DYNAMIC CHARACTERISTICS ANALYSIS OF AN ESCALATOR USING THE COMPUTATIONAL DYNAMICS PROGRAM

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Abstract

Predicting dynamic characteristics of an escalator by means of the computational dynamic analysis is a meaningful subject, and has not been thoroughly investigated before. The general purpose kinematic and dynamic analysis program, DADS which has been shown to be effective in the dynamic analysis of multi-body is utilized to analyze the interaction of the escalator to be more than 900 independent degree-of-freedom. Thousands of friction contact elements are applied to correctly simulate impact, permanent contact and temporary contact of rollers and the handrail. The presented model is experimentally verified to substantiate the accuracy and efficacy.

1. Introduction

Due to the design trend toward ~~to~~ higher speed and higher rise in ~~the escalator~~ in order to ~~raise~~ operating efficiency(Ho, 1993; Sturgeon, 1994; Daniotti, 1995; Caporale, 1997; Saito, 1997), a thorough understanding of dynamic behavior and forces is necessary. Previous investigations ~~on the escalator~~ have dealt primarily with determination of static load and torque based on the static condition and with the experiments partially that are very ~~hard~~ and time-consuming. In these days, it is possible to ~~make~~ reliable dynamic results using the general purposed dynamic analysis program applied the advanced dynamic analysis methods ~~for the~~ computer program (Wehage, 1982; Haug, 1986). Predicting dynamic characteristics of the escalator by means of the computational dynamic analysis is a meaningful subject, and has not been thoroughly investigated before.

In this paper, the general purposed dynamic analysis program, DADS(Dynamic Analysis and Design System) which has been shown to be effective in the dynamic analysis of multi-body is utilized to analyze the interaction of the escalator with more than 900 independent degree-of-freedom. In the presented dynamic model thousands of friction contact elements are applied to correctly simulate impact, permanent contact and temporary contact of rollers and the handrail on rails and drive parts. A thorough understanding of the interaction of the escalator is obtained by applying dynamic properties for each of components to the presented model. The dynamic properties like center of gravity, moment of inertia, stiffness and damping that is crucial to study its interaction are determined by either analytical or experimental methods. The following phenomena are realized by the presented model.

1) Rolling contact and impact of rollers on rails and terminal gears
2) Sliding contact of the handrail on guides and the driving pulley
3) Various bending resistance of the handrail according to each bending region and multiple non-linear friction characteristics of rollers.

It is shown that the presented model is verified to show simulation results within 10% error through experiments for the validation. The results verified by experiment are dynamic behavior ~~like~~ the velocity and the vibration of the moving parts and dynamic force ~~like~~ reaction force of rollers, tension force of chains and torque of driving parts.

Nomenclature

C_r = coefficient of restitution
$\{g\}$ = generalized force vector
$[M]$ = diagonal mass matrix
$\{q\}$ = generalized coordinate vector
R_1 = radius of point body
R_2 = radius of segment body
V_p = normal velocity of contact
V_t = tangential velocity of contact
V_ε = transition velocity
δ = normal deflection of contact
$\{\lambda\}$ = lagrange multiplier vector
μ_{nom} = nominal friction coefficient
$\{\Phi\}$ = constraint equation vector
$[\Phi_q]$ = jacobian matrix of constraint equation

2. Analysis Method

In general, the mechanical system composes of bodies that are connected by kinematic joints and force elements to ~~make~~ prescribed motions. Equations of motion for the constrained mechanical system are defined ~~as~~ in Eqs. (1) and (2) (Wehage, 1982).

$$\begin{bmatrix} M & \Phi_q^T \\ \Phi_q & 0 \end{bmatrix} \begin{Bmatrix} \ddot{q} \\ -\lambda \end{Bmatrix} = \begin{Bmatrix} g \\ \gamma \end{Bmatrix} \tag{1}$$

$$\Phi = 0 \tag{2}$$

$\{\gamma\}$ is right-hand-side of constraint equation and expressed as in Eq. (3).

$$\{\gamma\} = -\left(\Phi_q \dot{q}\right)_q \dot{q} \tag{3}$$

Continuous analysis of the escalator assumes that contact is continuous event(Han, 1993). Continuous contact is assumed for rolling friction contact and impact of rollers on rails and terminal gears, and sliding friction contact of the handrail on guides and the driving pulley. Reaction force at ~~the~~ contact ~~instance~~ is calculated using material properties, shapes and coefficients of restitution. The elastic modulus-coefficient of restitution method calculates contact force using elastic modulus and coefficient of restitution at the ~~time~~ of contact(Lankarani, 1990). Point-segment contact is assumed to detect the contact event.

