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DESIGN PROGRAM FOR THE KINEMATIC AND DYNAMIC CHARACTERISTICS OF THE BUS DOOR MECHANISM

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ABSTRACT–The bus is regarded as one of the most frequently used public transportation systems, the research and development on driving stability, safety, and convenience for drivers and passengers has tremendously increased in recent days. This paper investigated the design of the bus door mechanism composed of an actuator (or motor) and linkages. The bus door mechanism is divided into many types according to the coupling of the linkages and the driving system. The mathematical models of all types of door mechanism have been constructed for computer simulation. To design the bus door mechanism, we developed a simulation program, which automates the kinematic and dynamic analysis according to the input parameters of each linkage and the driving system. Using this program, we investigated the design parameters that affect the kinematic and dynamic characteristics of the bus door mechanism under various simulation conditions. In addition, simple examples are examined to validate the developed program.

KEY WORDS : Bus door mechanism, Actuator-drive folding door mechanism, Motor-drive folding door mechanism, Kinematics, Direct dynamics, Inverse dynamics, Simulation, Design program

1. INTRODUCTION

The techniques that can provide convenience and comfort for the drivers and passengers are considered as the critical techniques in the automobile industry. The research and development on this area has recently progressed actively. The convenient systems aim to provide safety, stability, usefulness, and comfort for the driver and passengers. The driver assistance systems and the driver-vehicle systems, which relieve the burdens of driving, are also considered as a part of the convenient systems (Lin *et al.*, 2002).

In this paper, we have concentrated on the door mechanism in the bus as a convenient system. Since the bus is regarded as one of the most frequently used public transportation systems, past research has focused on transport capacity. In recent days, the research and development on driving stability, safety, and convenience for drivers and passengers has tremendously increased. The door mechanism, which opens and shuts the door for passengers to get on and off as the bus run a route of many scattered depots, is a central mechanism of the bus.

The motions of the door mechanism are controlled by various linkages and actuators (or motors). To design the door mechanism, the kinematic and dynamic characteristics of the combined linkages must be analyzed. Lee *et al.* (1996) presented a method for the inverse dynamic analysis of mechanical systems. Actuating forces (or torques) depending on the driving constraints were analyzed in the relative coordinate space by using the velocity transformation techniques. Yan and Soong (2001) introduced a novel method that integrates kinematic and dynamic design with variable input speeds to describe the trade-off of the dynamic balance of four-bar linkages. Shin *et al.* (1997) proposed the closed loop method and a tangent substitution method to formulate the relationships of kinematics chains and to calculate the displacement, velocity, and acceleration of the cam driving slider mechanism. Also, an instant velocity center method was proposed to determine the cam shape from the geometric relationships of the cam and the roller follower.

Computer simulation has been considered as a useful method for analyzing the kinematic and dynamic characteristics of the combined linkages. It becomes important in the automotive industry because it can save development time and costs by carrying out the parameter analysis very easily (Redmill *et al.*, 2000; Holdmann and Holle, 1998).

Although research on the kinematics and dynamics of

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various linkages has been active, research on the adaptation and the design of the bus door mechanism has been insufficient. In the kinematic and dynamic analysis of a mechanical system, commercial softwares such as ADAMS and DADS has been very useful and accurate. However, commercial software for analysis of a door mechanism would require additional work and an effort.

In this paper, we develop a design program for the bus door mechanism, which automates the kinematic and dynamic analysis according to the input parameters of each linkage and the actuator (or motor). The dynamic analysis includes direct dynamics and inverse dynamics. The design program contains the mathematical models of all types of door mechanism, although the types of bus door mechanism vary depending on the purpose and the place. Using this design program, which may reduce time and cost of a vehicle test and an experiment, we investigate the design parameters that affect the kinematic and dynamic characteristics of the bus door mechanism under various simulation conditions. Also, simple examples are examined to validate the developed program.

2. BUS DOOR MECHANISM

The door mechanism of vehicles is divided into many types depending on the coupling of the linkages and the driving system. In this chapter, the door mechanism used in the bus is investigated. In addition, the motions of each door mechanism type are explained to analyze the kinematic and dynamic characteristics of the bus door mechanism.

2.1. Category of the Door Mechanism

The bus is equipped with various kinds of the door mechanisms such as a folding door, an engine room door, a sliding door, a flap door, a vent door, and a swing door. The representative door mechanism is shown in Figure 1. A folding door, a sliding door, and a swing door are used when passengers get on and off the bus. An engine room door in the backside of the bus is used when the driver wants to check the engine condition. A flap door is opened and closed to carry luggage. A vent door is used for ventilation. Consequently, the type of door mechanism is defined by considering the capacity of the actuator or motor, the purpose and the place of installation, and the kind of bus.

2.2. Motions of the Door Mechanism

In a bus door mechanism, the driving actuators or the motors operate the forces or torques. From these tractions, the linkages generate the translational or rotational motions.

