

8-7-99

Description:

Method of Force Limitation for Automatic Elevator Doors ✓

5 The invention relates to a method of force limitation for automatic elevator doors with a door drive comprising a control, motor, and drive mechanism for imparting motion to a car door and a hoistway door according to a pattern of speed and pattern of force corresponding to the position of
10 the door from an open position to a closed position or vice versa, the pattern of force itself being adaptable to door parameters which change with the passage of time, and the doors being stoppable and/or reversible due to a disruptive force being caused by an obstruction occurring while they
15 are in motion.

From patent specification DE 39 21 158 a device has become known for controlling a hinged door driven by a direct current motor. The drive torque is proportional to the
20 current in the armature of the motor. A memory device stores the pattern of the motor current in relation to the angle of opening of the door as it moves without obstruction and with the maximum permissible torque. These values of current can be obtained by calculation or
25 experiment. To take account of losses due to friction acting on the door, the reference value for the armature current is formed by adding to the value of the current mentioned above a moving average value which is derived from the actual value of the armature current during
30 obstruction-free operation. There is provision for calculating the reference value after each unobstructed opening and closing of the door. If the door becomes obstructed, the actual value of the armature current increases disproportionately. This actual value is compared
35 with the reference value in the control device. If the actual value is greater than the permissible reference

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value, the armature current is reduced, thereby reducing the drive torque on the door.

5 A disadvantage of the known device is the laborious and voluminous storage of the position-dependent current curves required for the average value for the entire range of movement of the door.

10 It is in this respect that the invention aims to provide a remedy. The objective of the invention as characterized in Claim 1 is to avoid the disadvantages of the known device and to define a method for limiting the driving force which has an optimized ratio between the driving force and the smallest detectable disruptive force and a greater degree
15 of safety for users of the elevator.

The advantages resulting from the invention relate mainly to the fact that it makes it possible to describe the unobstructed pattern of driving force in a compact form.
20 This enables an automatic, optimal setting of the driving force limiter to be achieved, and the effort required for commissioning to be reduced. A further advantage is that a limiting value of force is available not only for a specific reference speed function of the door, but can also
25 be generated for patterns which depart from this, for example for reduced speed or increased acceleration, without first carrying out a new measuring travel.

While the door is closing there is a danger of obstructions
30 such as, for example, persons or objects being present in the steadily diminishing door gap and becoming trapped there. While the door is opening there is a danger of, for example, children's hands or flat objects being inserted between the door panels as they move relative to each
35 other, or between the door panels and the door frame.

The method according to the invention relates to the door closing procedure as well as to the door opening procedure. Force limitation means limitation of the closing force while the door is closing, and limitation of the opening force while the door is opening. The pattern of force refers to the way in which the force changes while the door is closing or opening.

A more detailed description of the invention follows below by reference to drawings illustrating an embodiment. The drawings show:

Fig. 1 A schematic representation of the method according to the invention, and

Fig. 2 Statistical functions for analyzing the difference between reference values and actual values of closing force.

Fig. 1 shows a system for operating an automatic elevator door consisting of a reference value generator 1 for the speed, an actual value sensor 2 for the door speed/position, a movement controller 3, a speed generator 4 in the form of a door drive consisting of a control, a motor, and a drive mechanism, and an actual value sensor 5 for the driving force generated or produced. The drive or motor force is defined as the force generated by the motor and transferred to the door after taking into account the implemented gearing ratios. The closing force or opening force is the force which is applied to an obstacle by the door edge or door while the door is closing or opening. A driving force model 6 for the driving force calculates on the basis of a mathematical model and the calculated door parameters the driving force which is needed during unobstructed operation. Using the value given by the driving force model and a permissible disruptive force, a limiting value generator 7 calculates a limiting value for

the force which is compared by means of a comparator 8 with the actual value of the driving force or the driving force generated. If the limiting value of force is exceeded the door is stopped and/or a reversal of direction is initiated.