First, if contact is detected then combined curvature C_c is calculated as in Eq. (4) (Lankarani, 1990).

$$C_c = \frac{1}{R_1} + \frac{1}{R_2} \tag{4}$$

Nominal stiffness coefficient K_{nom} is calculated as in Eq. (5) (Lankarani, 1990).

$$K_{nom} = 0.733E\sqrt{\frac{1}{C_c}}) \tag{5}$$

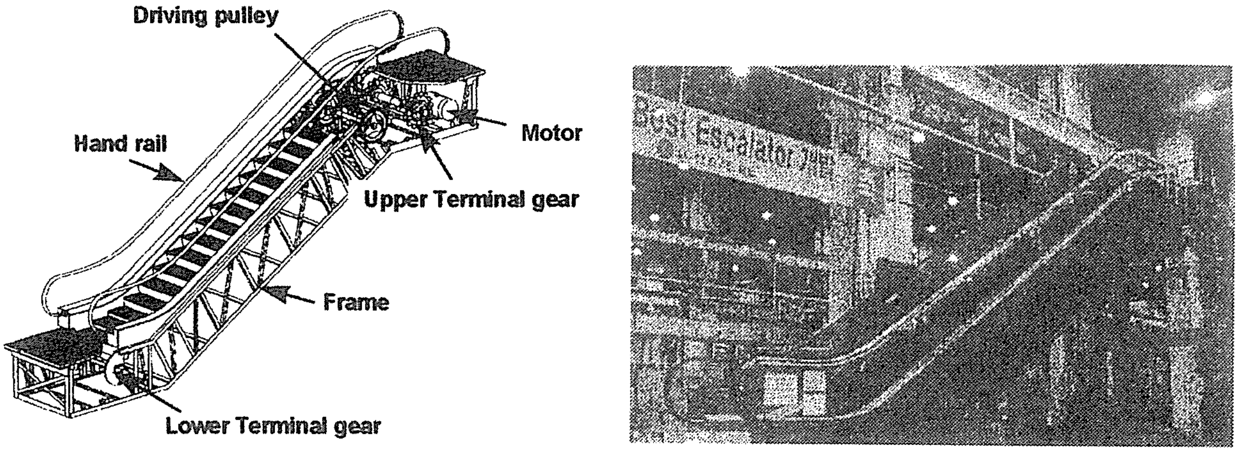
In Eq. (5), E is an elastic modulus.
Normal contact force F_n is calculated as in Eq. (6) (Lankarani, 1990).

$$F_n = k_{nom}\left[1 \pm \left(\frac{(1-C_r^2)}{(1+C_r^2)}\right)\tanh\left(2.5\frac{V_p}{V_\varepsilon}\right)\right]\delta^{1.5} \tag{6}$$

Tangential contact force F_f is calculated as in Eq. (7).

$$F_f = \mu_{nom}\tanh\left(2.5\frac{V_t}{V_\varepsilon}\right)F_n \tag{7}$$

After contact is detected, the elastic modulus-coefficient of restitution method can be used to reaction and friction contact force.



(a) A schematic of the escalator

(b) The Picture of the escalator

Fig. 1 A schematic of an escalator

3. Modeling

Figure. 1 shows the escalator considered in the computational model. It is 4.5m in vertical rise 1200mm wide. The model is considered as 2-dimension because of ~~symmetric~~. In the model, Drive is applied to the upper terminal gear and the driving pulley directly ~~without the~~ motor. Figure. 2 shows the computational model of the escalator.

