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Development of Active Suspension System with Electromechanical Actuators for Railway Vehicles

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Abstract

In 2001, pneumatically actuated active suspension systems to improve lateral riding comfort were fitted to the Shinkansen trains of East Japan Railway Company (JR East) as the first case of this kind worldwide. Over the ten-odd years since then, new model trains running at higher speeds have been introduced, and the market demand for better ride quality has grown. The pneumatically actuated systems, however, had problems of high air consumption and slow response to the body vibration at high train speeds. As a solution, Nippon Steel & Sumitomo Metal Corporation developed electromechanical actuators to replace the pneumatic ones. Through unit tests and system tests on a model vehicle and roller rigs, the developed actuators proved effective, and were adopted for use for all the vehicles of the series E5 and E6 high-speed trains of JR East commissioned in 2011 and 2013, respectively, designed for a maximum cruising speed of 320 km/h.

1. Introduction

Active suspension systems are provided to improve the ride comfort of railway vehicles. As shown in **Fig. 1**, the system consists of accelerometers on the body, a control box that receives vibration information from the accelerometers and outputs control signals to the actuators, and actuators provided between the body and the bogie trucks to suppress lateral sway.

Development studies of such systems began in the 1990s, and it was in November 2001 that an active suspension system using pneumatic actuators to improve lateral riding comfort was commercially applied, for the first time in the world, to the series E2 "Hayate" vehicles for the high-speed lines (such lines of Japanese railway companies being hereinafter called "Shinkansen") of East Japan Railway Company (JR East).[1)] The system was then introduced to the series E3 Shinkansen "Komachi" trains in December 2002, the series E259 "Narita Express" trains in October 2009, the series E657 "Super Hitachi" trains in March 2012 (these three being of JR East), the series 50000 "Romance Car" trains of Odakyu Electric Railway Co, Ltd. in March 2005,[2)] the new "Sky Liner" AE express trains of Keisei Electric Railway Co., Ltd. in July 2010,[3)] totaling to 312 cars; all equipment for the abovementioned systems was supplied by Nippon Steel & Sumitomo Metal Corporation. The control unit was designed applying the H∞ control algorithm suitable for vibration control, which has proved effective at reducing the vibration of the frequency band perceptible to human body to less than a half, and the ride quality improved as intended. However, pneumatic actuation had some problems, and to solve them, another

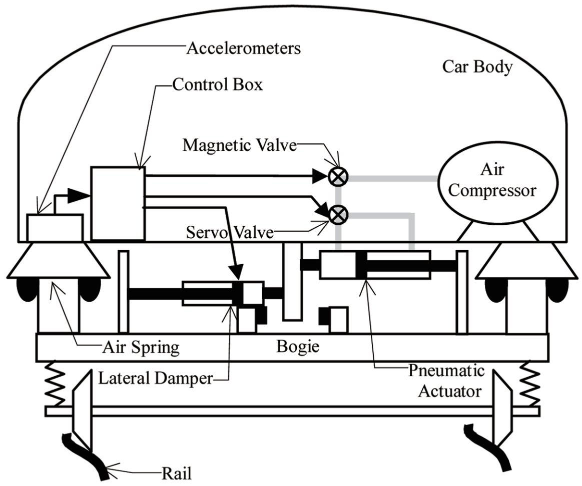

Fig. 1 Construction of active suspension system with pneumatic actuator

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system based on electromechanical actuation has been newly developed and put into commercial use. This paper reports the details of the newly developed electromechanical active suspension system.

2. Problems with Pneumatic Vibration Suppression System

2.1 Compressed air consumption

A major problem with the pneumatic system was the large consumption of compressed air by the actuators. Railway vehicles use compressed air for brakes, height control with air springs, doors, toilet flushing, etc., but the total consumption is limited by the heat capacity of the reciprocating air compressors. On the other hand, higher vibration damping capacity means greater consumption of compressed air, and for this reason, it was considered difficult to provide all the cars of a train with pneumatic active suspension systems.

In view of this, Nippon Steel & Sumitomo Metal began development of pneumatic actuators of a low-air-consumption type having less air consumption than that of conventional ones by 30 to 50% (see **Fig. 2**), and after tests on a roller rig, fitted them to real vehicles for trial use in December 2003 to obtain satisfactory results. Then, in June 2008, jointly with Deutsche Bundesbahn (German federal railway company), the developed actuators were installed on the German three-car test train ICE-S together with centering actuators (see **Fig. 3**), and subjected to a series of tests at 300 km/h. The result was that the root mean square (RMS) of the vehicle body's lateral acceleration was reduced to virtually half. Later, however, through tests on the MUE-Train of JR East in April 2009, it became clear that the effects of the new type actuators were decreased at curves where large actuation strokes were required.[4)]