The actuator-drive folding door has two main doors, an actuator, and a roller as shown in Figure 2(a). By the translational and rotational motions of the actuator, one main door (Door-1) rotates around the fixed point A while the other main door (Door-2) rotates, and the roller translates along the guide as described in Figure 2(b). When this door is open, the two main doors are folded, facing each other. The motor-drive folding door is similar to the actuator-drive folding door. The motor-drive folding door has many linkages and more complicated composition as described in Figure 3. By the rotational motion of the motor, the driving linkage (Arm-Link) rotates around the fixed point A. One after another, the roller translates along the guide and the doors are folded. An engine room door is a very simple structure in which the translational motion of the lifter rotates the linkage (Flap); the lifter is represented in Figure 4. Finally, the sliding door translates along the guide by the rotational motion around the fixed point A, which is represented in Figure 5. There are two kinds of the rollers to control the door motions.

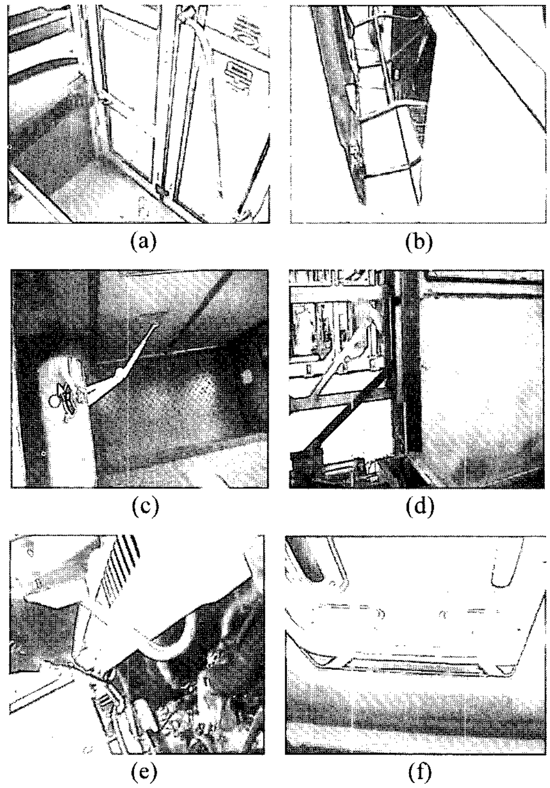


Figure 1. Category of the bus door mechanism: (a) Actuator-drive folding door; (b) Flap door; (c) Motor drive folding door; (d) Sliding door; (e) Engine room door; (f) Vent door.

3. MATHEMATICAL FORMULATION

The bus door mechanism is classified into two types

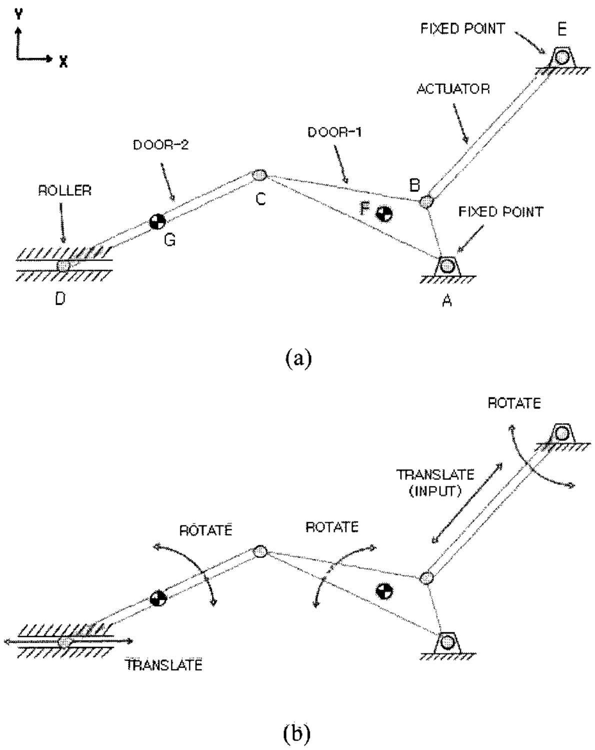


Figure 2. Actuator-drive folding door: (a) Composition of the door mechanism; (b) Motions of each linkage.