With the aid of a mathematical model of the involved components of the door and drive, the driving force model 6 gives the driving force to be applied. By reference to equations of motion and the door parameters determined beforehand, this mathematical model calculates the driving force needed at a specified acceleration and a specified speed under normal, unobstructed conditions. The limiting value for the force is calculated from the driving force needed and the maximum permissible obstructive force. If while the door is moving it strikes an obstacle, then if the force limiting value is exceeded by the driving force being generated, stopping and/or reversal of the elevator door is initiated to ensure the safety of the elevator users.

The mathematical model can be set in a fixed manner or, in a further embodiment, it can be adaptively constructed, adaptation taking place to the changes in parameters occurring during operation.

The model can be implemented (explicitly) on the basis of differential equations. The explicit mathematical model is based on the Newtonian equations of motion for the door mechanism. They are given here for a simplified model of the door mechanism.

For the purposes of the following discussion all forces and speeds in the direction of the closing door are defined as positive. If the mechanism is modeled as a single-mass system with the total door mass transferred to the door edge being m_{GT} , this results in the following relationship

between speed and force (Newtonian equation of motion, assuming direct transmission of force between counterweight and door edge)

$$v'_T = \frac{F_{MT} - F_R \cdot \text{sign}(v_T) + g \cdot m_G}{m_{GT}} \quad [1]$$

where

10

v'_T is the acceleration,

v_T the speed of the door edge,

F_{MT} the driving force generated by the motor and applied to the door edge/door taking into

15 consideration the transmission and transformation of the force by the mechanism,

F_R the sum of all the sliding and rolling friction forces of the door mechanism transferred to the door edge, assumed to be constant,

20 $\text{sign}(v_T)$ the sign function, which takes on the value 1 for $v_T > 0$ and the value -1 for $v_T < 0$,

g the acceleration due to gravity of 9.81 m/s^2 ,

m_G the mass of the counterweight, and

m_{GT} the sum of the masses of all moving parts (door panel, rollers, toothed belt, belt pulley, steel

25 ropes, counterweight, rotor of the motor, etc.) taking into consideration the transmission and transformation of the force by the mechanism.

30 Rearranging with reference to the force F_{MT} we obtain

$$F_{MT} = v'_T \cdot m_{GT} + F_R \cdot \text{sign}(v_T) + g \cdot m_G \quad [2]$$

$$35 \quad v'_T \approx \frac{v_T(t) - v_T(t-T)}{T} \quad [3]$$

This is a mechanical door model in explicit form, in which the physical parameters are still recognizable as such.

By means of the above equation the driving force needed at any time can be calculated depending on the parameters and the acceleration v_T . As shown in equation [3], the
 5 acceleration is calculated as an approximation from the speed values, T being a suitably selected sampling time.

Equations [2], [3] can easily be programmed and give the driving force model value for monitoring the force. If the
 10 parameters F_R , m_G , and m_{GT} are given a fixed value once only, for example when the door is manufactured or commissioned, the model is described as being permanently set. If the parameters of the model are automatically adapted to the actual parameters of the door mechanism
 15 while the door is in operation, the model is described as being adaptive.

The reference value generator 1 generates a reference value for speed as a function of time, or of the distance
 20 traveled by the door, or of its position. The movement controller 3 can be, for example, a speed/position controller which uses information concerning measured speed/position to generate a prescribed speed value.

25 The mathematical model reproduces the dependency of the driving force generated on the acceleration, the prescribed speed, and the position of the door. The mathematical model calculates the motor force which generates the specified speed curve in the absence of an obstacle. This normal
 30 pattern depends, for example, on the specified acceleration, the characteristics of the speed generation, the frictional forces, the mass of the moving parts, and on the parameters of the mechanism and the frictional conditions in the mechanism.

35

During the course of operation of the door, the driving force needing to be applied, and generated by the driving

force model 6, is subject to changes due to wear and aging. For this reason the driving force model 6 can be constructed in such a manner that a slow adaptation takes place of the driving force needing to be applied to the pattern which is subject to changes. The actual value of the driving force, or the driving force generated, can be analyzed in conjunction with the reference/actual speed to determine the actual moving masses, the closing weight of the door, and the frictional force either once only or continuously during operation of the door.