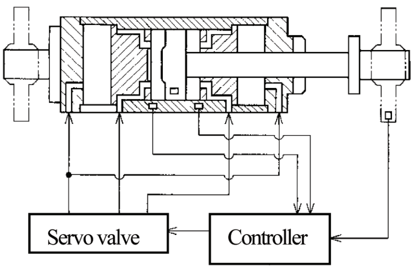


Fig. 2 Pneumatic actuator with reduced air consumption

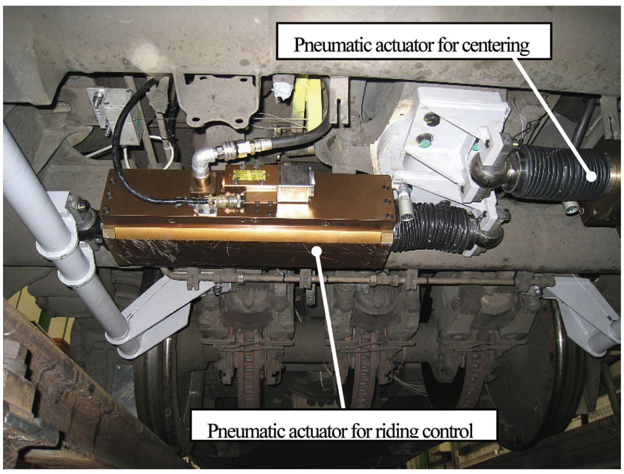


Fig. 3 Fitting pneumatic actuators on bogie for ICE-S

Nevertheless, Kintetsu Corporation combined Nippon Steel & Sumitomo Metal's pneumatic oscillation control system with scroll-type air compressors in order to allow for large air consumption and installed them on all the cars of the Premium Express Trains "Shimakaze," which entered into commercial operation in March 2013.

2.2 Frequency response

A second problem with the pneumatic actuators was frequency response. With the latest increase in train speed, the frequency of vehicle vibration has increased, and consequently, higher response is required for the actuators to suppress it. Because of the compressibility of air, however, the response of pneumatic actuators is limited. In addition, when tilting control is provided to reduce steady lateral acceleration at curves to allow high-speed running, a longer stroke is required for the horizontal actuators provided between the bogies and the body, which means a larger cylinder capacity.

This inevitably leads to poorer response of the pneumatic actuators; for example, when the stroke is doubled, the response decreases to a half. A measure to avoid the deterioration of response is to decrease the sectional area of the cylinder, although this decreases the maximum thrust. As a countermeasure, a new type of pneumatic system was developed: the cylinder inner diameter was reduced from 100 to 80 mm, the response increased 1.6 times, although the maximum thrust decreased by 36%. This system is being used on the above-mentioned type AE express trains "Sky Liner" of Keisei, running at a maximum cruising speed of 160 km/h, the fastest operation in Japan except on Shinkansen lines. The higher response of this system has proved effective at decreasing air consumption.

2.3 Motivation for developing electric actuation

To solve the above problem of pneumatic actuators, JR East decided in January 2004 to use new direct-acting electromagnetic actuators for the series E954 and E955 high-speed test trains aiming at developing a next-generation Shinkansen operation.[5,6)] To this end, Nippon Steel & Sumitomo Metal started development of a new high-response electric actuator, which would not consume compressed air, to be in time for the next-generation operation.[7)]

3. Investigation into Electric Actuators

3.1 Required specifications for electric actuators

The specifications of the present pneumatic actuators are as follows.

(1) Maximum continuous thrust: 6 kN
(2) Frequency band of vibration to control: 3 Hz or lower
(3) Unit mass: approx. 20 kg

As stated in Sub-section 2.2 above, lateral acceleration of vehicle bodies increases with increasing train speed owing to aerodynamic turbulence.[8)] When, for example, series E2 and E3 Shinkansen trains of JR East run coupled together, this becomes pronounced especially with the section behind the coupling. Therefore, at higher speeds, higher thrust than that of pneumatic actuators is required in wider frequency bands. Assuming the same outer dimension, electric actuators are generally better in response but poorer in continuous thrust when compared with pneumatic ones. In other words, an electric actuator having the same continuous thrust as that of a pneumatic one will be too heavy to suitably fit into a bogie truck. In view of this, the required specifications of the electric actuator were defined as follows.

(1) Maximum thrust: 8 kN or more
(2) Continuous thrust: 3 kN or more
(3) Frequency band of vibration to control: 5 Hz or higher

Table 1 Comparison of actuators

Type	Response	Weight	Gear	Heat generation	Oil
Pneumatic		Light		None	
EMA	High		Required	Low	Required
EHA	High			High	Required
VCM	High	Heavy		High	
LSM	High	Heavy		High	

(4) Unit mass: 36 kg or less (comparable with a yaw damper)
(5) Size: to be fitted into bogie frames without major modifications.

3.2 Comparison between electric actuators

In search of electric actuators as specified in Sub-section 3.1, information was collected from actuator manufacturers and research institutes in and outside Japan. **Table 1** summarizes the collected information.

The characteristics of different types of electric actuators are described below.

The electromechanical actuator (EMA) converts the rotation of a built-in electric motor into linear movement using a drive mechanism, which may be a ball screw or a roller screw. Since the latter uses line contact for force transfer, it is superior in terms of durability to the former, which uses point contact. For this reason, the actuators for the body tilting systems presently used in Germany, the U.K., and Spain are of the roller screw type. While the most serious concern about this type of actuator is the sticking of the drive mechanism, there have been no such reports.