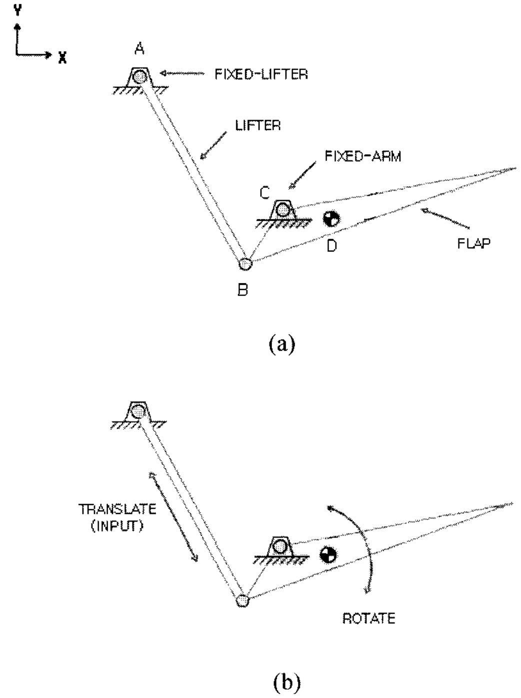


Figure 4. Engine room door: (a) Composition of the door mechanism; (b) Motions of each linkage.

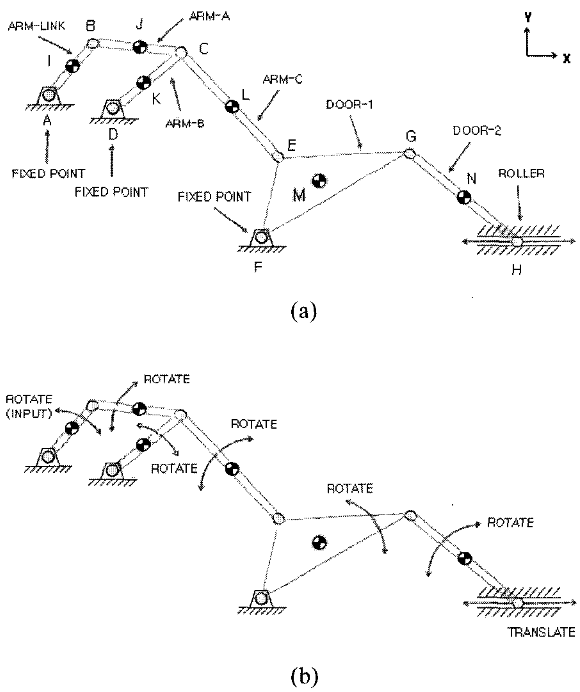


Figure 3. Motor-drive folding door: (a) Composition of the door mechanism; (b) Motions of each linkage.

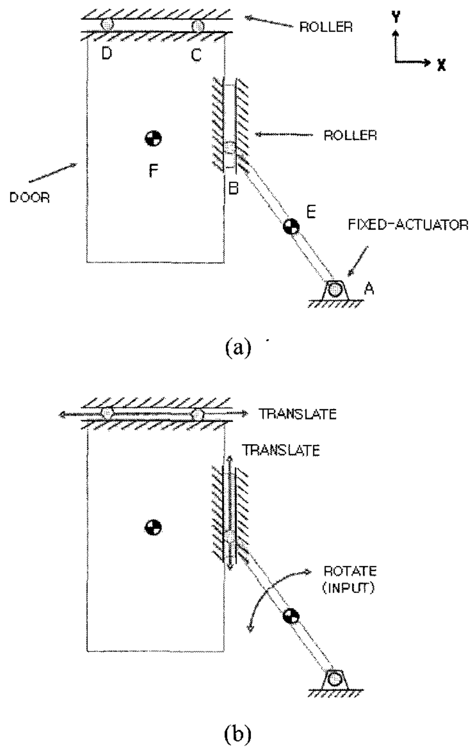


Figure 5. Sliding door: (a) Composition of the door mechanism; (b) Motions of each linkage.

according to the driving system: the actuator-drive door mechanism and the motor-drive door mechanism. In this paper, the actuator-drive folding door mechanism is selected as the example door mechanism type to explain the mathematical formulations for the kinematic and dynamic analysis.

The actuator-drive folding door is the representative door installed in most of urban buses. The kinematic analysis calculates the displacement, velocity, and acceleration of each linkage. In this paper, the dynamic analysis includes both inverse dynamics and direct dynamics. The dynamic analysis can be carried out by either of two methods according to the input parameters which are the force or the velocity in the actuator.

3.1. Kinematic Analysis

The relationship between the actuator and the door is defined in Figure 6. The position of the door as a function of the actuator length is calculated as follows:

$$\theta_A = \cos^{-1}\left(\frac{b^2+c^2+a^2}{2bc}\right) \tag{1}$$

$$\dot{\theta}_A = \frac{a\dot{a}}{bc\sin\theta_A} \tag{2}$$

$$\ddot{\theta}_A = \frac{-1}{\sin\theta_A}\left(\frac{-a\dot{a}-a\ddot{a}}{bc} + \cos\theta_A\dot{\theta}_A\dot{\theta}_A\right) \tag{3}$$

where a is the actuator length, b is the distance between the fixed point E and the fixed point A, c is the distance between the fixed point A and the connecting point B. Thus, θ_2 is represented as follows:

$$\theta_2 = \theta_A + \theta_K + \theta_L \tag{4}$$

where θ_K and θ_L are the constant values that can be calculated by the position data of the folding door. Also, the closed loop equation of the linkages, which construct the door mechanism, is defined by the following vectors:

$$\vec{L}_2 + \vec{L}_3 - \vec{L}_1 = 0 \tag{5}$$

$$l_2(\cos\theta_2 + j\sin\theta_2) + l_3(\cos\theta_3 + j\sin\theta_3) - l_1 = 0 \tag{6}$$

