Development of an Electromechanical Brake

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The NTN electromechanical brake (EMB) system was designed and launched with the intention of improving overall performance of future automotive braking systems. NTN has designed and developed a new linear actuator that can be applied to this system. This paper reports on the configuration, design principles, efficiency calculation methods and related experiments.

1. Introduction

In the automotive industry there has been an increased emphasis on vehicle safety. Improvement in brake technology has greatly contributed to stable running of vehicles. Increased functionality has resulted in products like ABS, ESC, and brake assist \textsuperscript{1)-2)}. An example of the increased functionality of automotive brakes is improvement in control techniques for hydraulic brakes. Furthermore, in an effort to continue this improvement in functionality and reduction in environmental impact, automotive components manufacturers and car manufacturers are developing electromechanical brake (EMB) systems.

Many of newly developed electromechanical brake systems employ linear actuators such as ball-screws and ball-ramps (torque cams). However, when any of these linear actuators is used to develop the sufficient thrust required to brake a traveling vehicle, greater input torque is needed because the load conversion ratio with the linear actuator alone is insufficient. To design a more compact, lightweight electromechanical brake unit, the motor must be more compact. Therefore an independent reducer needs to be incorporated. Additionally, the electromechanical brake is situated in the “unsprung” section of the vehicle and will be subjected to violent vibration. Therefore it must be positively fretting-resistant.

Incidentally, when the electromechanical brake unit is used as a parking brake without any modification, a separate mechanism will be needed to lock the revolution motion of the motor because a linear actuator such as a ball-screw lacks a thrust holding function. To address this issue and satisfy the functions required for such an electromechanical brake unit (high load conversion ratio, fretting-resistant quality, load-holding function), NTN has invented a unique linear actuator mechanism that doesn’t require an accompanying mechanism and developed a unique electromechanical brake unit that includes an electric motor.

In this paper, we describe the constitution and operating principle of this electromechanical brake unit, the method for calculating the efficiency of the brake unit, as well as the evaluation tests we have performed.

Legends
\begin{align*}
a, b & \quad \text{half width of Hertz contact ellipse on threaded surface} \\
D_S & \quad \text{sun roller outside dia.} \\
D_P & \quad \text{planetary roller outside dia.} \\
d_{BS} & \quad \text{ball center diameter on ball-screw} \\
d_O & \quad \text{outer ring inside dia.} \\
F & \quad \text{force acting on the piston} \\
k & \quad \text{number of effective thread ridges on each planetary roller} = \frac{b_d}{P} \\
L_P & \quad \text{thread lead on planetary roller} \\
\end{align*}
2. Linear actuator

2.1 Constituent Elements and Operating Principle

The constitution and operating principle of NTN’s linear actuator are discussed below.

NTN’s linear actuator comprises, as shown in Fig. 1, a sun roller, planetary rollers, an outer ring, a carrier, a piston and a threaded member which constitutes the screw of the outer ring. Several planetary rollers are shrink-fitted between the sun roller and the fixed outer ring; thereby the planetary rollers rotate and revolve as the sun roller rotates. Spiral threading is provided on the outer circumference of each of the planetary rollers as well as on the inner circumference of the outer ring, wherein these threads have an identical pitch so that they can be correctly meshed with each other.

As a result of this layout, while revolving and rotating, the planetary rollers will be axially shifted relative to the outer ring. The carrier and piston each support rotation and revolution of the planetary rollers; then, the rotary motion of the sun roller is finally converted into the linear motion of the piston.