The electro-hydraulic actuator (EHA) comprises an electric motor and a hydraulic pump as integral parts, and for this reason, the vehicle is not required to have a hydraulic system separately. This type of actuator is considered promising for the next-generation body tilting systems for European railways, and the Railway Technical Research Institute of Japan is also developing a variety of applications for the EHA.[9)]

The voice coil motor (VCM) is a linear actuator like the one used for driving the coil of a loud speaker. Thrust is generated by the Lorentz force arising from an electric current applied to a movable coil in the magnetic field of a permanent magnet, but it is impossible to obtain large strokes.

The linear synchronous motor (LSM) is a direct-acting synchronous motor; thrust is generated by the attraction between a permanent magnet and a shifting magnetic field formed by electromagnets arranged in the direction of the thrust. Although this motor has high cost, its control is simple, its efficiency is high, and it is versatile with respect to stroke. Like VCM, however, its downsizing and power increase depend on intensification of the flux density of the permanent magnet, and products that met the required specifications were not available in the market at the time of the research in 2004.

3.3 Opting for EMA

In the first place in the comparative study of the above mechanisms, since the EHA included a hydraulic system, it was feared that it would require considerable amount of maintenance labor, and unsuitable in consideration of the present field practice of vehicle maintenance.

In the second place, the VCM was examined in more details in view of the fact that it does not use any mechanical parts, which are prone to troubles, to convert electric energy into kinetic energy. But, according to a study report, even if the required maximum thrust was decreased to 4.5 kN, the unit mass would exceed 200 kg, and another said that if the unit mass was decreased to 53 kg, the maximum thrust would be only 1.5 kN, and the stroke of actuation as small as ±10 mm.

Thus, Nippon Steel & Sumitomo Metal decided against using the VCM and instead chose to pursue the comparatively light and powerful EMA, while aiming at differentiating the development fruit from those of competitors.

4. Performance Test

Of the performance items of the EMA, its basic capability to damp vibration was evaluated in the first place.

4.1 Trial production of electromechanical actuators

Units of the EMA were manufactured for test purposes; **Fig. 4** shows an example. The specifications for the trial products were defined as follows to satisfy the initial requirements.

(1) Maximum thrust: 8.5 kN
(2) Continuous thrust: 4 kN
(3) Frequency band of vibration to control: 10 Hz or higher
(4) Unit mass: approx. 29 kg

What was of special importance in defining the trial production specifications was the lead of the roller screw, as it had significant effects on the back-drive force. Because the lowest operating pressure of pneumatic actuators is 50 kPa or lower, by multiplying it by the cylinder sectional area, its back-drive force is estimated at 345 N or less. Based on this, the back-drive force of the EMA was set at 560 N or less so that the stroke could be adjusted by manual force, and to make it possible, the lead was set at 20 mm. With a shorter lead, the motor rotation will be higher, the energy conversion efficiency higher, and the motor size smaller. On the other hand, however, the back-drive force will increase, and it was feared that the ride quality would be poor when the control is switched off. Later, EMA units having a lead of 10 mm were tested; however, the back-drive force was excessively large and interfered with its own thrust exertion.

4.2 Method of performance test

To evaluate if the EMA had satisfactory performance, trial products were tested using a real-size model vehicle shown in **Fig. 5**: it consisted of a simulated body, two real bogie frames set at 13.8 m from each other, and a hydraulic actuator fixed to each of the bogie frames to apply lateral accelerations independently from each other to simulate the vibration of running vehicles.

The concept of the control command for the hydraulic actuators to simulate the vibration of real vehicles is as shown in **Fig. 6**, where u is the lateral acceleration measured on a real vehicle body, B.P.F. is a band-pass filter that defines the frequency band of the acceleration to reproduce, $G(s)$ is the function of force transfer from the vibration commands given to the hydraulic actuators to the later-

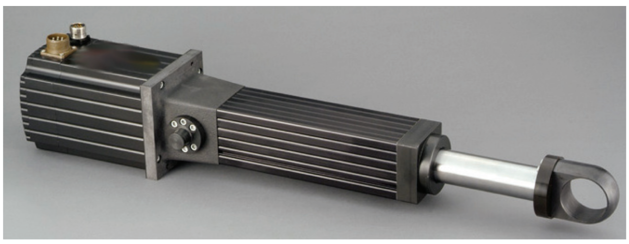


Fig. 4 Trial product of EMA

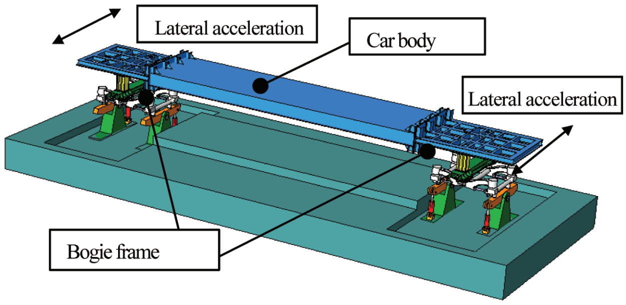


Fig. 5 Model vehicle for test

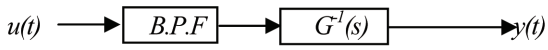


Fig. 6 Control command to hydraulic actuators

al acceleration of the simulated body of the model vehicle, and y is the vibration command given to the actuators.