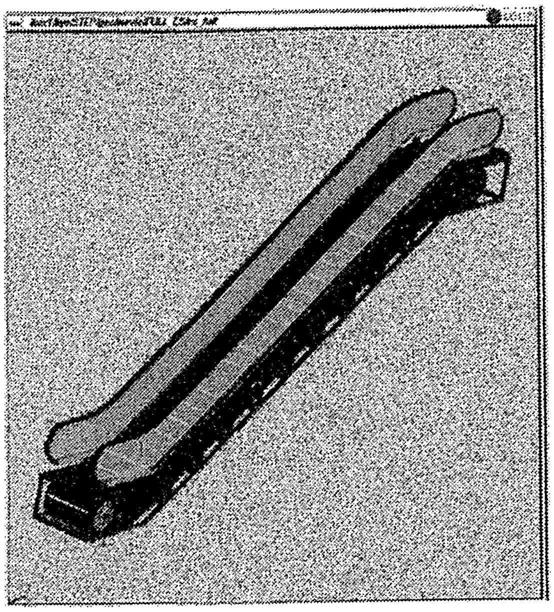


Fig. 2 The computational model of an escalator

Equations. (6) and (7) are used to consider rolling friction contact and impact of rollers on rails and terminal gears, and sliding friction contact of the handrail on guides and the driving pulley. Material properties like mass, center of gravity, moment of inertia, multiple non-linear friction coefficients, stiffness and damping coefficient of bodies are determined by either 3D cad software or experimental methods. Coefficient of restitution is obtained by experimentation (Lankarani, 1990). To analyze efficiently the model, the model is divided into the step part and the handrail part.

3.1 Step Part

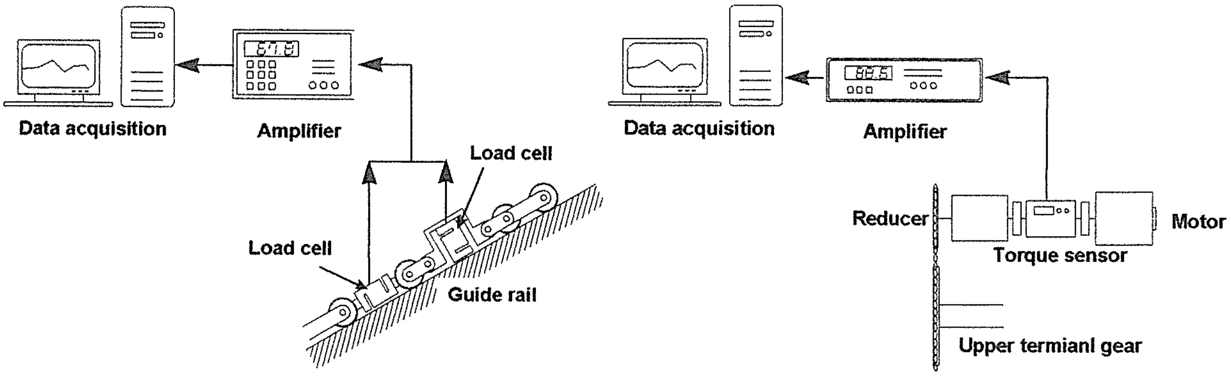
The step part model is composed of 58 step bodies and 116 roller bodies. In order to consider the elastic effect of chains, Rollers are connected by 174 spring and damper elements. All bodies are assumed rigid bodies since they do not deform in operating speed. The frame is fixed to the ground. The upper terminal gear is constrained to the frame by a revolute joint and the lower terminal gear is set the frame by a translational joint and a spring element to make proper tension force of the chains. The upper terminal gear is driven at the angular velocity corresponding to the step velocity, 500 mm/s.

Independent degree-of-freedom of the step part model is 523. Friction contact elements applied to correctly simulate rolling contact and impact of rollers on rails and terminal gears are 1044.

3.2 Handrail Part

A continuous elastic handrail is divided into 127 discrete rigid bodies. In order to consider the elastic effect of the handrail, each handrail body is connected by 127 spring and damper elements. The handrail is divided into as small as possible in order to prevent geometric intervention at the bending region. The driving pulley is constrained to the frame by a revolute joint and driven at the angular velocity corresponding to handrail velocity, 510mm/s. The lower tensioner and the belt tensioner are constrained to make proper tension force on the handrail. To consider the bending resistance of the handrail, bending resistance coefficients corresponding to relative bending angle of each handrail body is determined by the experiment and applied to the model.

Independent degree-of-freedom of the handrail model is 381. Two friction contact elements per one handrail body are applied to prevent rotational motion of each handrail body. Friction contact elements applied to correctly simulate sliding contact of the handrail on guides and the driving pulley are 3048.