Suppose that there is no slipping at the contact points between the outer circumference of sun roller, outer circumferences of planetary rollers and inner circumference of outer ring, the amount of axial displacement \( x \) of the piston relative to the rotary motion of the sun roller can be expressed with the formula (1). At the same time, the amount of axial displacement \( x_{BS} \) of the nut on the ball-screw can be expressed with the formula (2). The axial displacement \( x \) of the piston is dependent on the difference between the lead angle of the thread on the planetary rollers and that on the outer ring; thereby the axial displacement \( x \) of the piston (our linear actuator) can be smaller than the axial displacement \( x_{BS} \) of the nut on the ball-screw. In other words, compared with a value obtained with the ball-screw arrangement, the load conversion ratio, which can be defined as the thrust relative to the input torque, can be greater with our linear actuator.

\[
x = \frac{d_O}{2} \cdot (\tan a_O - \tan a_F) \cdot \theta_{REV} \quad \cdots \cdots (1)
\]

\[
x_{BS} = \frac{d_{BS}}{2} \cdot \tan a_{BS} \cdot \theta_{BS} \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdOTS
formed on the outer ring by adding a coil-shaped thread member in the spiral grooves formed on the bore surface of the outer ring.

2.2 Efficiency

In order to be able to determine the efficiency of our linear actuator, we provided the following assumptions [1] through [4]:

[1] The thrust occurring on the piston is uniformly carried by all the planetary rollers and threads.

[2] Because of the smaller lead angle (not greater than 5 degrees), the circumferential component of the load occurring on the thread can be ignored.

[3] No slipping occurs at the contact points between the outer circumference of the sun roller and the outer circumference of each planetary roller and between the inner circumference of the outer ring and the outer circumference of each planetary roller.

[4] The areas where loss appears to occur are the revolution supporting bearing, rotation-supporting bearing, and sun roller supporting bearing and contact surfaces on threads.

In addition to these areas, the axial sliding at the contact areas between the planetary rollers and sun roller and between the planetary rollers and outer ring is regarded as a loss. However, this sliding accompanies rolling contact, and is considered to be fairly small.

By referring to Fig. 2, suppose that the torque being input from the sun roller causes the piston to move axially. Then, the efficiency of the linear actuator \( \eta \) and the relation between the work input and work output can be expressed with the formulas (3) and (4), respectively.

\[
\eta = \frac{W_{\text{OUT}}}{W_{\text{IN}}} = \frac{F \cdot x}{T_S \cdot \theta_S} \quad \cdots \cdots \cdots \cdots (3)
\]

\[
W_{\text{OUT}} = W_{\text{IN}} - W_{\text{REV}} - W_{\text{ROT}} - W_S - W_{SC} \quad \cdots \cdots \cdots \cdots (4)
\]

The torque loss from each bearing was calculated utilizing the Palmgren \(^3\) experimental formula for friction torque.

Now, we would like to discuss the load acting on the sun roller supporting bearing. The normal force and tangential force from a planetary roller, shown in Fig. 3, act on the sun roller. From the relation with a frictional circle, we determined the axial tangential force \( P_x \) with the formula (5) below, and took the resultant force value as the axial load acting on the sun roller supporting bearing.

\[
P_x = \mu \sqrt{(\mu P_S)^2 - P_f^2} \quad \cdots \cdots \cdots \cdots (5)
\]

Next, we would like to explain the losses arising from sliding on the screw thread. On the screw threads between the planetary rollers and outer ring, the Hertz contact ellipse shifts, as illustrated in Fig. 4, while the planetary rollers rotate. Suppose that each planetary roller moves along the inner circumference of the outer ring. Then, the contact ellipse on the screw thread shifts with the sliding motion that consists of the tangential displacement \( U \) of the center of ellipse (expressed with the formula (6)) and the rotational displacement \( \theta \) on the center of ellipse (expressed with the formula (7)).

\[
U = \left( \frac{d_O}{2} - \delta \right) \cdot \theta_{\text{REV}} + \left( \frac{D_p}{2} - \delta \right) \cdot (\theta_{\text{ROT}} - \theta_{\text{REV}}) \quad \cdots \cdots \cdots \cdots (6)
\]

\[
\theta = (\theta_{\text{ROT}} - \theta_{\text{REV}}) \cdot \cos \beta = \theta'_{\text{ROT}} \cdot \cos \beta \quad \cdots \cdots \cdots \cdots (7)
\]
Then, take the sliding-induced losses within the contact ellipse as the sum of losses within a miniature area such as a one given in Fig. 5. Then, from the amount of sliding $V(x, y)$, determined with the formula (8) and the normal load $f(x, y)$, determined with the formula (9), the sliding-induced loss $W_{SC}$ on the screw thread can be expressed with the formula (10).