To obtain the unknown physical parameters of the explicit model, test trips are carried out in which the measured values for the motor force transferred to the door edge/door and the speed of the door edge/door are periodically recorded and stored. According to equation [1] the acceleration is dependent on the motor force. The right-hand side of the equation [1] contains a component which is linearly related to the force, and a constant component.

$$v'_T = \frac{1}{m_{GT}} \cdot F_{MT} + \frac{-F_R \cdot \text{sign}(v_T) + g \cdot m_G}{m_{GT}} = a \cdot F_{MT} + b \quad [4]$$

If the values V_T and F_{MT} are recorded over a period of time for an opening or closing operation, the coefficients a and b of the linear equation [4] can be easily determined, for example by linear regression. Let a_s and b_s be the values calculated for a closing operation, and a_o and b_o those for an opening operation. Then

$$a_s = a_o = \frac{1}{m_{GT}} \quad [5]$$

$$m_{GT} = \frac{1}{a_s} = \frac{1}{a_o} \quad [6]$$

$$b_s = \frac{-F_R \cdot \text{sign}(v_T) + g \cdot m_G}{m_{GT}} = \frac{-F_R \cdot 1 + g \cdot m_G}{m_{GT}} \quad [7]$$

$$b_0 = \frac{-F_R \cdot \text{sign}(v_T) + g \cdot m_G}{m_{GT}} = \frac{-F_R \cdot (-1) + g \cdot m_G}{m_{GT}} \quad [8]$$

$$m_G = \frac{(b_s + b_0) \cdot m_{GT}}{2g} \quad [9]$$

$$F_R = \frac{(b_0 - b_s) \cdot m_{GT}}{2} \quad [10]$$

As a result, all the parameters of interest in the explicit model are known. (The acceleration due to gravity g is assumed to be known). If identification of the parameters as described above is carried out once only, the resulting model is permanently set. The measured values can, however, also be recorded and processed during operation. The up-to-date parameters obtained in this way can be used to update the model parameters and to adapt to slow changes in the door mechanism due, for example, to wear and dirt. In this case the model is adaptive.

The mathematical model can also be implemented as an implicit model. An implicit mathematical model also creates for a given acceleration pattern a reference value for motor force, but without having to make use of the identifiable physical parameters. An implicit mathematical model can be represented by a neural network.

An implicit model is prepared by means of a training phase in which the behavior of the model is defined by a large number of examples of input/output behavior. These data examples are created by stimulating a real system whose behavior is to be imitated by the model with various input

data, and at the same time the input signal and the output signal which indicate the reaction of the system are recorded. In the present case, this would mean carrying out a number of opening and closing movements of the door and
 5 recording the pattern of measurements that occurs. The internal parameters of the implicit model are optimized until for all input data the model produces output data similar to the real-life system, and the model and reality correspond adequately.

10

The speed generator 4 can take the form of, for example, an asynchronous motor in conjunction with a frequency converter with a rotor flux type of current regulation and overlaid speed control, the current component i_{sq} which is
 15 orthogonal to the rotor flux and creates the torque being used as the internal value.

Creation of the torque in a rotating asynchronous motor requires a magnetic field which rotates around the motor
 20 axis. An especially simple description of the relationship between motor current, magnetic flux, and motor torque using equations becomes possible if a transformation of coordinates is carried out.

25 The stator currents measured in the three phases of the motor combine to form a resultant current vector i_s whose magnitude and angle are defined in relation to the first motor winding axis. The transformation of coordinates consists of taking as reference point not the position of
 30 the first winding axis but the momentary magnetic flux in the rotor of the machine. The current in the stator i_s can then be resolved into a component i_{sd} parallel to the rotor flux and a component i_{sq} at right angles to it. The magnitude of the rotor flux can be held constant by the
 35 suitably controlled current component i_{sd} . There is then a proportional relationship between i_{sq} and the motor torque

generated so that i_{sq} is a measure of the driving force acting on the door edge/door.