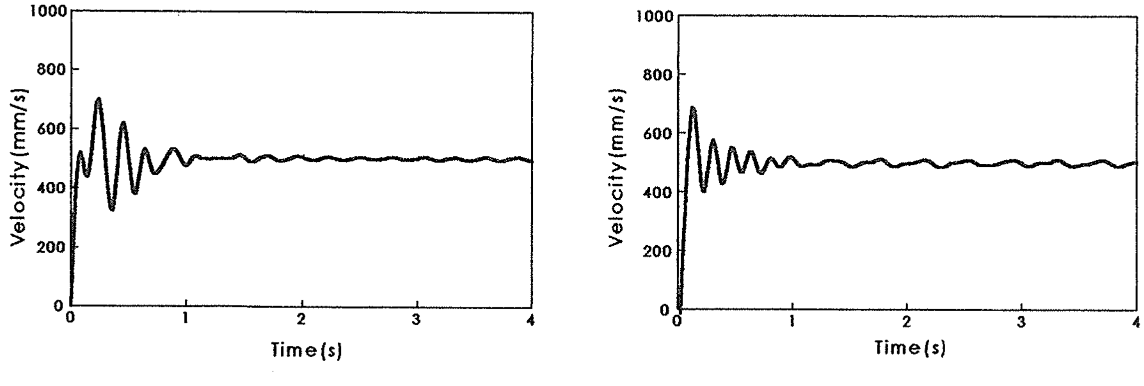


(a) Force measurement (b) Torque measurement

Fig. 3 Experimental set-up

4. Experimental Validation

The following dvnamic characteristics are selected in order to validate the presented model. a step's acceleration, reaction force of a roller, tension force of a chain and torque of the upper terminal gear and the driving pulley. A step's acceleration is measured by a low frequency accelerometer and the frequency analyzer. The experimental set-up of force measurement is shown in Fig. 3(a). It is composed of two load cells, jigs to connect chains of sides each, an amplifier and an analyzer. The experimental set-up of torque measurement is shown in Fig. 3(b). It is composed of a strain gauge type torque sensor, an amplifier and an analyzer. The torque sensor is set between the motor and the reducer to measure the driving torque more precisely. All of results ~~tested~~ are measured ~~in condition that~~ the escalator is ~~rising~~. Each experiment is performed several times at the same condition and the results are ~~satisfied~~ with less 10% ~~in~~ variation.