For example, assuming the value of the vibration command for the front bogie as y and shifting the phase of the vibration applied to the rear bogie by 180°, the equation of motion for the body yawing $L\varphi$ is given by Equation (1). Note here that force transfer characteristics of the actuators are negligible because the response of the hydraulic actuators is sufficiently high compared with the same of a vehicle.

$$mi^2 L\ddot{\varphi}(t) = -2c\left(L\dot{\varphi}(t) - \dot{u}(t-\Delta t)\right)L - 4k\left(L\varphi(t) - u(t-\Delta t)\right)L \qquad (1)$$

Through the Laplace transformation and rearrangement of Equation (1), the function $G(s)$ of the force transfer from the value of the yawing acceleration command y to the actual yawing acceleration is given by Equation (2):

$$G(s) = \frac{s^2 L\hat{\varphi}}{\hat{y}} = \frac{s^2(2cL^2 s + 4kL^2)}{mi^2 s^2 + 2cL^2 s + 4kL^2} e^{-\Delta ts} \qquad (2)$$

By fitting the transfer function $G(s)$ to the measurement results of acceleration tests at different frequencies so as to minimize the deviations as shown in **Fig. 7**, the parameters used in the function were defined as given in **Table 2**.

Then, the value of the yawing acceleration command y was obtained by applying the measured yawing acceleration u to the inverse function $G^{-1}(s)$ given as Equation (3). An example of such calculation results is shown in **Fig. 8**, and the agreement between the test results on the model vehicle and the calculation in **Figs. 9** and **10**. The simulation results agreed well with the measured results in the frequency band of the vibration, which indicates that it is possible to assess the performance of the actuators before actually using them on real vehicles.

$$G^{-1}(s) = \frac{mi^2 s^2 + 2cL^2 s + 4kL^2}{s^2(2cL^2 s + 4kL^2)} e^{\Delta ts} \qquad (3)$$

4.3 Results of performance test

To compare the EMA and the pneumatic actuator in terms of ride quality improvement effects, an EMA was installed at the body-end side of the king pin of each bogie of the model vehicle, and a pneumatic actuator on the other side; an EMA unit fitted to one of the bogie frames of the model vehicle is shown in **Fig. 11**.

Figure 12 compares the lateral acceleration waves of the model

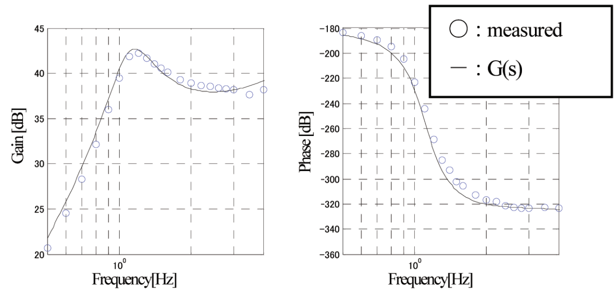


Fig. 7 Result of parameter identification for yawing estimation

Table 2 Parameter values

Parameter	Value	Sign
Vehicle weight	30 t	m
Inertia radius of yawing	4.53 m	i
Distance between bogies	13.8 m	$2L$
Air spring	160 kN/m	k
Lateral damper	18 kNs/m	c
Delay time	18 ms	Δt