The speed generator 4 can also take the form of, for example, an asynchronous motor in conjunction with a U/f control, the measured slip serving as a measure of the driving force generated.

The slip s is defined by the following equation:

$$s = \frac{w_s - w}{w_s} = \frac{n_s - n}{n_s} \quad [11]$$

$$n_s = f_s / z_p$$

where

- s is the slip,
- n_s the synchronous rotational speed of the rotating magnetic field,
- n the mechanical rotational speed of the motor shaft,
- w_s the synchronous angular velocity of the magnetic field,
- w the mechanical angular velocity,
- f_s the momentary synchronous, or output, frequency of the frequency converter, and
- z_p the number of poles of the motor being used.

According to the known Klossian formula

$$m_M = \frac{2M_K}{s/s_K + s_K/s} = \frac{2M_K \cdot s}{s^2/s_K + s_K} \quad [12]$$

where

- M_K is the pull-out torque, and
- s_K the pull-out slip.

Both values remain constant for a given motor and U/f characteristic control.

For small amounts of slip ($s < s_K$) the approximation

$$5 \quad m_M = \frac{2M_K \cdot s}{s^2/s_K + s_K} \approx \frac{2M_K}{s_K} \cdot s \quad [13]$$

applies, so that from a measured mechanical rotational speed n and the known frequency of the output voltage f_s of a frequency converter, the slip, and from this in turn the motor torque, can be calculated according to the formula

$$15 \quad m_M = \frac{2M_K}{s_K} \cdot \frac{f_s/zp - n}{f_s/zp} \quad [14]$$

The speed generator can take the form of, for example, a voltage and frequency controlled asynchronous motor, the measured value of the stator current serving as a measure of the driving force.

With U/f control, the mean value over time of the current through the stator winding of the asynchronous machine depends on the generated motor torque m_M according to the formulae

$$m_M = -K \cdot I_{r\alpha} \quad [15]$$

$$30 \quad |I_s| = \sqrt{(I_\mu^2 + I_{r\alpha}^2)} \quad [16]$$

where I_r is the mean value over time of the component of current proportional to torque, K is a constant depending on the motor data, and I_μ is the constant value of the magnetization current. The value of the torque resulting from the measured value of current is then given by

$$m_M = -K \cdot I_{r\alpha} \quad [15]$$

$$40 \quad |m_M| = 1/K \cdot \sqrt{(I_s^2 - I_\mu^2)} \quad [17]$$

$$K = 3/2 \cdot z_p \cdot \frac{L_m \cdot U_{nom}}{L_s \cdot 2\pi \cdot f_{nom}} \quad [18]$$

$$I_\mu = \frac{U_{nom}}{2\pi \cdot f_{nom} \cdot L_m} \quad [19]$$

where

- 10 z_p is the number of pole pairs,
- I_s the value of the stator current,
- L_m the main self-inductance of the motor,
- L_s the stator self-inductance of the motor,
- U_{nom} the rated voltage of the motor, and
- 15 f_{nom} the rated frequency of the motor.

This makes it possible to calculate the value of the drive torque from the measured value of current. Other arrangements and methods of control as, for example, synchronous drives with measurement of the rotor displacement angle or of the value of the stator current, or direct current drives with measurement of the stator current, etc., which allow conclusions to be drawn about the force actually generated by the driving agent, are other possibilities for the speed generator.

The speed generator 4 can also take the form of, for example, a synchronous motor.

30 The limiting value generator 7 calculates from the model value for driving force derived from the mathematical model, and a permissible obstructive force, a limiting value of force. In the simplest case, this is done by addition of the maximum permissible obstructive force specified by regulations of, for example, 120 N.

