMPACT FORCE SUPPRESSION CONTROL

### *A. Impact Force Suppression Control*

In the previous chapter, some safe door control algorithms are proposed, assuming door contacts with human. However force generated when the door hits a human is another big problem. To realize safe door, the impact force should be taken into account. The impact force is difficult to control, since it arises in very short time up to a great deal [6]. In this chapter, we propose a new impact force suppression method by estimating the environmental stiffness, in order to ease impact force.

Figure 9 shows the impact force generated when a door impacts against iron. It is measured with a force sensor. In this measurement, the door closes at velocity -200[mm/s]. It can be seen from Figure 10 that the impact force is up to 250[N], and it is generated in very short time. Generally speaking, a human tolerates a force pain up to 50[N], which may be different for region. Thus, a new impact force suppression method which ease the impact force down to 50[N] is required.

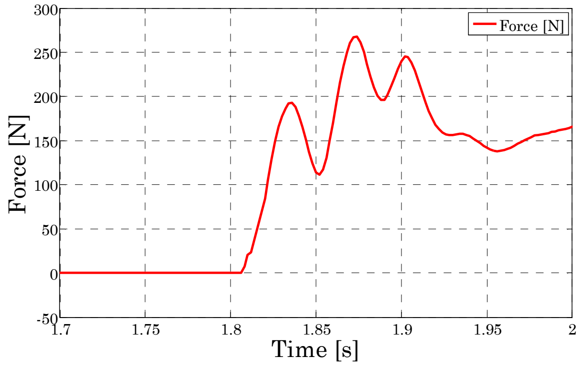


Fig. 9. Impact force measured using force sensor

Many methods which ease impact force have been proposed . Most of these methods require a force sensor [7]. As for phenomena like impact which is generated in very short time, we need force sensor to detect the impact accurately and quickly. Because the estimated external force by disturbance observer (DOB) contains not only actual external force but also any other disturbances, such as friction resistance, it is difficult to ease the impact force with DOB. However, the proposed method can suppress impact force with DOB by estimating environmental stiffness.

### *B. Estimation of Environmental Stiffness*

The impact force is related to the stiffness of the environment which the door impact against. The impact force increases with the environmental stiffness; if the impacted environmental stiffness becomes higher, the impact force becomes greater. In proposed method, we estimate environmental stiffness by assuming the environment as a simple spring-system. (Figure 10 )

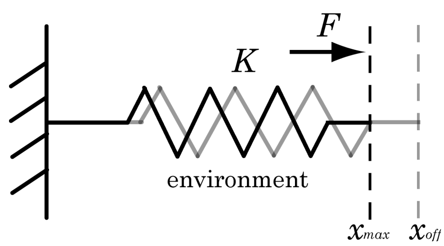


Fig. 10. Environmental stiffness (spring system)

When we assume the environment as spring -system, the impact force given as

$$F = K\left(x_{\max} - x_{off}\right) \qquad (1)$$

by differentiating both sides, the following equation is given.

$$\frac{d}{dt}F = Kv \tag{2}$$

The environmental stiffness $K$ is defined in the following form.

$$K = \frac{F'}{v} \tag{3}$$

Note that $F$ in Eq. (1) - (3) is the output of the DOB. The environmental stiffness $K$ is easily computed, so that even slow computer, like a microcomputer, is enough to work. Moreover, undesirable effect is removed by differentiation of the estimated external force with DOB.

Figure 11 shows the estimated environmental stiffness $K$, when the impact force is applied to the door during closing motion. These graphs contain estimation of the impact force by DOB, environmental stiffness and the door velocity door. The results show that the environmental stiffness rises 20 - 50[ms] as quick as the estimated disturbance by DOB. Therefore, we can detect the impact by estimating environmental stiffness before it generates great impact force.

### *C. Impact Force Suppression Control with Environmental Stiffness*

An impact force suppression method with the estimation of environmental stiffness is proposed in this section. We detect the impact with environmental stiffness, estimate the maximum impact force and make the door stop by applying feedforward torque input. The feedfoward torque input to ease the impact force to a certain level can be designed as follows.

When the door is stopped by a fixed acceleration, the velocity of the door given

$$v = v_0 - \alpha t \tag{4}$$

The position where the door stops is derived as below

$$x_{\max} - x_{off} = \frac{v_0^2}{2\alpha} \tag{5}$$

Assuming impact force is suppressed to 50[N], we can calculate the acceleration from Eq(1) and Eq(5).

