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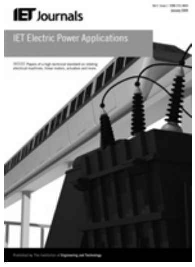

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Characteristic research of electromagnetic force for mixing suspension electromagnet used in low-speed maglev train

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Abstract: Suspension electromagnets are an essential component of the low-speed maglev train. Their performance has a direct bearing on the technical and economical performance, as well as the safety, of the entire train. This report describes a new form of electromagnet, whose structure combines permanent magnets and electromagnetic coils. This report then uses a two-dimensional (2D)/3D finite element approach in order to analyse the electromagnetic characteristics of this new form of hybrid electromagnet. A simulation was conducted according to four typical operating conditions: a full load with a fixed suspension gap of 8 mm; a full load with an initial suspension gap of 18 mm; a full load with a suspension gap of 10 mm; and an empty load with a 3 mm gap as well as a guard that prevented the magnet from getting caught on the tracks. The report equally discusses the extent to which the suspension gap and the current of the electromagnetic coil affect the electromagnet's force. The calculations and experiments reveal that this new, hybrid form of electromagnet is feasible and significantly contributes to saving energy.

1 Introduction

Low-speed maglev trains are a new type of transportation technology [1]. The train's levitation relies on U-shaped exciting coils which, when stimulated with electricity, produce an electromagnetic field for the F-shaped tracks. Traditionally, electromagnets are exclusively composed of exciting coils. Via this method, these coils, once stimulated with electricity, inevitably create a certain amount of resistance loss. This resistance loss is present as long as the train is levitating, regardless of whether or not the train is in motion. In recent years, in order to save energy, certain scholars have attempted to use a new form of electromagnet, whose hybrid structure consists of both coils and permanent magnets. The electromagnetic field produced by this electromagnet is created via these coils and permanent magnets. When the train is levitating under normal conditions, the hybrid electromagnet's energy consumption is close to none. Such a magnet therefore indisputably contributes to reducing the energy consumption of maglev trains, and as such constitutes a viable option in the maglev train's future development.

Certain scholars have analysed the electromagnetic field generated by the electromagnets currently used in low-speed maglev trains. The scientific community has already conducted reasonably detailed analyses into the traditional coil-based electromagnets used in today's low-speed maglev trains – from two-dimensional (2D) and 3D analyses, to theoretical calculations, to practical considerations regarding certain elements of the electromagnet's engineering (such as lateral deviation and rolling). Additionally, the findings of these analyses have been validated by their real-life implementation [2–5]. However, hybrid electromagnets that rely both on permanent magnets and coils are a relatively new phenomenon that appeared following developments in the composition of NdFeB permanent magnets as well as in the energy-saving capabilities of maglev trains. Some scholars have discussed the possibility of incorporating permanent magnets into the electromagnetic systems of maglev trains as a means of reducing energy consumption. For example, Kehrer and Mc Kenna [6] have attempted to apply permanent magnets to the electro dynamic suspension (i.e. EDS) maglev system. Sources [7, 8] concern the use of a synchronous traction system that combines both suspension and traction for use in high-speed maglev trains; these sources include structural plans and parametric designs for a hybrid electromagnetic that relies on a magnetic circuit. Geoffrey A. Long *et al.* [9] put forth the concept for a maglev vehicle which relies on permanent magnets, and therefore differs from conventional EDS and electro magnetic suspension maglev vehicles. However, as for the low-speed maglev train, which adopts the asynchronous linear motor traction as well as the suspension electromagnet structure composed by the U-shaped permanent magnet and electromagnetic, its electromagnetic performance and electromagnetic field are yet to be further analysed and studied.

In contrast to high-speed maglev trains, the suspension and traction of low-speed maglev trains are conducted separately: the train's suspension is achieved via the attractive force generated by the U-shaped suspension magnets and the F-shaped tracks. Within the context of a low-speed maglev train that uses a hybrid electromagnet, the permanent magnet's magnetic field generates the majority of the force required in order to suspend the train when it is at a standstill, while the magnetic field generated by the coils provides stability for the train as it is in motion, thus reducing the energy consumption inherent in the train's suspension and constituting an important improvement on traditional suspension methods.

Since the distribution of a suspension electromagnet's field is comparatively complicated, it is difficult to achieve a high level of accuracy when analysing this electromagnetic field using the traditional calculation methods used for magnetic circuits. Therefore, in the interests of obtaining accurate results, this study adopted a finite numerical method when analysing the proposed new form of hybrid electromagnet's electromagnetic field.