\[
V(x, y) = \sqrt{(U + r \theta \sin \phi)^2 + (r^2 \theta^2 \cos^2 \phi)} \quad (8)
\]

\[
f(x, y) = \frac{3P_{SC}}{2 \pi a b} \sqrt{1 - \frac{x^2}{a^2} - \frac{y^2}{b^2}} \, dx \cdot dy \quad (9)
\]

\[
W_{SC} = nk \int f(x, y) \cdot V(x, y) \, dx \cdot dy \quad (10)
\]

Under the calculation conditions given in Table 1, the thrust $F$ and efficiency $\eta$ for the units No. 1 through 4 were calculated, and the result is plotted in Fig. 6; and the loss ratios relative to the inputs to the unit No. 1 are illustrated in Fig. 7. For these calculations, it was assumed that $\mu = \mu_{SC} = 0.1$. From Fig. 6, it should be understood that the thread can be variously specified and a variety of linear actuators each featuring unique efficiency can be designed. With Fig. 7, it is possible that the proportion of the loss resulting from sliding on the screw thread is large and increases as the torque increases.

**Table 1 Calculation condition**

<table>
<thead>
<tr>
<th>Technical data</th>
<th>No.1</th>
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</table>

**Fig. 4** Contact ellipse in thread of the screw

**Fig. 5** Contact ellipse

**Fig. 6** Calculation results of thrust and efficiency

**Fig. 7** Ratio of losses
3. Evaluation for characteristics of linear actuators

3.1 Units being tested and test method

We have evaluated the efficiency and thrust holding function of our linear actuator. The specifications of the linear actuator units tested are summarized in Table 2, and the configuration of the test rig is illustrated in Fig. 8. With the test rig, torque was applied to the linear actuator by, for example, applying a weight to the lever, thereby the efficiency of our linear actuator was determined based on the torque input to the sun roller and the thrust from the piston detected by the load cell.

<table>
<thead>
<tr>
<th>Unit</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
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<th>F</th>
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<td>←</td>
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<tr>
<td>(\nu)</td>
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<td>←</td>
<td>4</td>
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<td>←</td>
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<tr>
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<td>2</td>
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<td>3</td>
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<td>(L_O), mm</td>
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<td>0.220</td>
<td>0.419</td>
<td>0.640</td>
<td>0.331</td>
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</table>

Table 2 Specifications of linear actuator

To address this issue, we developed the relationship between the equivalent lead angle of the linear actuator defined with the formula \(11\), efficiency of the linear actuator when it develops 30 kN and availability of its thrust holding function, and this relation is plotted in Fig. 11. With a greater equivalent lead angle, the efficiency is better; when the equivalent lead angle is 0.331 deg or greater, the thrust holding function is not available. To sum up, it must be understood that the linear actuator needs to be designed to have an equivalent lead angle of approximately 0.3 deg so that it can have the thrust holding function.

\[
a = \tan^{-1} \left( \frac{2\nu}{D_S \cdot \theta_S} \right)
\]  

Fig. 8 Test rig for measuring efficiency

3.2 Efficiency and load holding function

The test results of thrust and efficiency for the units A and B are given in Fig. 9. These results coincide with the result of simulated calculation. This means our calculation practice is reliable.

The relation between the torque and thrust on the linear actuator in one cycle (a duration where the thrust is increased from a zero level to a particular level, and then is decreased to a zero level) is shown in Fig. 10. When the thrust is decreased, a negative torque is necessary on the unit A while a positive torque occurs on the unit B. This is because the sun roller rotates by the thrust and, consequently, its thrust holding function is lost.

To sum up, it must be understood that the linear actuator needs to be designed to have an equivalent lead angle of approximately 0.3 deg so that it can have the thrust holding function.