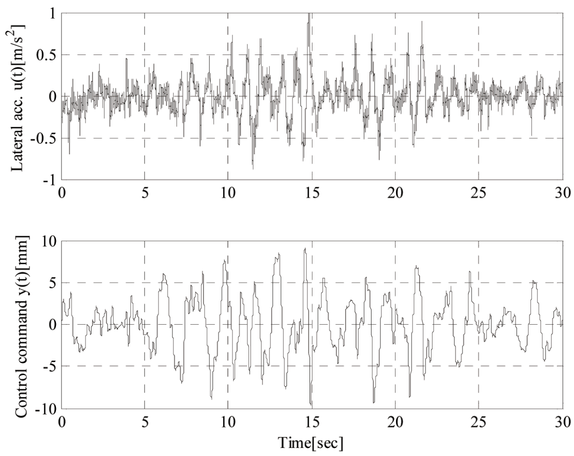


Fig. 8 Control command for simulating real lateral acceleration

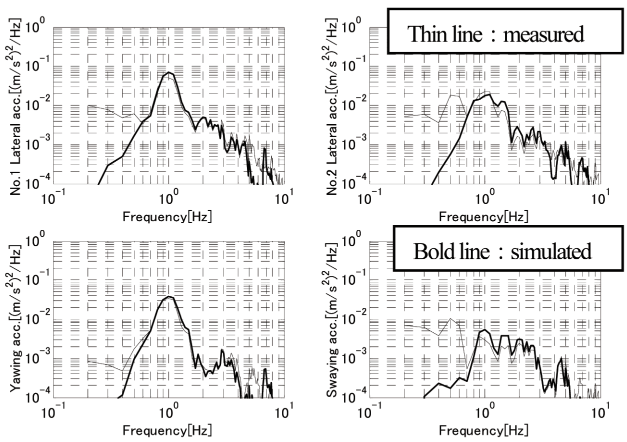


Fig. 9 Measured and simulated power sector density

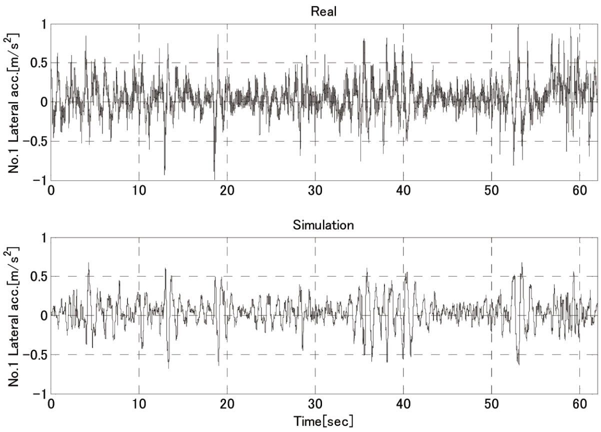


Fig. 10 Measured and simulated lateral acceleration waves

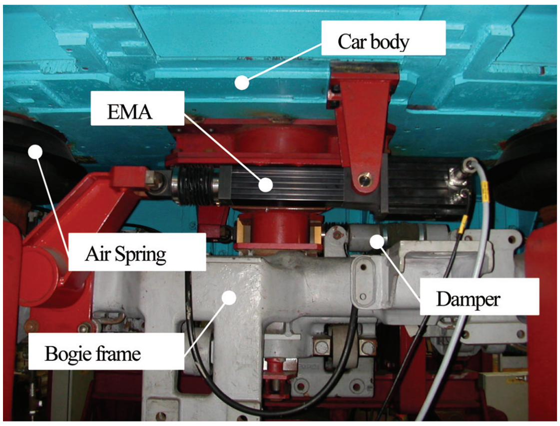


Fig. 11 Fitting EMA onto model vehicle

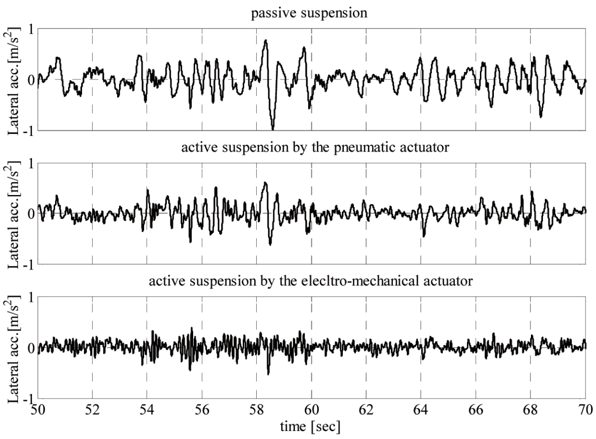


Fig. 12 Lateral acceleration by different control methods

vehicle body in the cases of no vibration control (passive suspension) and control using pneumatic and electromechanical actuators. The lateral acceleration of the vehicle body was evaluated in terms of the RMS and the ride quality level L_T specified in ISO 2631-1 (1997). **Table 3** shows the evaluation results: the pneumatic actuator reduced the RMS to a half without vibration control, and decreased (improved) the ride quality level L_T by roughly 6 dB. In comparison,

Table 3 Evaluations of RMS

Control type	RMS	L_T
Passive	0.172 m/s²	88.5 dB
Pneumatic	0.083 m/s²	81.9 dB
EMA	0.051 m/s²	77.6 dB

the EMA decreased the RMS to one-third, and the value of L_T by roughly 10 dB, evidently showing performance superior to that of the pneumatic. However, as is clear from the vibration wave form, the vibration under the EMA control tended rather to increase in the high-frequency band above that of vehicle vibration because of its high response. This can be remedied by adequately modifying the weight function for the vibration acceleration or the control command at the design stage of the controller based on the H∞ control theory.

5. Endurance Test

After confirming the EMA's sufficiently good ride quality improvement performance as described above, the actuators underwent various endurance tests to verify their suitability for actual use.

5.1 Heat generation of actuators

Electric actuation inevitably incurs energy loss in the form of heat when electric energy is converted into kinetic energy. In consideration of this, the developed EMA units were subjected to continuous actuation test at positions where they would not be cooled by air during running. The measured temperature rise of the EMA is given in **Fig. 13**; the readings are those at the surface of the motor casing—the position where the temperature is highest. After an operation for 2 h, the temperature rose by as little as 14˚C, which demonstrates that the heat generation of the EMA would not pose any problem for use on real vehicles.

In addition to the above, to examine the performance of an LSM introduced by a competitor into the market, LSM units were manufactured for test purposes according to the specifications of the competitor given below, installed in the model vehicle, and subjected to a series of tests. Eventually, the temperature rose to greater than 100°C within a few minutes of testing, which indicated that the LSM was unsuitable for the application because of the heat generation, in addition to its heavy weight (see **Fig. 14**).