2 Creating models using numerical analysis

In contrast with traditional suspension electromagnets, the proposed new form of hybrid electromagnet generates an electromagnetic field via a combination of permanent magnets and exciting coils. High-performance NdFeB is embedded into the U-shaped yoke of the permanent magnet. Fig 1 represents the structures of two different types of electromagnets as well as the F-shaped tracks.

When conducting 2D calculations using Ansoft, it is assumed that the iron cores of both the electromagnet and the F-type track are limitless in length. Although 2D calculations cannot account for the length of the iron core, the cross-section of the magnetising iron core takes all other factors into account.

Constructing a 2D model is simple; calculations are convenient, as well as being relatively accurate. However, a 3D model is necessary where highly accurate calculations of an electromagnet's force, as well as an acute understanding of the magnet's internal components and field distribution, are required. When conducting 3D calculations using Ansoft, it is assumed that the two polar plates of the hybrid electromagnet's U-shaped iron core, and the F-shaped iron core, are longer than the two ends of the yoke by 30 mm. Since the iron core has a high level of permeability, the effect of an additional longitudinal iron core length for electromagnetic field distribution can be ignored. Fig. 2 displays the model obtained using 3D calculations.

3 Analysis of the electromagnetic field under four typical working conditions

3.1 Typical working conditions

We have conducted a numerical analysis of the prototype of the hybrid suspension electromagnet; the parameters for the prototype's structure are as follows: the lateral surface area of the permanent magnet is 0.055 m^2; its depth is 28 mm; the width of the two polar plates for the iron core of the U-shaped electromagnet is 28 mm; the exciting coil has 240 loops.

The calculations were conducted in accordance with the four following typical working conditions: (i) a full load with a fixed suspension gap of 8 mm, whereby the permanent magnet is responsible for providing the majority of the suspension force, and where the exciting coil provides the extremely small supplementary amount of required force; (ii) a full load with an initial suspension gap of 18 mm, whereby both the permanent magnet and the coil work together in order to provide the suspension force required by the vehicle at intervals where the suspension gap is at its greatest; (iii) a full load with a suspension gap of 10 mm (because of fluctuations in the suspension gap, this working condition will be reasonably common when the vehicle is in motion); and (iv) an empty load with a suspension gap of 3 mm, where additional guards have been installed in order to prevent the magnet from clipping on the tracks. In contrast with conventional maglev vehicles (which rely solely on exciting coils), the main problem that needs to be considered when using a hybrid suspension method is the possibility that the electromagnet will 'clip' against the tracks, thus posing a threat to the safe operation of the vehicle. Therefore, in order to ensure that the vehicle may operate safely down to a minimal suspension gap of 3 mm, we have installed copper plates on the two plates

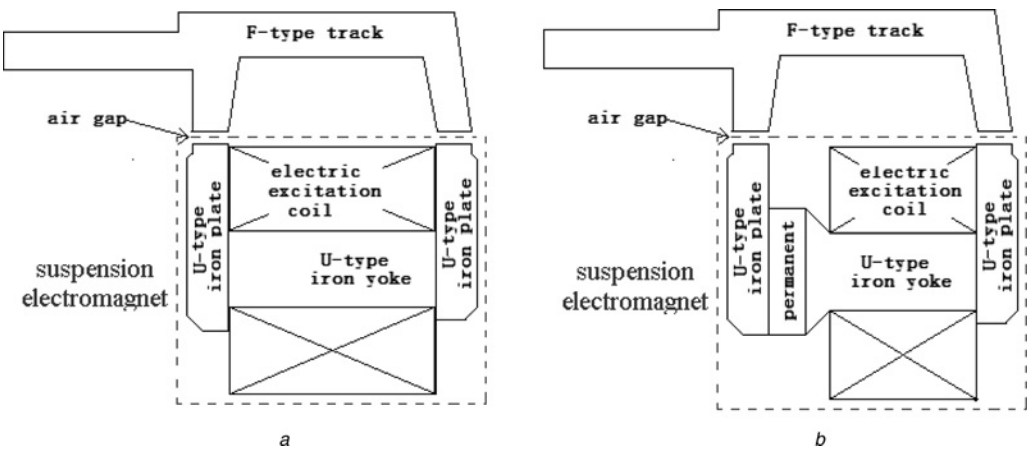

Fig. 1 *2D representation of the structure of the F-shaped tracks' hybrid electromagnets*
a Traditional electromagnet
b Hybrid electromagnet

