An Analysis of the Mechanism of the Self-Increasing Brake System

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Abstract. The auxiliary brake is closely associated with the safety of passengers. Despite the issues of insufficient braking torque and excessive impact in the existing auxiliary brake, the self-increasing brake system has the characteristics of stable and reliable braking in favor of passengers’ safety. It is of great significance to study the mechanisms in the self-increasing brake system. In this paper, kinematic analysis along with mechanical analysis is used to study the braking torque under both static and dynamic conditions. The equivalent braking torque test and braking deceleration test are also conducted to evaluate the braking performance. It is shown that the braking in down direction conforms with the regulations. Researches have indicated that, even under the circumstance of a small theoretical value of braking torque, the self-increasing brake still meets the norms with a stable braking process as well as a limited impact, thanks to the combined effect of self-increasing torque. It can be seen that the self-increasing torque can directly influence the braking torque and the maximum deceleration.

1. Introduction

The auxiliary brake is an important safety component of the escalator. There are three main types of auxiliary brakes prevailing in the market, namely Wedge Type, Clutch Type, and Block Type. The Wedge Type inclines to damage itself and risk passengers’ safety in a braking process due to the excessive impact brought by direct collisions of metal components.

Clutch type and block type auxiliary brake are not able to maintain enough braking force when the brake linings wear out, resulting in an excessively long braking distance or function failure. The lack of force compensation mechanism inevitably causes a decrease of the braking force in those types of brakes.

In recent years, casualty accidents occur frequently due to the function failure of auxiliary brakes. Although there are no specific requirements in the code of ASME [1]. As stipulated in the standards
like EN115-1:2008[2] and GB/T16899:2011[3], the auxiliary brakes should be equipped in the public transport escalators and inclined moving walks even when the lifting height is less than 6m. In the case of commercial escalators and inclined moving walks, the equipment of auxiliary brakes is compulsory when the lifting height exceeds 6m. Besides, the deceleration should be not more than $1\text{m/s}^2$ after the second-order Butterworth filtering at 4.0 Hz, in either no-load or full-load condition.

According to Newton's second law:

$$F = m \cdot a$$  \hspace{1cm} (1)

Where: $a\leq1 \text{ m/s}^2$; $m$: the mass from empty loads to full loads (kg); $F$: braking force (N)

Then the braking force $F$ is the key to the brake. If $F$ is too large, it may exceed the requirement of $1\text{m/s}^2$; if $F$ is too small, it may cause an excessively long braking distance or function failure.

Therefore, the self-increasing auxiliary brake system is proposed to solve these problems. The friction pair composed of the brake linings and the metal brake disc avoids the excessive impact; on the other hand, self-increasing torque will not only compensate for the decrease of braking force, but also increase the braking force during the braking process.

2. Load Requirements and Calculations

An escalator is shown in Figure.1, the motor drives the main drive sprocket by the roller chain; the step chain sprocket and main drive sprocket are assembled together rigidly. The loads or the passengers stand on the step, under which the step chain is installed. The step chain sprocket transmits the power through the step chain to make the loads or the passengers move up or down.

The maximum load of an escalator is divided into static load and dynamic load, whose requirements are as follows:

$$m_{\text{H-stc}} = H \cdot m_{\text{stc-unit}}$$  \hspace{1cm} (2)

Where: $H$: lifting height (m); $m_{\text{H-stc}}$: static load (kg); $m_{\text{stc-unit}}$: static load (kg/m), as shown in Table 1.