(1) Maximum thrust: 3.6 kN
(2) Continuous thrust: 1.3 kN
(3) Frequency band of vibration to control: 10 Hz or higher
(4) Unit mass: 68 kg
(5) Outer diameter: 178 mm

5.2 Lateral loading test

In the same manner as the endurance test of pneumatic actuators, the EMA units underwent continuous actuation test under the conditions given below; here pinching loads were applied to the rubber cushions at both the mounting ends. However, soon after the start of the test, the bearings began to show abnormal wear, and also the roller screw was damaged as shown in **Fig. 15**.

(1) Reaction force of the rubber cushion: 140 Nm
(2) Amplitude: ±5 mm
(3) Frequency: 5 Hz
(4) Bogie inspection interval: 1,068 h (calculated assuming a running distance of 600,000 km)

It became clear from the above that the EMA was very vulnerable to lateral loads. As a countermeasure, special spherical bearings

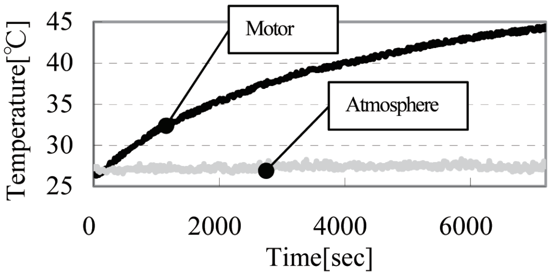


Fig. 13 Heat generation from EMA motor

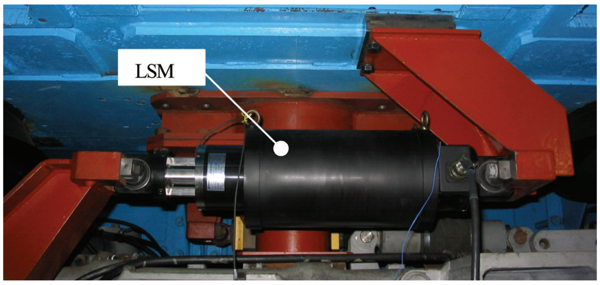


Fig. 14 Fitting LSM onto model behicle

Fig. 15 Failure of roller screw

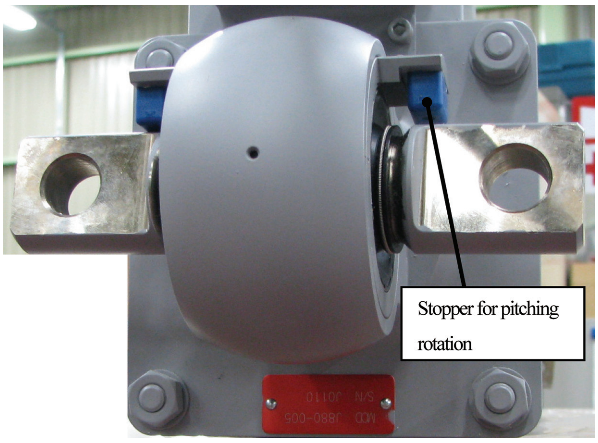


Fig. 16 Spherical bearing restricting pitching rotation

rotating about only two axes were newly designed (see **Fig. 16**) and used to allow for the displacement of bogies with respect to the body; the displacement was taken care of by rubber cushions. Here,

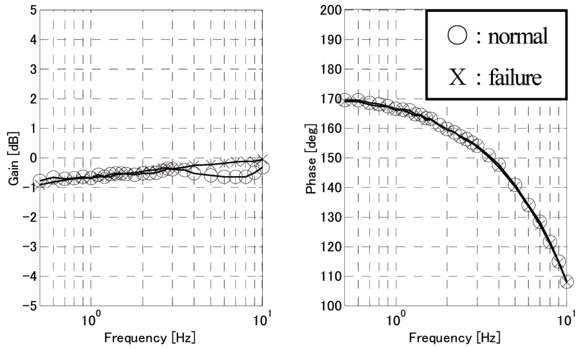


Fig. 17 Frequency characteristics of control force

the move about the third axle was restricted by the linear contact between a cylindrical surface and a flat plane. The reason for restricting the turn of the thrust shaft by using the spherical bearing is that restricting it inside the EMA will increase the reaction force, and the reason why it is restricted at all is to prevent the EMA from falling down. To cut the vibration from the bogies and electrically insulate the body from the bogies, a structurally simple rubber cushion ring was used only on the bogie side where heating of the motor would not cause any problems.

Without the spherical bearings, the lateral loading test was continued to the end of the truck inspection interval (corresponding to 600,000 km running) leaving the damaged roller screw unattended and without lubricant inside the unit. Nevertheless, sticking did not occur, and as seen with **Fig. 17**, the EMA was little affected by the problems and continued working effectively in the frequency band of vibration. This test was continued to complete a period of general vehicle inspection (corresponding to 1,200,000 km running), but still no sticking occurred.

5.3 Tests with iron fines

Next, 0.8 g of iron fines roughly length 0.5 mm × width 0.1 mm in size were intentionally mixed into the lubricant of the EMA units, and for comparison with normal ones, the units underwent unit actuation test on a test rig and vibration control test on the model vehicle. In either test, no sticking occurred to the units in question, but the lateral ride quality level deteriorated by about 2 dB. Sticking did not occur presumably because the iron fines were crushed as they passed through the gaps of the roller screw.