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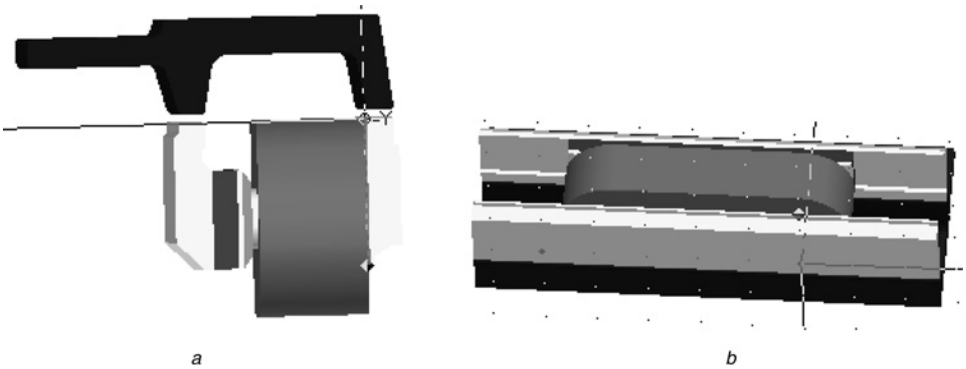

Fig. 2 *3D numerical model of the hybrid electromagnet and the F-shaped tracks*

a Lengthways front view
b Slanted view looking downwards

U-shaped iron core surface that will prevent against clipping. These plates are to be incorporated into the final manufacturing design for the hybrid electromagnet. The vehicle is most liable to clip against the tracks when it has no load and is at its lightest. At this point, when the suspension gap has reached its minimum limit (as defined by the copper plates), the electromagnetic field produced by the coil's reverse current in part counteracts the field of permanent magnet; correspondingly, the suspension force drops, bringing the suspension gap back to the normal state of 8 mm. The analyses and calculations conducted with regard to the aforementioned four working conditions can be used in order to discuss the differences in the performance of a hybrid electromagnet against a conventional exciting coil electromagnet, as well as to judge whether or not the design parameters for the magnet's structure are reasonable and satisfactory.

3.2 Analysis of the electromagnetic field

Fig. 3 demonstrates, via 3D calculations, the magnetic flux density of both the iron core of the F-shaped tracks and the iron core of the hybrid suspension magnet during working condition (i) (suspension gap of 8 mm and a coil current of 2.5 A).

As Fig. 3 demonstrates, the magnetic flux density is greatest in the iron core of the F-shaped tracks as well as in the facing components of the U-shaped electromagnet. The area in the U-shaped electromagnet's two polar plates where the flux density is greatest is the area adjacent to the coil and the two longitudinal ends of the permanent magnet. Similarly, the area of the U-shaped yoke with the highest magnetic flux density is the yoke's two longitudinal ends. Within the permanent magnet, the side that is closest to the iron core plate has a higher magnetic flux density than the other side.

Meanwhile, the analysis demonstrates that the magnetic field of the different parts of the iron core is distributed similarly under all four typical working conditions; however, under working condition (ii) (a full load with an initial suspension gap), because the suspension gap is greater, the different parts of the U-shaped iron core have a higher magnetic flux density than in working condition (i).

The flux leakage is most severe in working condition (iv), because even though both the magnetic field and the suspension gap are small, the magnetic fields of the exciting coil and the permanent magnet are of opposite directions.