From equations (4) and (6), the position, velocity, and acceleration of each linkage according to the motions of the actuator can be obtained as follows:

$$\theta_3 = \sin^{-1}\left(\frac{-l_2\sin\theta_2}{l_3}\right) \tag{7}$$

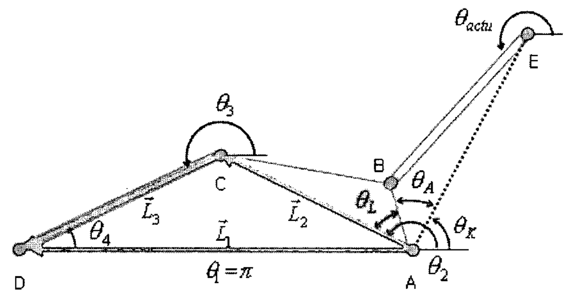


Figure 6. The kinematic analysis model.

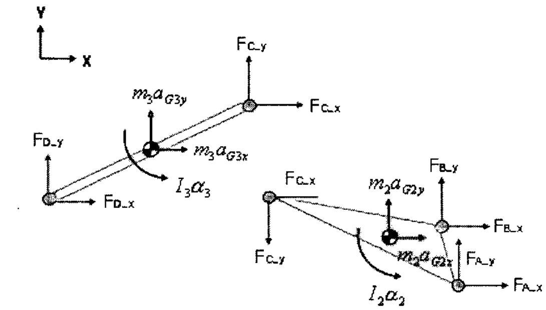


Figure 7. Free body diagram for dynamic analysis.

$$\theta_4 = \theta_3 - \pi \tag{8}$$

$$\omega_3 = \omega_4 = \frac{-l_2\omega_2\cos\theta_2}{l_3\cos\theta_2} \tag{9}$$

$$\alpha_3 = \alpha_4 = \frac{-l_2\alpha_2\cos\theta_2 + l_2\omega_2^2\sin\theta_2 + l_3\omega_3^2\sin\theta_3}{l_3\cos\theta_3} \tag{10}$$

where ω is the angular velocity, and α is the angular acceleration.

3.2. Inverse Dynamic Analysis

To analyze the inverse dynamics, the velocity and the acceleration of the actuator are set up as a function of time. Based on the kinematic analysis in previous section and the free body diagram in Figure 7, the equations of motion are calculated by equation (11):

$$[A]\cdot[B] = [C] \tag{11}$$

where $[A]$ is the matrix that has the geometric data of each linkage, $[B]$ is the matrix of the reaction force in each linkage point, $[C]$ and is the matrix of inertia force at

$$\begin{bmatrix} 1 & 0 & -1 & 0 & \cos\theta_{actu} & 0 \\ 0 & 1 & 0 & -1 & \sin\theta_{actu} & 0 \\ -R_{A\_y} & R_{A\_x} & R_{C1\_y} & -R_{C1\_x} & (R_{B\_x}\cdot\sin\theta_{actu} - R_{B\_y}\cdot\cos\theta_{actu}) & 0 \\ 0 & 0 & 1 & 0 & 0 & \pm\mu \\ 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & -R_{C2'\_x} & R_{C2\_x} & 0 & R_{D\_x}\mp\mu\cdot R_{D\_y} \end{bmatrix} \begin{bmatrix} F_{A\_x} \\ F_{A\_y} \\ F_{C\_x} \\ F_{C\_y} \\ F_B \\ F_{D\_y} \end{bmatrix} = \begin{bmatrix} m_a a_{G2x} \\ m_a a_{G2y} \\ I_2\alpha_2 \\ m_3 a_{G3x} \\ m_3 a_{G3y} \\ I_3\alpha_3 \end{bmatrix} \tag{12}$$

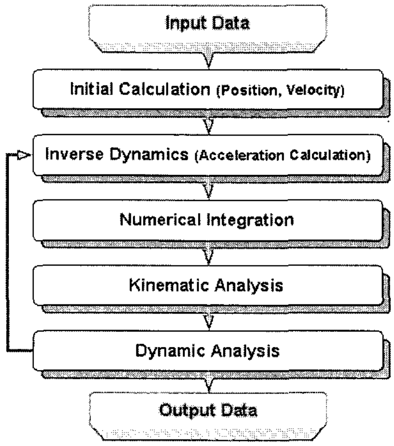


Figure 8. Flow chart of direct dynamics.

each center of gravity. From equation (11), $[B]$ can be calculated by numerical analysis. In this paper, LU decomposition is used to obtain the matrix of the reaction force. Also, the detailed formulation of equation (11) is obtained by Equation (12).