Calculations of dynamic load:

$$m_{\text{H-dyn}} = H \cdot m_{\text{dyn-unit}}$$  \hspace{1cm} (3)

Where: $m_{\text{H-dyn}}$: dynamic load (kg); $m_{\text{dyn-unit}}$: dynamic load (kg/m), as shown in Table 1.
Table 1. Escalator Full Loads Assumption when $\alpha=30^\circ$.

| Nominal width [2-3] (mm) | Dynamic load per step [2-3] (/kg) | $m_{\text{stc-unit}}$ (/kg/m) | Static load per step (/kg) | $m_{\text{dyn-unit}}$ (/kg/m) |
|--------------------------|----------------------------------|-------------------------------|---------------------------|-------------------------------|
| 600                      | 60                               | 295.3                         | 108.6                     | 534.5                         |
| 800                      | 90                               | 442.9                         | 145.1                     | 714                           |
| 1000                     | 120                              | 590.6                         | 181.6                     | 893.6                         |

The maximum lifting height of a single auxiliary brake is generally 12 m. So for example, if the nominal width is 1000 mm, the inclination angle $\alpha=30^\circ$ and $H=12$m, then the static load and the dynamic load at full load are $m_{H\text{-stc}}=10723.2$kg and $m_{H\text{-dyn}}=7087.2$kg respectively. As only the dynamic load is considered in the braking process, static and dynamic braking analysis of the self-increasing brake system is carried out on the basis of the dynamic load below.

3. Structure and Mechanism Analysis

3.1. Drive structure

Figure 2 (a) shows the structure of the drive unit in upper landing. The main engine is bolted to the truss base. The low speed output shaft of the gearbox is equipped with a small roller sprocket, and is connected to a large roller sprocket on the main drive shaft through multiple rows of roller chains. The large roller sprocket, the left and right step chain sprocket, the brake disc and the shaft are connected together and are integrally mounted on a truss. When the motor rotates, the main drive is made to rotate clockwise or counterclockwise around the axis by a mechanical linkage drive. With the rational reduction ratio, the low-speed, high-torque output of the motor is achieved, conveying passengers up and down.

Figure 2 (b) shows the structure of self-increasing brake. The brake arm is mounted on the truss base by the pivot point. Both sides of the front end of the braking arm are equipped with the brake linings, which form the friction pairs along with the brake disc, as shown in Figure 2(c), similar to the v belt-transmission. The rear end is provided with a compression spring, the other end of which is mounted on the fixed bracket of the truss base. By controlling the compression spring to be compressed or relaxed, the brake states of occlusion and detachment are realized.

The specific working mechanism is summarized in the following Table 2:
Table 2. Braking Process

| Working state | Load | Self-increasing Torque | Unloading Torque | Friction Force | Brake Arm |
|---------------|------|------------------------|------------------|---------------|-----------|
| Stationary    | No load | no | no | no | It is just put on the brake disc |
|               | On load | yes | no | Yes, and there is an increasing trend. | |
| Going down    | Either | yes | no | Yes, and there is an increasing trend. | |
| Going up      | Either | no | yes | Yes, and there is a decreasing trend. | |

As can be seen from table 2, when the escalator is stationary, the brake arm and the brake disc just touch each other, and no friction occurs.

When the escalator is on load or going down, there is friction generated between the brake arm and the brake disc. Because of the mechanism design, there is an extra self-increasing torque making the brake arm move clockwise and press on the brake disc more tightly. This self-increasing torque has an enhancing effect on the braking force.

When the escalator is going up, friction force is initially generated by the contact between the brake arm and the brake disc. However, there is an extra unloading torque because of the mechanism design, making the brake arm rotate counterclockwise, which has an unloading and reducing effect on the friction force. When the unloading torque is greater than the pressing torque produced by spring force, the brake arm forms a cycle of pressing down – bounced off – pressing down; when the unloading torque is smaller than the pressing torque, a friction force of a dynamically changing magnitude is generated.

In practice, it is the down-going process that influences the passengers’ safety. As analyzed above, the self-increasing brake will generate an extra braking force when the escalator is going down or has a tendency of going down, which helps the load braking. When the escalator is going up, there is an unloading torque which helps to decrease the pull force required for brake reset.

3.1. Force analysis
The force analysis of the stationary, down-going and up-going conditions is shown in Figure. 3 below. And the detailed calculations are summarized in Table 3.
Figure 3. Force Analysis.