Fig. 9 Test results of thrust and efficiency
4. Evaluation for electromechanical brake units

4.1 Electromechanical brake units tested

We have manufactured a prototype electromechanical brake unit that can be incorporated into an actual car. It has been evaluated on a test rig and tested as mounted on an actual car. The specifications of the electromechanical brake units and motor used are summarized in Tables 3 and 4, while the configuration of the electromechanical brake (EMB) unit is illustrated in Fig. 12 and that of the motor is given in Fig. 13. So that the axial length of EMB unit can be shorter, the motor is arranged parallel with the linear actuator and the motor itself is an axial clearance-type motor that has two stators. From this motor, the torque is transmitted via a gearing to the sun roller. For convenience of incorporation into an actual car, the linear actuator used is the type B unit described in Sec. 3, which features a compact size.
This is because with a greater voltage applied, the maximum motor speed is greater.

Next, we want to discuss the effect of an initial clearance between the piston and load cell. Let us think of the cases where the initial clearance is set to 0.2 mm. When the voltage applied is 12 V, the time needed for a thrust to occur takes approximately 0.1 second while this time span is as short as approximately 0.05 second when the voltage is 20 V. Thus, the size of initial clearance significantly affects the response time.

4.2 Evaluation about response

On the test rig illustrated in Fig. 14, we evaluated the response time relative to thrust on our EMB unit (increase and decrease characteristics). The thrust was measured with a load cell that was mounted in place of a brake rotor and pad. The test conditions are summarized in Table 5, and the test results are plotted in Figs. 15 and 16.

In our test project, a particular voltage was fed into the motor 0.1 sec. after the beginning of each measuring run, thereby the thrust increase/decrease characteristics were evaluated. Under any combination of test conditions, the time-dependent variation in the thrust is nearly constant in the region approximately 10 kN or greater. In the thrust range 10 kN or lower, this variation does not appear to be linear. It is possible, by applying a greater voltage to the motor, to promote the variation in thrust, in either a thrust increase or decrease mode, to shorten the time needed to reach a targeted load.

This is because with a greater voltage applied, the maximum motor speed is greater.

Next, we want to discuss the effect of an initial clearance between the piston and load cell. Let us think of the cases where the initial clearance is set to 0.2 mm. When the voltage applied is 12 V, the time needed for a thrust to occur takes approximately 0.1 second while this time span is as short as approximately 0.05 second when the voltage is 20 V. Thus, the size of initial clearance significantly affects the response time.

<table>
<thead>
<tr>
<th>Parameter</th>
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<th>Thrust decrease characteristic</th>
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<tbody>
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<td>Voltage applied</td>
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<tr>
<td>Initial clearance</td>
<td>0 mm, 0.2 mm</td>
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</table>
4.3 Test on actual car

As illustrated in Fig. 17, we incorporated our prototype EMB unit into each of rear wheels on the test car. Our EMB unit could be readily installed to the test car only with adjustment to the mounting position, and without modification to the area including the knuckle. Also, we have already verified that our EMB unit can be incorporated into the front wheels of the car without any significant modification. On the system configuration shown in Fig. 18, a thrust value detected by the strain gage relative to a command value from the controller is fed back to the controller in order to control the motors. We attempted to brake the car traveling at a speed of approximately 30 km/h, by only actuating the EMB units on the rear wheels, and could reliably stop the car. For this test, we used a 12-V battery for automotive applications.
5. Conclusion

NTN has invented a unique linear actuator for EMB units that will be marketed in the near future, wherein our linear actuator, though not having any additional mechanism, not only boasts a high level of load conversion ratio and high degree of fretting resistance but also features a unique load holding function. Then, we have evaluated an electromechanical brake (EMB) unit that includes our linear actuator and an electric motor, and obtained the following results:

1. We have developed an efficiency calculation technique for our linear actuator, and verified the validity of this technique through a series of tests.
2. We have measured the thrust and efficiency of our linear actuator, thereby we have clarified the thread specifications for satisfying the thrust holding function.
3. We have learned the characteristics of the EMB unit (a unit including an electric motor) through a response evaluation test and a braking test on an actual car.

References
2) Bo Cheng, Tetsuo Taniguchi, Tadashi Hatano, Toshiya Hirose: Effect of Brake Assistance System in Emergency Situation, Society of Automotive Engineers of Japan, Lecture Session Preprints, No.20065894