In Equation (12), R_x and R_y are the distances from the center of gravity to each linkage point, μ is the friction coefficient of the roller, m is the mass, I is the mass moment of inertia, and a_G is the acceleration of each door.

3.3. Direct Dynamic Analysis

To analyze the direct dynamics, a flow chart is presented in Figure 8. The force causing the translational motion of the actuator is set up as a function of time. In the kinematic analysis, based on the initial input data, θ_2 and ω_2 are calculated beforehand. From this data, θ_3, θ_4, ω_3 and ω_4 can be obtained. Also, α_2 and α_4 are represented by equation (10), which is a function of α_2.

Substituting equation (10) for the matrix of the inertia force in equation (12), equations (13) and (14) are obtained:

$$F_B = f(\alpha_2) \tag{13}$$

$$\alpha_2 = f^{-1}(F_B) \tag{14}$$

where F_B is the force of the actuator. The angular acceleration α_2 is calculated from equation (14). By integrating this angular acceleration, $\theta_{2\text{-}new}$ and $\omega_{2\text{-}new}$ can be obtained. Also, the kinematic analysis calculates α_3 and α_4. With this data, the dynamic analysis can be carried out.

4. DEVELOPMENT OF THE DESIGN PROGRAM

The design program for the bus door mechanism is shown in Figure 9. This program specific to the door mechanism is more efficient and flexible than

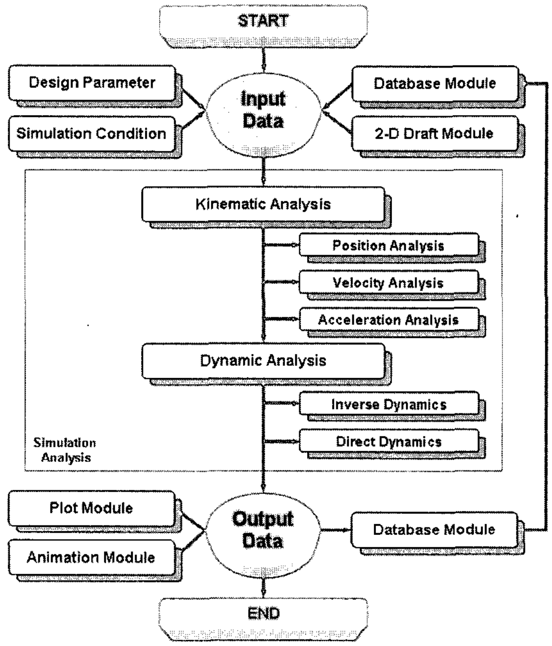


Figure 9. Flow chart of the design program.

commercial software. Also, this program is active and useful according to various values of the design variable and simulation conditions. To input the design variables and analyze the simulation results easily, the equations of kinematics and dynamics are modularized in the computer program, and the compiler used is Microsoft Visual C++ 6.0. The design program is divided into three parts: input part, analysis part, and output part. Each task and function is as follows.

4.1. Input Part

The design program contains all types of door mechanism installed in the bus, which are folding doors, swing doors, flap doors, a vent door, and a sliding door.

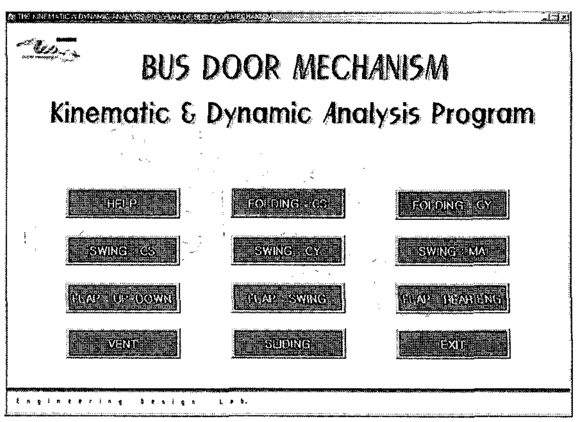


Figure 10. Main panel of the design program.

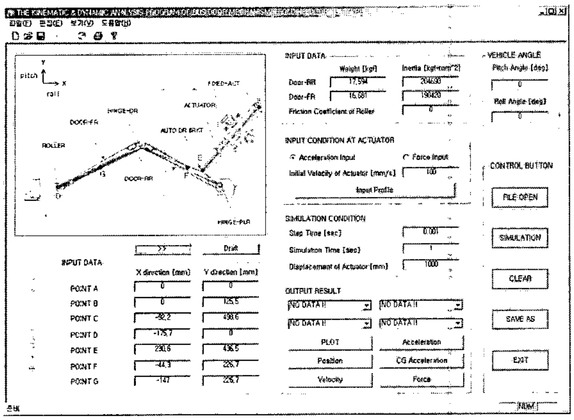


Figure 11. Input panel of the design program.