(a) Step's velocity (b) Handrail's velocity

Fig. 4 Velocity of the moving parts in simulation

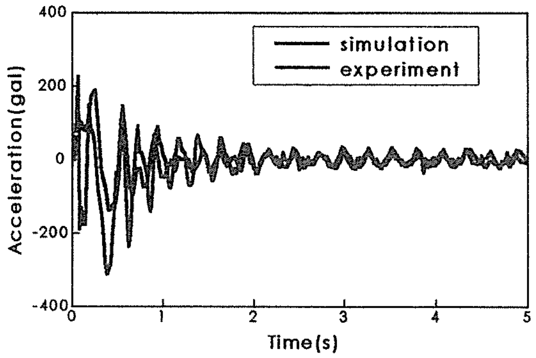


Fig. 5 Step acceleration

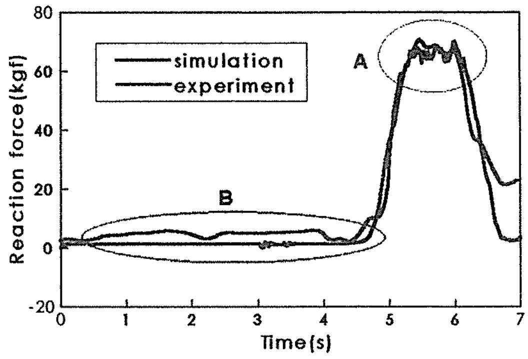


Fig. 6 Reaction force of the roller

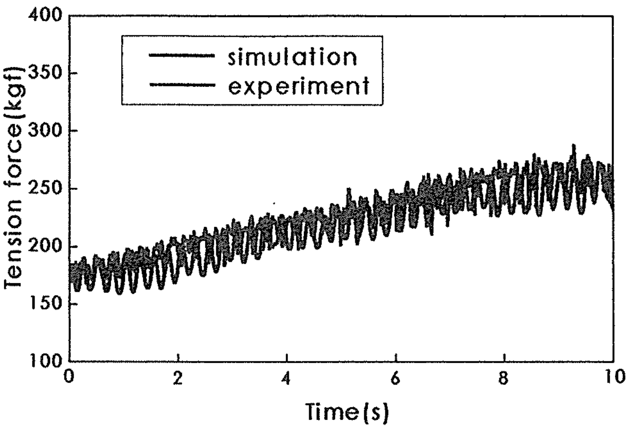
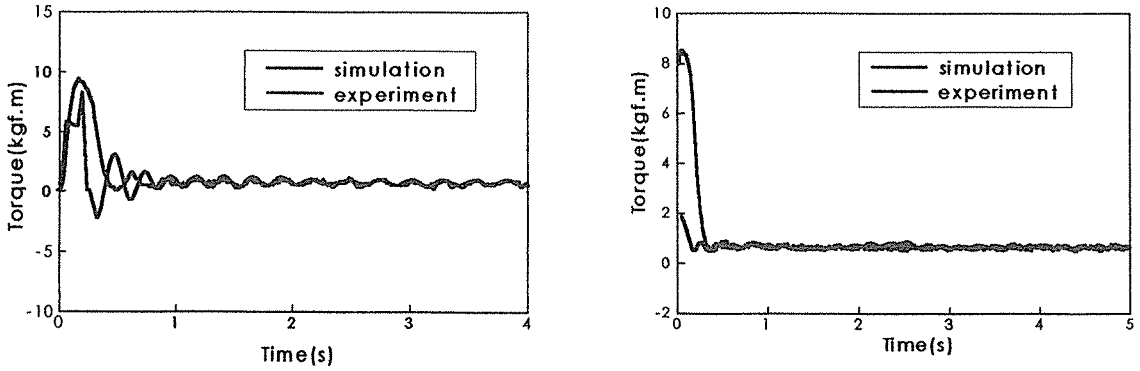


Fig. 7 Tension force of the chain



(a) Torque of the motor(step part)

(b) Torque of the motor(handrail part)

Fig. 8 Torque of the motor

As shown in Fig. 4, velocity of the moving parts in simulation converged to 500mm/s. Figure 5 shows a step's acceleration. It is shown that the forward directional vibration frequency of a step is 3.66Hz. The magnitudes of simulation and experiment are 40gal and 45gal each at steady state. 10% error in magnitude may be ~~because of~~ ~~excepting~~ the motor and the reducer in the model. Reaction force of a roller is shown in Fig. 6. As shown in circle (A) where a roller is rising near the upper terminal gear, the simulation result agrees very well with the experimental result within 6% error. The difference of reaction force between simulation and experiment in circle (B) where a roller is on the rail is caused by weight of jigs. Tension force of the chain is shown in Fig. 7. The maximum tension force and the slope of tension force of the chain of simulation are nearly the same those of experiment within 3% error. Figure 8 shows torque of the motor considering the step part and the handrail part separately. To compare torque of simulation and experiment, torque of the upper terminal gear and the driving pulley in simulation is changed to that of the motor considering the reduction ratio, 1/24, 1/24.1 each. Torque at steady state agrees well with that of experiment within 9%, 5% error each. The difference in starting up in Fig. 8(b) is caused by experimental condition including the step part inevitably.

5. Conclusion

Dynamic characteristics of the escalator that is about a thousand independent degree-of-freedom are simulated by the general purposed dynamic analysis program. Impact, permanent contact and temporary contact of rollers and the handrail on rails and drive parts are realized by applying thousands of friction contact elements. Many difficulties of modeling the continuous elastic handrail have been obviated since the handrail is divided into 127 discrete rigid bodies that are connected with spring and damper elements. The presented model is experimentally verified to substantiate the accuracy and efficacy. The authors believe this work to be the first to present and experimentally verify the dynamic analysis model for the escalator with about a thousand independent degree-of-freedom.

An extension of this work, currently in preparation by the authors, examine the computational dynamic model of the mega high rise escalator more than 30m in vertical height and the moving walk more than 150m long.

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