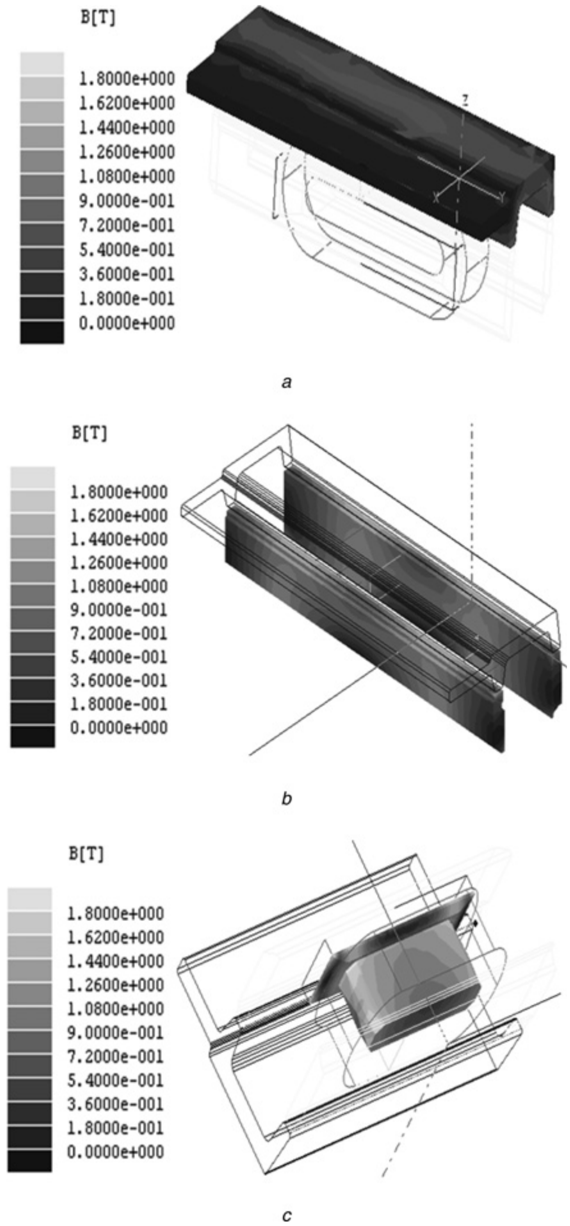

Fig. 3 *Magnetic flux densities via 3D calculations for different parts of the iron core during working condition (i) (full load with fixed suspension gap)*

a Iron core of the F-shaped tracks
b Two polar plates of the U-shaped iron core
c Yoke of the U-shaped iron core

Table 1 Calculations for suspension force under four typical working conditions

Working condition	Details of the working condition	3D calculation, N	2D calculation, N	Difference between both, %
(1)	full load, 8 mm, 2.5 A	7328.9	7935.1	7.6
(2)	full load, 18 mm, 66.7 A	6116	7907.3	22.7
(3)	full load, 10 mm, 22.1 A	7827.8	7934.1	1.34
(4)	empty load, 3 mm, −41.7 A	4676.1	5631.5	17

3.3 Calculations for suspension force

Table 1 below lists the results obtained for both the 2D and 3D analyses of the suspension force under the four different typical working conditions. Since the 3D analysis takes into account the length of the iron core, its calculations of the suspension force are more accurate.

Since the mass and loading conditions of the hybrid electromagnet-powered vehicle are the same as with a conventional maglev vehicle, the amount of suspension force required for different suspension gaps is the same. Furthermore, the amount of vehicle guiding force produced between the U-shaped suspension electromagnet and the F-shaped tracks is also the same.

Under a suspension gap of 8 mm, when the exciting coil's current is equal to 0, the suspension force for an individual electromagnet is 7120.1 N: only slightly less than the suspension force produced by the coil when its current is 2.5 A. This demonstrates that within the context of working condition (i), the permanent magnet is primarily responsible for the vehicle's suspension; therefore little energy is wasted during the vehicle's suspension. Similarly, we can observe via Table 1 that the 3D calculations for working condition (i) were slightly less than the 2D calculations, with a difference of 7.6% between the two.

4 Influence of the coil current and the suspension gap on the electromagnetic force

4.1 Relation between electromagnetic force and the suspension gap under normal working conditions

Fig. 4 demonstrates the changes in the suspension force of the electromagnetic following increases in the suspension gap under the four typical working conditions (with their corresponding coil current values).

From Fig. 4, we can obtain the following conclusion: when the electrical current is stable, the suspension force falls as the suspension gap is increased. When the suspension gap is 11 mm and the electrical current is inferior to 22.1 A, there is an almost linear relationship between suspension force and suspension gap, where the suspension force is expressed in smooth curves that directly correspond with fluctuations in the suspension gap. When the suspension gap is inferior to 6 mm, the relationship between suspension force and the suspension gap is evidently non-linear; this is primarily because of magnetic saturation.

4.2 Influence of the exciting coil's current on the electromagnetic force

Fig. 5 demonstrates the changes in the suspension force produced by the hybrid electromagnetic following increases in the coil current under the four typical working conditions (with their corresponding suspension gap values).

From Fig. 5, we can observe that, when the suspension gap is stable, the greater the forward current of the exciting coil, the greater the suspension force that it produces. However, once the forward current has increased past a certain value (such as 15 A when the suspension gap is 3 mm), the influence it has on the suspension force gradually decreases and its line on the graph correspondingly plateaus. This demonstrates that the iron core is close to attaining magnetic saturation.