Since lubricant containing iron fines or other foreign matter deteriorates the service life of lubricated parts, magnetic plugs were provided for the EMA units at commercial manufacture for maintenance purposes.

5.4 Test of simulated sticking

Although the EMA proved considerably free from sticking through the above tests, it was necessary to confirm how the vehicle would behave if sticking occurred. For this purpose, bar jigs to simulate sticking actuators were prepared (see **Fig. 18**).

First, the restricting jig was fitted to the No. 2 bogie of the model vehicle, and vibration simulating track misalignment was applied; the result is shown in **Fig. 19**. Since the vibration of the bogie was transferred to the body directly, the vibration of frequencies higher than 2 Hz increased significantly, and the ride quality level deteriorated by about 10 dB.

After the above, the restricting jig was fitted to a bogie on a roller rig (see **Fig. 20**) in order to examine the critical speed for the bogie hunting due to self-excited vibration; **Table 4** shows the test re-

Fig. 18 Bar jigs to simulate sticking actuator (upper: for model vehicle test, lower: for roller rig test)

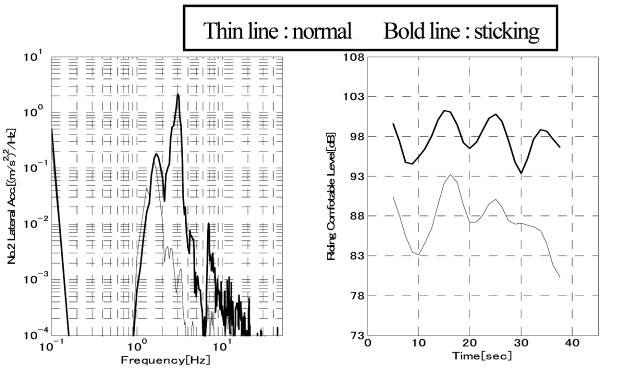


Fig. 19 Ride quality on model vehicle with and without sticking of actuator

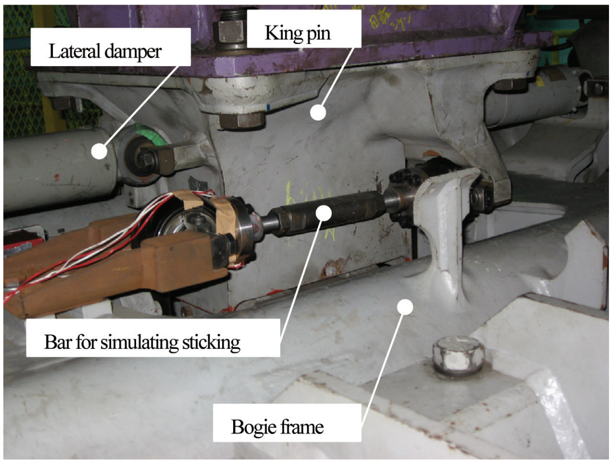


Fig. 20 Examination on roller rig for simulating sticking

sults. When only the actuator of the vibration control system stuck, the critical speed for the hunting was over 400 km/h, the same as in normal conditions. Then, when the yaw damper of the bogie failed to function and the actuator stuck, the bogie began to behave unstably at 340 km/h. Yet, this was well above the planned maximum cruising speed of the next-generation Shinkansen trains, 320 km/h, and thus, stable running performance was confirmed. However, when the damping force of the lateral damper was changeable and its damping force was set to low and when the yaw damper failed causing the actuator to stick, the bogie began to behave unstably at 310 km/h, which was below the target maximum cruising speed. A countermeasure against this was worked out as follows: the cumulative stroke of the EMA is monitored during running based on the motor revolution information from the EMA, and also the RMS of the lateral body acceleration; to judge the occurrence or otherwise

Table 4 Critical speed of hunting on roller rig

Actuators	Damping force of lateral dampers (kNs/mm)	Yaw dampers (outside vibration control system)	Critical speed of hunting (km/h)
Normal	80	Both working	> 400
Normal	80	One failure	> 400
Sticking	80	Both working	> 400
Sticking	80	One failure	340
Sticking	20	One failure	310

of sticking, they are compared with respectively prescribed threshold figures at prescribed intervals; and when sticking is judged to have occurred, the vibration control system is switched off, and the damping force of the lateral damper is set at the high position to secure stable running.

5.5 Long-term actuation test

Finally, to examine the durability of the EMA under normal operating conditions, the system was subjected to long-term function test on a stationary bed under the conditions given below for a period equivalent to five intervals of general vehicle inspection; the system was overhauled at each timing of the inspection. All the system components except for those made of rubber or resin were free of wear, which would require replacement; this showed satisfactory durability of the developed system under stationary conditions.