Folding doors, swing doors, and flap doors are classified into several types according to the coupling of each linkage and the driving system. Figure 10 shows the main program panel, which displays selections for 10 types of door mechanisms. The user can select the door type for analysis and design.

For example, Figure 11 shows the input panel for the actuator-drive folding door. In this panel, the design parameters of the folding door mechanism, which are the position of each linkage point, the position of the center of gravity, mass and mass moment of inertia of each door, the friction coefficient, and the vehicle position angle (pitch angle, roll angle) can be inputted. The simulation conditions, which are the simulation time, step time, and termination criteria, can be specified. Also, the driving data which is the velocity or the force of the actuator can be established. For the user's convenience, the database module is developed for users to load previously-stored input data, and 2-D draft module is developed to refer the design constraints when changing the design parameters.

4.2. Analysis Part

In the analysis part of the design program, the computer simulation is carried out for kinematic and dynamic analysis to get the continuous simulation results with respect to time. In the kinematic analysis, based on the input data, the position, velocity, and acceleration of each linkage as well as each center of gravity are calculated. In the dynamic analysis, both direct dynamics and inverse dynamics are carried out according to the driving condition of the actuator. Direct dynamics is due to the translational motion generated by the force of the actuator. Inverse dynamics is due to the translational motion generated by the acceleration and velocity of the actuator.

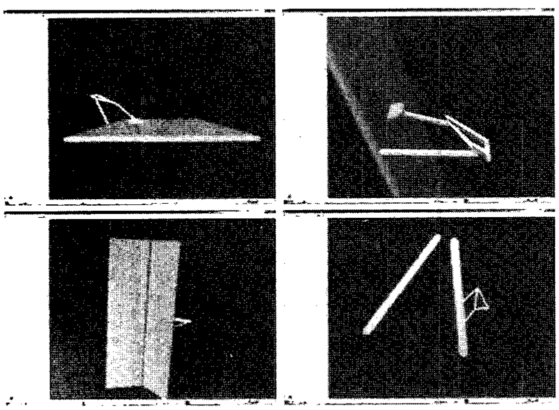


Figure 12. 3-D animation module.

4.3. Output Part

After the program finishes the computer simulation, the program constructs the output part to analyze the motions and dynamic characteristics of the door mechanism, such as the position, the velocity, the acceleration, and the reaction force of each point and linkage. The simulation result is connected with the plot module and the animation module, which provide the graphical analysis. Figure 12 represents the 3-D animation of the motor-drive folding door, which is developed by JAVA 3-D. The database module enables one to analyze the simulation results as the value of the design parameters change.

5. APPLICATION EXAMPLE

To confirm the usefulness of the developed program, the actuator-drive folding door mechanism as detailed in Figures 2, 6, and 7 is applied. The design parameters are

Table 1. Design Parameters of the folding door mechanism.

Design parameter	Model A		Model B		Model C	
	X	Y	X	Y	X	Y
Point A (mm)	0	0	0	0	0	0
Point B (mm)	0	125.5	0	170	0	125.5
Point C (mm)	−92.2	498.6	−92.2	498.6	−92.2	498.6
Point D (mm)	−175.7	0	−175.7	0	−175.7	0
Point E (mm)	230.6	436.5	230.6	436.5	230.6	436.5
Point F (mm)	−44.3	226.7	−44.3	226.7	−80	300
Point G (mm)	−147	226.7	−147	226.7	−100	110

explained in Table 1. In this table, Model A represents the initial design parameters of the actuator-drive folding door mechanism. Model B represents the design parameters that change the connecting point between the actuator and the door. Model C represents the design parameters that change the points of the center of gravity. Simulation is carried out for three cases, which are the input of the actuator velocity, the input of the actuator force, and input of the vehicle position angle.

5.1. Input of Actuator Velocity

In this simulation, the translational motion of the actuator to drive the folding door mechanism is assumed to be uniform. The actuator velocity is fixed to 100 [mm/sec] and the simulation step time is 0.001 [sec]. The simulation is continued until the door is closed completely when it reaches 180 [degree]. In this situation, the reaction forces at point B, which is the connection point between the actuator and the door, are presented in Figures 13 and 14.

As the positions of the point B in Model B change, the point of action by the actuator varies. Model B requires relatively lower forces to move the linkage. Therefore, the reaction forces of the point B in Model B by the uniform motion of the actuator are shown in a lower region than in Model A. Because the positions of the center of gravity in Model C are changed, the inertia force of each linkage is changed. To maintain the uniform motion of the actuator, Model C needs to have relatively higher forces than Model A. Also, the reaction forces of the point B in Model C are shown in a higher region than in Model A.

The simulation results show that the variations of the reaction forces at point B affect the strength of the connecting part and safety of the door. The kinematic and dynamic analysis program developed in this paper allows the user to select the design parameters considering the reaction forces of the connecting part.