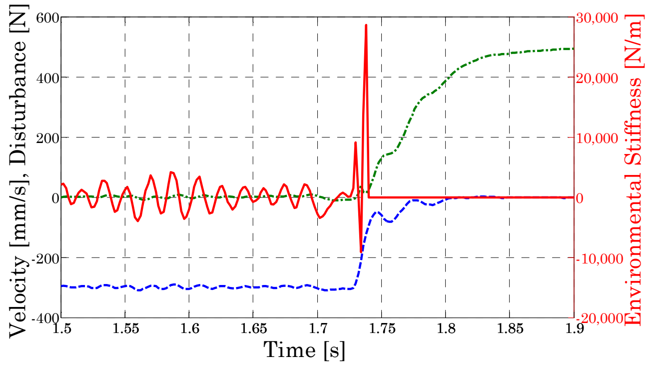
$$F = K\left(x_{\max} - x_{off}\right) = \frac{v_0^2}{2\alpha}K = 50[N] \tag{6}$$

$$\alpha = \frac{v_0^2 K}{100}$$

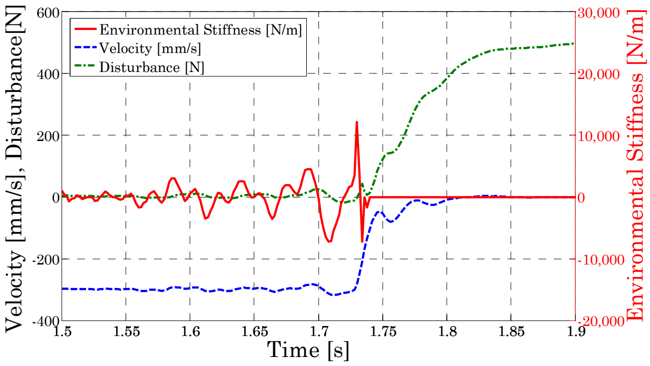
The required motor torque is computed with the nominal model.

$$T = J_n\alpha = \frac{v_0^2}{100}KJ_n \tag{7}$$

The feedforward torque command to stop the door after detecting the impact is decided as Eq. (7).




(a) Impact against iron




(b) impact against wood

Fig. 11. Estimated environmental stiffness

### *D. Experimental Result*

The experiment of the proposed method is tested with train door experimental machine. In this experiment, the door impacts against a force sensor when it closes at -200[mm/s].

The result is shown in Figure 12.

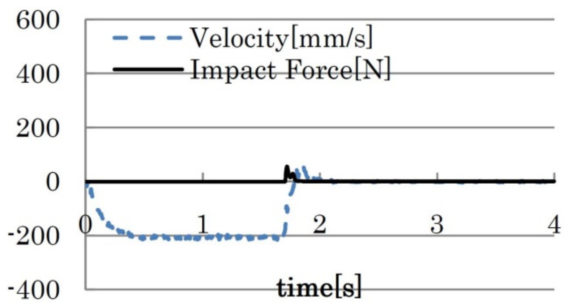



Fig. 12. Experimental result for impact force suppression

We see from in Figure 12, the impact force is eased to 50[N]. Compared to the experiment without proposed method in Figure 9, which shows the proposed method is effective to ease impact force without force sensor.

### E. Summary

In this chapter, a new impact force suppression method is proposed. In the proposed method, we can detect the impact before the impulsive force rises by estimating environmental stiffness. Moreover, a new impact force suppression method is proposed based on environmental stiffness. The effectiveness is demonstrated by experiment.

## IV. Conclusion

This research aims to propose safe and robust control system for train doors to decrease accidents by automatic door. Experiments are carried out with train door experimental machine from Fuji Electric Systems Co., Ltd. Two novel methods for train door that do not need force sensor are proposed in this paper.

First, a new impedance control method with the external velocity command is proposed as an extended force sensor-less impedance control. In this method we set the door impedance for human force arbitrarily without abandoning the response characteristic for external velocity command. In addition, one of the practical uses of the force sensor-less impedance control for train doors is shown. The example is implemented by changing model impedance. By changing model impedance according to the circumstances, we can achieve a good balance between safe door motion and the robustness of door closing.

Second, a new impact force suppression method is proposed. In the proposal method, we estimate environmental stiffness with disturbance observer. Since the environmental stiffness contains the differentiation of estimated disturbance, the impact is detected before it generates impact force. Moreover, an impact force suppression method based on estimated environmental stiffness is proposed.

Finally it should be emphasized that the proposal method is not limited to train doors. The proposed method can be applied to various mechanical systems.

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