To better compare the differences between the hybrid electromagnet and its conventional counterpart, Fig. 6 demonstrates the relationship between coil current and suspension force in an electromagnet that relies solely on an exciting coil with a suspension gap of 8 mm. For the purposes of this research, the traditional suspension electromagnet's exciting coil has 360 loops; moreover, the yoke of the iron core does not have a permanent magnet. Other than these two major differences, the design parameters of the traditional electromagnet are the same as those of the hybrid electromagnet.

In comparing Figs. 5 and 6, we can observe that the hybrid suspension electromagnet still produces suspension force

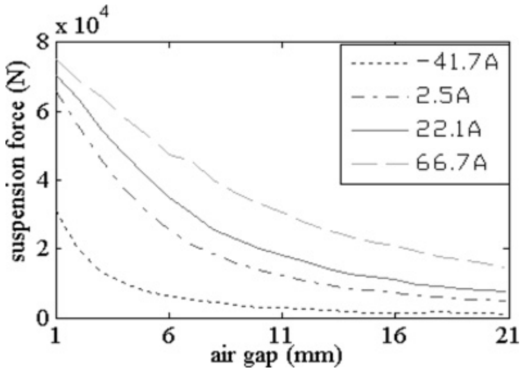

Fig. 4 *Relationship between the suspension force and suspension gap under the four different working conditions*

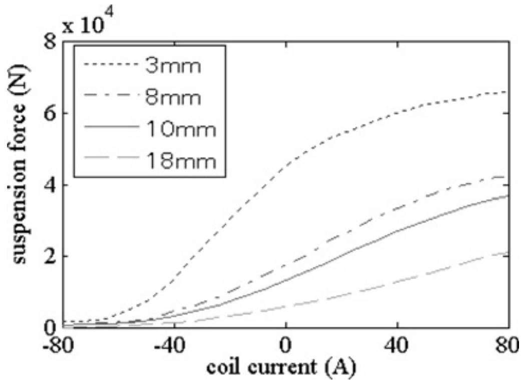

Fig. 5 *Relationship between the current of the exciting coil and the suspension force under the four different working conditions*

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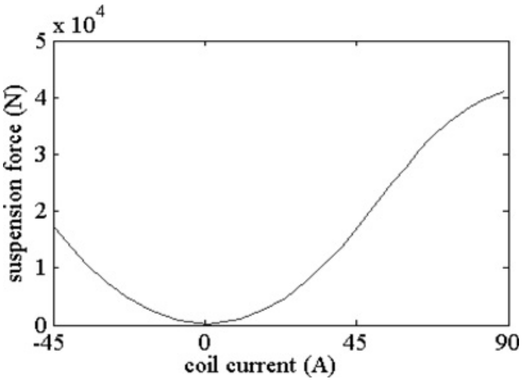

Fig. 6 *Relationship between suspension force and coil current for a traditional coil-based electromagnet*

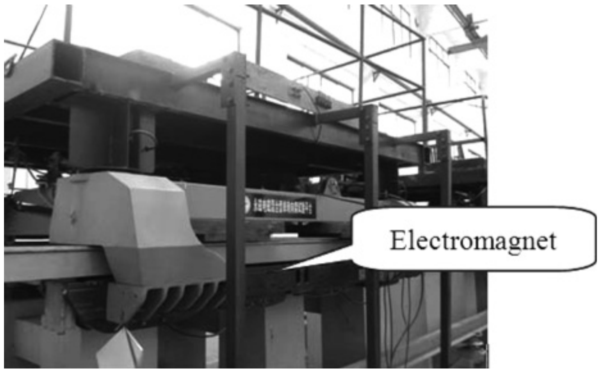

Fig. 8 *Experimental equipment used for measuring the suspension force of the hybrid electromagnet*

even when the current of its exciting coil is equal to zero; moreover, the smaller the suspension gap, the greater the amount of force that is independently generated by the permanent magnet. Additionally, the suspension force produced by purely coil-based suspension electromagnets is the same regardless of the direction of the coil's current, whereas in hybrid electromagnets, the suspension force produced by a forward coil current is different from that produced by a reverse coil current.

5 Experimental measurements

Fig. 7 is a photograph of a prototype for a hybrid electromagnet. Each car of a maglev train has five bogies, where one hybrid electromagnet is installed on both sides of each bogie. Each hybrid electromagnet is composed of four individual electromagnets which share the two polar plates of the iron core.