Table 3. Braking Process Formula Matrix

| Parameter                        | Equation                                                                 | Motionless-no load | Motionless-on load, Going Down | Going up |
|----------------------------------|--------------------------------------------------------------------------|--------------------|-------------------------------|----------|
| Pressing Force (N)               | \( F_D = \frac{FF \cdot LB}{LC \cos \delta - (LR \cdot RA \cdot \cos \delta) \cdot \sin \delta} \) | yes                | yes                           | yes      |
| Equivalent Friction Coefficient  | \( \mu_F = \frac{F_D}{L_L} \)                                           | no                 | yes                           | yes      |
| Friction Force (N)               | \( F_B = \mu_F \cdot F_D \)                                            | no                 | yes                           | yes      |
| Equivalent Braking Torque (Nm)   | \( T_{motor} = \frac{FB \cdot RA}{i_{motor \_md}} \)                     | no                 | yes                           | yes      |
| Self-increasing Torque (Nm)      | \( T_{stick} = FB \cdot LE \)                                          | no                 | yes                           | no       |
| Unload Torque (Nm)               | \( T_{release} = -FB \cdot LE \)                                       | no                 | no                            | yes      |
| Corrected Pressing Force (N)     | \( F_D' = \frac{FF \cdot LB - FB \cdot LE}{LC \cos \delta \cdot (L_H \cdot R_A \cos \delta) \cdot \sin \delta} \) | no                 | no                            | yes      |

Where: \( FF \) is spring force (N); \( LB \) is the distance between the pivot point of the brake arm and the center point of the spring (mm); \( LC \) is the horizontal distance between the pivot point of the brake arm and action center of brake lining (mm); \( \delta \) is the angle between vertical line and the line drew through the brake disc center and the action center of the brake lining (mm); \( L_H \) is the vertical distance between pivot point of the brake arm and brake disc center (mm); \( RA \) is the radius between the action center of the brake lining and circle center of the brake disc (mm); \( \mu \) is the nominal friction coefficient of brake lining; \( \psi \) is the angle of wedged gap (°); \( i_{motor \_md} \) is the reduction gear ratio between motor gear box and the drive shaft; \( LE \) is the distance of the pivoting point of the brake arm and the action line of friction FB.

In up-going states, when \( FF \cdot LB - FB \cdot LE \leq 0 \), there is no friction pair, thereby no friction; when \( FF \cdot LB - FB \cdot LE > 0 \), with equation (6),(10),(7) and (8), the friction will be in the dynamically changing process.

3.2. The analysis and calculations of load and braking force

Considering a condition where \( H=12m, \alpha=30^\circ, V=0.65m/s, n=1500rpm \), according to mechanics and kinematics, the minimum critical braking force (Ignoring its load friction) is shown in equation (11) and (12):

\[
m_{H-dyn} \cdot g \cdot \sin \alpha \cdot \frac{D_{STP}}{2} = FB \cdot RA
\]
and:

\[ m_{H\text{-dyn}} \cdot g \cdot \sin \alpha \cdot \frac{D_{STEP}}{2} = T_{motor} \cdot i_{motor-md} \]  

(12)

Where \( D_{STEP} = 0.8659 \) m is the pitch diameter of the step chain sprocket; \( g = 9.8 \) m/s\(^2\) is the gravity constant.

From equation (12), the equivalent torque of the load on motor is 143.7 Nm, which should be smaller than the actual braking torque.

According to the force analysis and the equation (4), (5), (6) and (7), the values of the equivalent braking torque and the self-increasing torque are 82.6 Nm and 572.6 Nm respectively.

4. Equivalent braking torque and deceleration test

By the analysis in section 3.2, the equivalent torque of the load on motor is 143.7 Nm, and the force generated by the brake should be larger than that, otherwise it will cause longer brake distance or even function failure.

Therefore, eliminating the interference factor, under the no-load condition, we measured the equivalent braking torque generated by the self-increasing brake using a digital torque wrench to evaluate the braking capability. Experimental devices are shown in Figure. 4 (a), can be seen, the digital display torque wrench was mounted on the top of motor, the high speed end of the motor. By pulling the wrench clockwise or counterclockwise, the maximum braking torque is measured before the steps are moved.