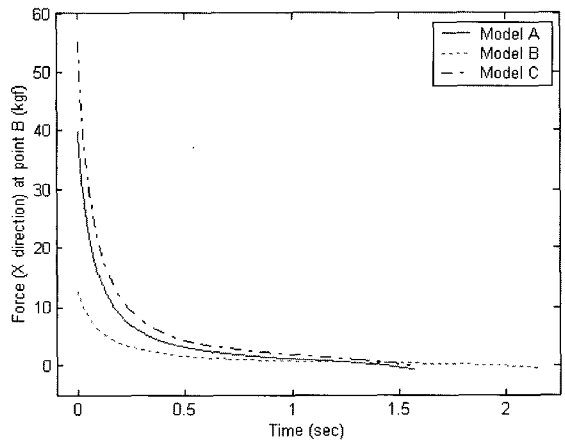


Figure 13. Force at point B in the X direction.

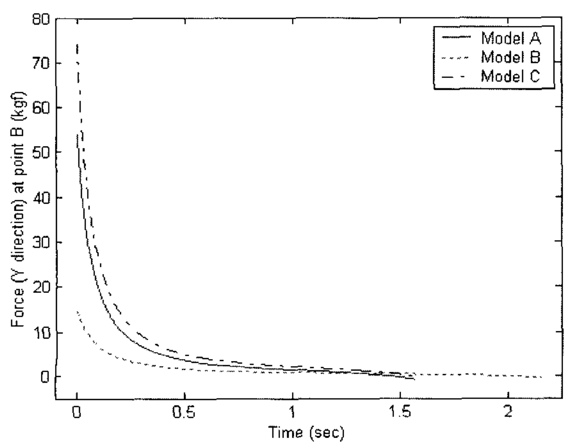


Figure 14. Force at point B in the Y direction.

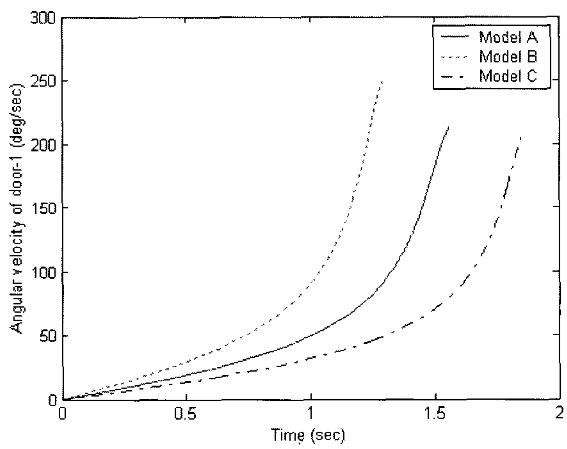


Figure 15. Angular velocity of the Door-1.

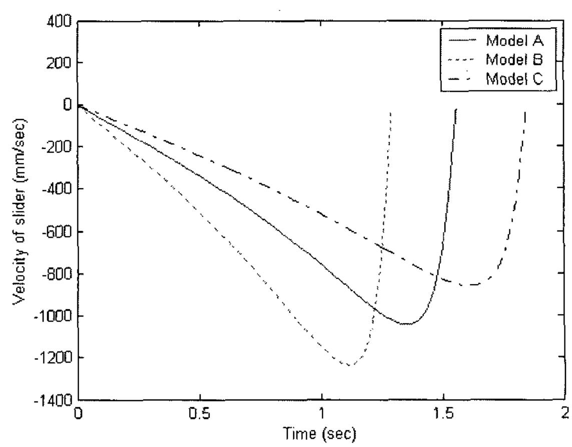


Figure 16. Velocity of the roller.

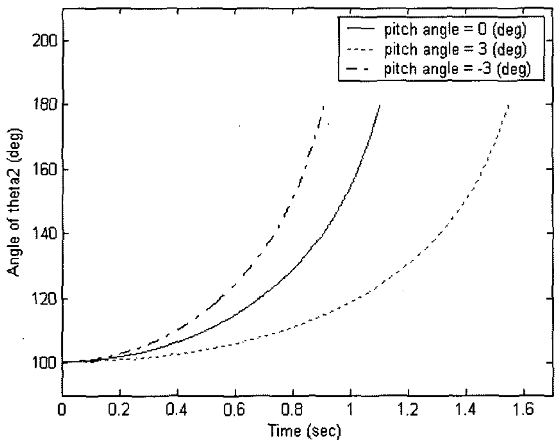
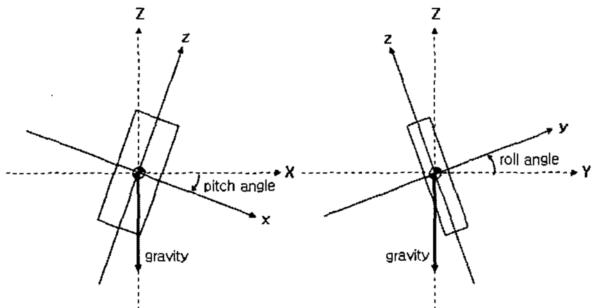


Figure 17. Angle variation of θ_2.