A more sensitive solution for determining the limiting value of force can be obtained by using a statistical method of analysis based on, for example, a Gaussian normal

distribution. The Gaussian normal distribution is only one of many possible distribution functions. Exponential, Weibull, or equipartition distributions can also be used. All of these functions have a density function and a
5 distribution function, it being possible, of course, for the calculated numerical values to differ. Statistical analysis of the difference between the actual value of the driving force and the value for the driving force delivered by the mathematical model makes it possible to determine
10 how well the measured values for unobstructed movement correspond with the theoretical values. As shown in Fig. 2, if a Gaussian normal distribution of the difference values is assumed, the calculated standard deviation can be used to determine what percentage of all difference values
15 exceed a specified limiting value due entirely to random influences, without an obstruction having in fact occurred during closing. Conversely, the minimum limiting value can be given and used for which the probability of an erroneously initiated reversal is acceptably small.
20

Let it be assumed that for a large number of measurements the difference values are distributed about the mean value 0 of the density function $\phi(z)$ (curve 9) of the normal distribution with a standard deviation of 10 N. In this
25 case, according to the distribution function $\phi(z)$ (curve 10) of the normal distribution, 50% of all difference values are less than 0. 84% of all limiting values are smaller than 10N, 97.7% are smaller than 20N, and 99.6% are smaller than 30N. If the limiting value is set 30 N higher
30 than the reference value for the door closing force produced by the mathematical model, only 0.14% of all measured values will exceed the limiting value as a result of random interference. This makes it possible to implement a lower initiation threshold and reduce the risk of injury
35 without impairing reliability. On the basis of continuous statistical analysis of the difference values adaptation can take place during operation.

Patent Claims

1. Method of force limitation for automatic elevator
5 doors with a door drive comprising a control, motor,
and drive mechanism for imparting motion to a car
door and a hoistway door according to a pattern of
speed and pattern of force corresponding to the
10 position of the door from an open position to a
closed position or vice versa, the pattern of force
itself being adaptable to door parameters which
change with the passage of time, and the doors being
stoppable and/or reversible due to a disruptive force
15 being caused by an obstruction occurring while they
are in motion,
characterized in that
the pattern of driving force needed during
unobstructed operation is determined by means of a
mathematical model for the door drive and compared
20 with the pattern of driving force generated by the
door drive,
and in that
differences of a specified amount between the
necessary pattern of force and the generated pattern
25 of force caused by the disruptive force stop and/or
reverse the doors.
2. Method according to Claim 1,
characterized in that
30 the mathematical model is based on Newtonian
equations of motion for the door mechanism.
3. Method according to Claim 2,
characterized in that
35 the mathematical model is an adaptive model in which
the parameters are automatically adjusted to the
actual parameters of the door mechanism while the



door is in operation.

4. Method according to Claim 1,
characterized in that
5 the mathematical model can be represented by an
artificial neural network, the model being prepared
by means of a training phase during which the model
imitates a real system.
- 10 5. Method according to Claim 1,
characterized in that
an asynchronous motor with voltage and frequency
control is provided to generate the pattern of force,
the measured motor slip serving as a measure of the
15 driving force.
6. Method according to Claim 1,
characterized in that
an asynchronous motor with voltage and frequency
20 control is provided to generate the pattern of force,
the measured value of the stator current serving as a
measure of the driving force.
7. Method according to Claim 1,
25 characterized in that
an asynchronous motor supplied by a frequency
converter is provided to generate the pattern of
force, the component of current i_{sq} orthogonal to the
rotor flux serving as a measure of the driving force.
30
8. Method according to Claim 1,
characterized in that
a synchronous motor is provided to generate the
pattern of force.
35
9. Method according to Claim 1,
characterized in that



5 a limiting value of force is determined from the
model value for the driving force obtained from the
mathematical model and a permissible disruptive
force, the doors stopping and/or reversing when the
limiting value of force is exceeded.

10. Method according to Claim 9,
characterized in that
the limiting value of force is determined by means of
10 a method of statistical analysis by reference to a
density function and a distribution function.