The impact of the braking process was also assessed by the test of No-load deceleration to determine whether it meets the standards of EN115-1:2008 and GB16899-2011. With Vibration Analysis Tools (PMT) and Tachometer (ETCH01), the No-load deceleration test was performed, the experimental devices are shown in Figure.4 (b). Can be seen, the tachometer is mounted on comb plate by a bracket, then the roller of tachometer contacts with the steps constantly. The original speed signal is transmitted to the PMT by a cable placed on the floor plate firmly. With the Vibration analysis software (EVA-625), the data was processed, and the processed results are shown in Figure.5. The start point of braking was detected by a sensor and the distance could be measured with a tape from the start point to the point where it stopped.

![Digital Torque Wrench](image)

![Motor High Speed End](image)

![ETCH01 PMT Step Comb Plate Floor Plate](image)

**Figure 4.** Experimental devices at upper landing.

The results are shown as follows:
Table 4. Brake Torque & Deceleration Test in No-load condition

| NO. | Max-deceleration /\(m/s^2\) | Brake Distance /\(mm\) | Equivalent Brake Torque-down /\(Nm\) | Equivalent Brake Torque-up /\(Nm\) | Theoretical Calculation Value \(T_{motor}\) /\(Nm\) | Theoretical Demand Value \(T_{motor} > \) /\(Nm\) |
|-----|-------------------------------|------------------------|--------------------------------------|------------------------------------|---------------------------------|--------------------------------|
| 1   | 0.725                         | 413                    | 210-217                              | 37-54                              | 82.567                          | 143.7                          |
| 2   | 0.759                         | 429                    | 200-210                              | 37-54                              | 82.567                          | 143.7                          |
| 3   | 0.785                         | 531                    | 200-212                              | 37-54                              | 82.567                          | 143.7                          |

On the one hand, from Table 4, the repeated measurements of no-load maximum deceleration indicate that the impact was minor in the braking process of the self-increasing brake, as displayed in Figure.5, the numerical differences are small, and \(a \leq 1 \, m/s^2\). The variance of braking distance remains small. The measured equivalent braking torques were of little difference and the braking requirements with a lifting height of 12 m at full load were met. From the three aspects of the deceleration, braking torque and braking distance of the braking process, the self-increasing brake has the characteristics of small impact, high repeatability and robust stability.

On the other hand, compared with the equivalent torque calculated in section 3, the value was smaller in the up-going process while larger in the down-going process, which is consistent with the analyzed trend above. Because of the existence of the unloading torque \(T_{release}\) in the up-going process and the self-increasing torque \(T_{suck}\) in the down-going process, there is a large difference between the calculated values and measure values.

As observed in the braking process, the brake arm and the brake disc were not relatively static in the radial direction, and a wedge-caulking tendency would be generated under the action of \(T_{suck}\). In this situation, the actual equivalent friction coefficient is different with theoretical equivalent friction coefficient in the equation (5), since only the factor of wedge angle was considered in the equation (5).

The researches of equivalent friction coefficient of V-belt by ZHEN Dayu [4], QIU Xiang [5], ZHU Lin [6-7] indicate that the equivalent friction coefficient was a dynamically changing value rather than a constant one. The braking process of the self-increasing brake differs from V-belt braking. The equivalent friction coefficient in this case needs further study.

5. Conclusion
Base on the structure analysis of self-increasing brake and the theoretical calculations of the brake torque, self-increasing torque and unloading torque, this paper analyzed the relations among brake torque, self-increasing torque and unloading torque in different operating conditions. With experiment validation, conclusions are as follows:
The self-increasing brake met the requirements of standards EN115-1:2008 and GB/T16899-2011 on deceleration $a \leq 1\text{m/s}^2$.

The self-increasing brake was effected not only by the pressing force of the spring mechanism, but also by the self-increasing Torque ($T_{\text{suck}}$). It was shown that $T_{\text{suck}}$ contributes more on the self-increasing brake.

The self-increasing brake can generate a relatively larger brake torque from a small theoretically calculated torque.

Because of choking effect, the brake linings slipped along the brake disc in radial direction. The theoretical calculation of equivalent friction coefficient was insufficient and needs further analysis.

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