As demonstrated in Fig. 8, we conducted tests into the static electromagnetic force of the hybrid suspension electromagnets after they were installed on the bogies of the prototype vehicle. Standard weights were applied to the bogies so that the suspension load could be determined in advance. Meanwhile, the suspension gap was measured using an eddy current sensor. By adjusting the current of the exciting coil according to different suspension gaps, the suspension force could be made equal to the suspension load.

Firstly, the hybrid electromagnet's suspension force was measured when the vehicle was at a standstill. These measurements were then compared with the results of the 3D finite numerical analysis. The deviation between the two calculations is inferior to 6%, as shown in Fig. 9.

The hybrid electromagnet's dynamic performance (i.e. its performance when the vehicle is in motion) was tested using a trial track measuring 1.5 km. This test revealed that the electromagnet performed successfully during different suspension loads. The hybrid electromagnet attained a maximum temperature of 35°; considerably cooler than the maximum temperature of 110° produced by its non-hybrid counterpart.

Furthermore, the measurements conducted (when the vehicle was at a standstill and in motion interleaving working model) with working condition (i) reveal that the energy consumption of a hybrid electromagnet is only a 1/4 of that of a traditional electromagnet; the hybrid electromagnet therefore constitutes an important innovation in saving energy.

Although the initial investment required in order to adopt hybrid electromagnets may be more expensive than the cost of adopting traditional, purely coil-based electromagnets, this investment will be offset by the amount of money saved because of the electromagnet's energy efficiency. To use Beijing's S1 Low-Speed Maglev Line as an example, studies have revealed that one car takes 1743.2 s to complete a round trip of the entire line. During this time, a maglev car using traditional electromagnets consumes 1667.2 kWh. Were the traditional electromagnet to be adopted in favour of a hybrid electromagnet, the car would only use 416.8 kWh. According to current costs, the initial investment could be offset in ~3.5 years.

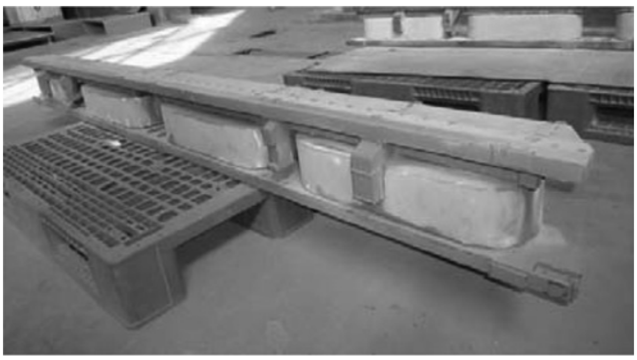

Fig. 7 *Photograph of the prototype for the hybrid suspension electromagnet*

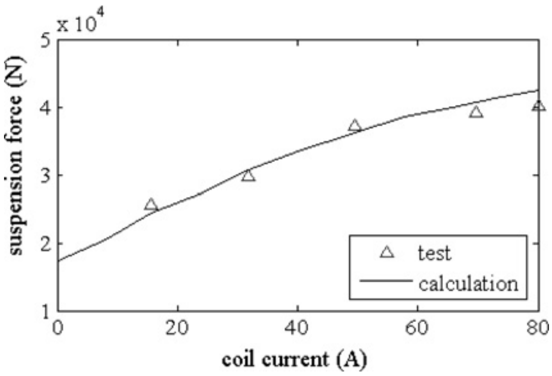

Fig. 9 *Comparison of the numerical analysis and the real-life measurements of the suspension force with a gap of 8 mm*

6 Conclusion

In this new form of hybrid suspension electromagnet, the electromagnetic field produced by permanent magnets is responsible for the vehicle's suspension, whereas the additional force provided by the exciting coil serves to keep the vehicle stable. This study adopted a finite numerical approach in order to analyse the performance of a hybrid suspension electromagnet for use in a low-speed maglev train. This study equally developed an engineering prototype, which was subsequently installed on an actual maglev car and subjected to a series of experiments. Both the experiments and their prior calculations reveal that adopting a hybrid suspension electromagnet is feasible, and that such an electromagnet is capable of providing the force required for the vehicle's suspension. This study equally reveals that, when the minimum limit for the suspension gap has been attained, the electromagnetic force can be regulated via an additional reverse current provided by the exciting coil. After abandoning a traditional electromagnet in favour of a hybrid structure, the maglev vehicle's energy consumption was reduced by 400% and the temperature of the electromagnet was dramatically decreased, thus achieving objectives for energy efficiency.

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