(a) Pitch angle (b) Roll angle

Figure 18. Vehicle position angles.

5.2. Input of Actuator Force

A uniform translational motion of the actuator is set up as 10 [kgf], and the simulation step time is fixed to 0.001 [sec]. The simulation is continued until the door is closed completely when it reaches 180 [degree]. The variations of the Door-1 angular velocity and the roller velocity under this condition are presented in Figures 15 and 16.

As the distance from the center of gravity of the Door-1 to the fixed point A is increased in Model B, the linkage can rotate with a lower force than required by Model A. Therefore, the Door-1 angular velocity and the roller velocity in Model B are changed rapidly, and the closing time of the folding door mechanism is decreased. Because the center of gravity changes in Model C, the Door-1 angular velocity and the roller velocity change more slowly than those in Model A. Finally, the closing time of the folding door mechanism is increased.

These simulation results show that designers can determine the actuator capacity according to the values of the design parameters of the folding door mechanism. The developed kinematic and dynamic analysis program will be very useful.

5.3. Input of Vehicle Position Angle

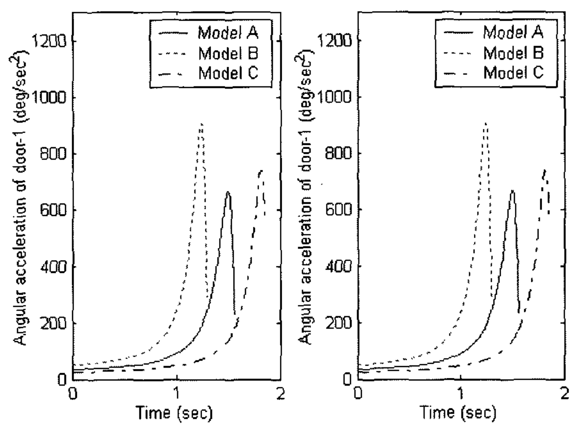
In this simulation, the uniform force of the actuator for translational motion is fixed to 20 [kgf], and the simulation step size is 0.001 [sec]. The applied design parameters are from Model A. To analyze the effects of the vehicle position angle, the pitch angle of the buses is applied in the region of ±3 [degree]. The simulation is continued until the door is closed completely when it reaches 180 [degree].

The simulation result of Figure 17 shows the angle variation according to the pitch angle. The pitch angle affects the closing time and the velocity of the door mechanism. When the pitch angle is -3 [degree], the door mechanism closes the door the fastest.

In this paper, the actuator-drive folding door mechanism is defined in X-Y coordinates as shown in Figure 2. The vehicle position angles such as the pitch angle and the roll angle affects the change of the gravity. The pitch angle rotates X-Z coordinates, and the roll angle rotates Y-Z coordinates as described in Figure 18. In the rotated coordinates, the gravity is a function of the external force. Therefore, the designers should consider the effect of the position angle of a vehicle on a slope or incline.

5.4. Verification of the Program

To verify the kinematic and dynamic analysis program developed in this paper, the simulation results were compared with those of ADAMS, the representative commercial software for kinematic and dynamic analysis. To check the validity of the simulation result, Figure 19 compares the results with those of ADAMS. The actuator-drive folding door mechanism described in Table 1 was the application object. The simulation condition of the actuator was the actuator force input, which was the same in section 5.2.



(a) SKKU program (b) ADAMS

Figure 19. Verification of the simulation results.

As shown in the simulation result, the kinematic and dynamic analysis program developed in this paper gave results which were in agreement with the result from the ADAMS. The developed program was verified to be an adequate and valid program.

6. CONCLUSION

This paper investigates the kinematic and dynamic characteristics of the bus door mechanism. Depending on the coupling of each linkage and the driving system, the bus door mechanism is divided into many types: a folding door; an engine room door; a sliding door; a flap door; a vent door; and a swing door. The mathematical models of all types of door mechanism were constructed for computer simulation. The dynamic analysis consisted of direct dynamics and inverse dynamics analysis for the various characteristics of the door mechanism.

In addition, the design program was developed and it automated the process of the kinematic and dynamic analysis according to the input parameters of each linkage and actuator (or motor). This design program consisted of three parts: input; analysis; and output. Also, the database module, the 2-D draft module, the plot module, and the animation module were added to the program for user convenience.

Through the developed design program, the design parameters of the door mechanism were investigated and the performance characteristics of the bus door mechanism according to the design parameters were analyzed. Also, simple examples were used to validate the developed program. Examples were tested for three cases to design the actuator-drive folding door mechanism: the input of the actuator velocity, the input of the actuator force, and the input of the vehicle position angle. The developed program gave exact and proper simulation results as verified by comparison with the results of ADAMS.

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