(1) Amplitude: ±5 mm
(2) Frequency: 5 Hz
(3) Inertial load: 4 kN
(4) General vehicle inspection interval: 2,136 h (calculated assuming a running distance of 1,200,000 km)

6. Ride Quality Improvement by Software Measures

The above sections have described the ride quality improvement effects from hardware approaches. Measures to improve it in curves at high speeds have been taken also from software approaches. Just like the practice of the body tilting control system, the information about curves is stored in the control unit of the lateral vibration control system, and the excessive centrifugal acceleration α at curves is accurately estimated using Equation (4). This makes it possible, in the design stage, to raise the gain of the controller for swaying and rolling vibrations in the targeted frequency band by cancelling out the low-frequency steady element from the lateral body acceleration measured by the accelerometers, and thus improve the vibration damping performance.

$$\alpha = \eta_{on}\left(V^2/R - gC/G\right),\ \text{or}\ \eta_{off}\left(V^2/R - gC/G\right), \quad (4)$$

where, $\eta_{on/off}$ is the correction coefficient applicable when the body tilting control is on or off, V the train speed, R the curve radius, g the gravitational acceleration, C the cant, and G the rail gauge.

7. Closing

With increasing train speed, the shortcomings of conventional pneumatically actuated vibration control systems came to be felt increasingly strongly. In view of this and considering the market demands, Nippon Steel & Sumitomo Metal developed electromechanical actuators for vibration control applications, and obtained the following results:

(1) After comparative study of different types of electric actuators

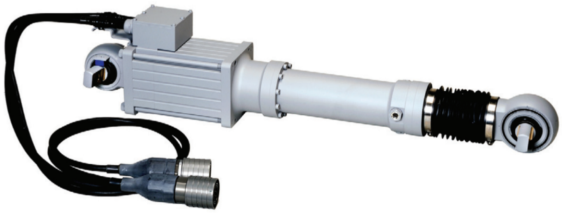


Fig. 21 EMA for E5 series Shinkansen train

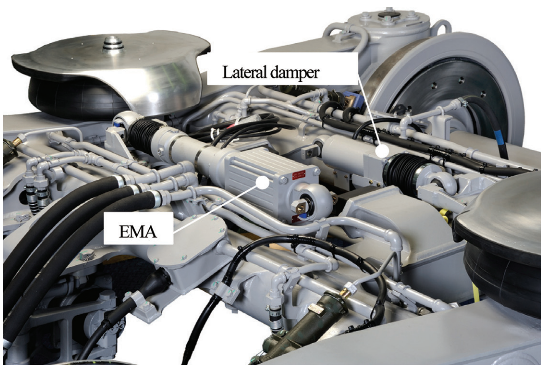


Fig. 22 Fitting EMA on bogie for E6 series Shinkansen train

available in the market, and in consideration of differentiating the development fruit from competitors' products, the company selected electromechanical actuation, and developed a new model of actuator for the application.

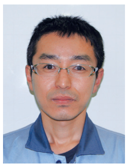
(2) The developed electromechanical actuator (EMA) proved highly durable through various tests.

(3) After evaluation by JR East, the vibration control system using the EMA was adopted for all the vehicles of the series E5 and E6 Shinkansen trains (see **Figs. 21** and **22**).[10)]

Nippon Steel & Sumitomo Metal will continue watching the technical trend of the railway industry and will pursue further possibilities of both pneumatic and electromechanical actuation.

References

1) Tahara, M. et al.: Practical Use of an Active Suspension System for Railway Vehicles. International Symposium on Speed-up and Service Technology for Railway and Maglev Systems. 2003, p. 225-228
2) Kijima, H.: The Advent of Odakyu's Type 50000 Romance Cars. Japanese Railway Engineering. (156), 22-25 (2006)
3) Sawada, et al.: Development of Truck Bogies for AE Express Trains of Keisei Electric Railway Co., Ltd. and Active Suspension. Rolling Stock and Technology. (157), 10-13 (2009)
4) Uekura, et al.: Development of Active Suspension Control System by Actuator of Decreased Air Consumption. Proc. 17th Jointed Railway Technology Symposium. Japan Society of Mechanical Engineers, S5-1-1, 305-308 (2010)
5) Makino, et al.: Development of Active Suspension System Using Electric Linear Motors for Railway Cars. Proc. 13th Jointed Railway Technology Symposium. Japan Society of Mechanical Engineers, No. 06-52, 519-522 (2006)
6) Iwanami, et al.: Development of Active Suspension for Railway Vehicles Using Electromagnetic Actuator. Proc. 13th Jointed Railway Technology Symposium. Japan Society of Mechanical Engineers, No. 06-52, 523-524 (2006)
7) Goto, O. et al.: The Development of an Active Suspension System with EMA for Railway Vehicles. International Symposium on Speed-up and Service Technology for Railway and Maglev Systems. 2009
8) Fujimoto, et al.: Lateral Vibration of Shinkansen Vehicles and Countermeasures. Quarterly Report of RTRI. 9 (1), 19-24 (1995)
9) Kamoshita, et al.: Electro-hydraulic Actuators for New Type Railway Vehicle with Tilting Control. RRR. 62 (5), 24-27 (2005)
10) Tajima: Driving Bogies for Series E5 Shinkansen Vehicles. Rolling Stock and Technology. (157), 7-9 (2009)



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