Repulsive Permanent Magnets Transportation System

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Experimental Tests, Linear Drives, Passive Repulsive Levitation.

Abstract

A semi-passive magnetic levitation system is presented, two prototypes of the magnetic levitation system and of the linear motor have been constructed and experimentally validated. The experimental results are in good accordance with the numerical ones showing the suitability of the models for designing levitation devices of this type.

1 Introduction

The device here presented consists in a semi-passive magnetic levitation system that assure the suspension and a linear motor that assure a contactless propulsion thrust [1].

This magnetic levitation solution can be classified as a semi-passive repulsive electromagnetic system and is a direct development of the so-called synthesis solution [2]. The term "semi-passive electromagnetic levitation" is referred to systems in which the main levitation forces are supplied by permanent magnets, which do not require energy consumption to maintain the vehicle in levitation.

This levitation system uses the repulsive forces, generated by permanent magnets on two magnetic guides (providing the lifting force), and lateral stabilisation forces generated by electromagnetic actuators (guidance forces) [3]. The main drawback of repulsive systems is that of needing a magnetic rail, with permanent magnets on the whole guideway. This kind of passive repulsive systems is stable in vertical direction in roll and pitch, while an active stabilisation is required for lateral and yaw motions. Permanent magnets producing levitation forces can supply also lateral forces if the vehicle is suitably displaced sideways.

The motor is a Double Side Ironless Linear Motor (DSILM) with a long induct and a short inductor. It is a brushless linear motor with a double induct and an ironless inductor. This topology of motor allows to get very high Thrust/Normal Force ratio and a very low normal negative stiffness as it is required by the magnetic suspension adopted [4,5].

In industrial applications, such contactless positioning system can represent an useful option for high speed positioning system or wherever maintenance production stops or dirt represent a problem (semiconductor manufacturer, white rooms, etc.).

2 Description of the system

The realised prototype (see Figure 1) consists of two structures, called "trolley", supporting moving magnets, controlled electromagnets, linear motor cursor and position sensors. Each trolley is a magnetic levitation system with two controlled axis and three axes passively stable, the sixth degree of freedom is controlled by the linear motor producing the propulsion and braking action.

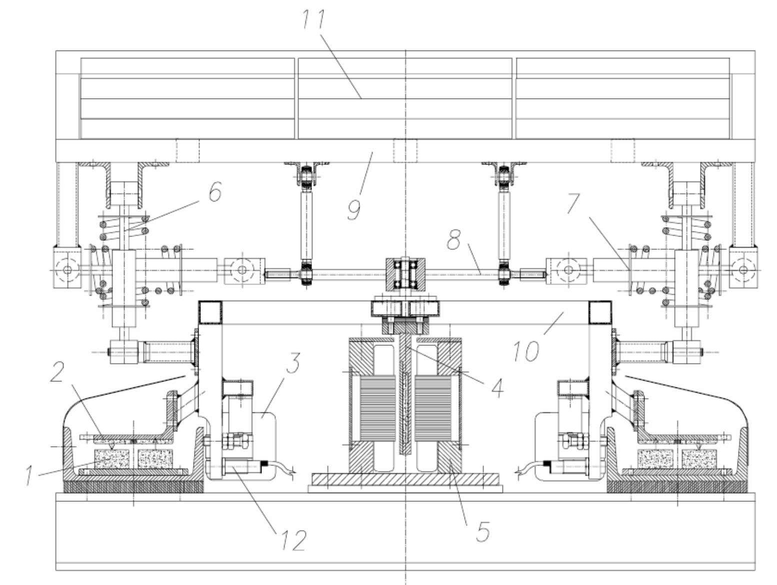

Figure 1: Transversal view of the prototype. (1) Fixed magnets, (2) Moving magnets, (3) Electromagnets, (4) Linear motor cursor, (5) Linear motor stator, (6) Secondary suspension, (7) Lateral dampers, (8) Watt mechanism, (9) Payload, (10) Trolley, (11) Ballast, (12) Position sensor.

The payload is connected to the trolleys by some spring-damper group constituting a secondary suspension in order to reduce roll and pitch vibrations and curves radius. The longitudinal force is transmitted from trolleys to the payload by a Watt mechanism permitting small displacements movements on the other degrees of freedom within the range necessary for the correct operation of the suspension. Each trolley is independent and the payload can be suspended on an indefinite number of trolleys. The choice of the optimal number of trolleys must be made according to the vehicle length and to the minimal curve radius.

Main system characteristics are resumed in Table 1.

Parameters	**Value**	**Unit**
Total Mass	320	Kg
Levitation Force	2000	N/m
Levitation Height	8	mm
Track Length	10	m
Thrust	250	N
Accuracy	1	mm

Table 1: Contactless linear positioning system nominal characteristics.

3 Magnetic levitation system

While electrodynamics systems are stable without the need of active control devices, electromagnetic systems are intrinsically unstable and require some form of control to achieve stable levitation. In the solution here investigated the main levitation forces are supplied by permanent magnets, which do not require energy consumption to maintain the vehicle in levitation.

This solution is stable in vertical direction in roll and pitch, while an active stabilisation is required for lateral and yaw motions. Permanent magnets producing levitation forces can supply also lateral forces if the vehicle is suitably displaced sideways: the stabilisation control can be designed with a "zero control power strategy" (under static loads), in which the current flowing in the stabilisation electromagnets is used as a reference state to be minimised instead of the position. The current error from a null current reference is integrated in order to generate a command (integrative action, a memory of the system conditions), which minimises the energy employed when the system is subject to quasi-static lateral forces. Moreover the controlled system moves to a new equilibrium position and the external forces are countered by using the lateral component of levitation forces and reducing lateral air gap without increasing the required current.

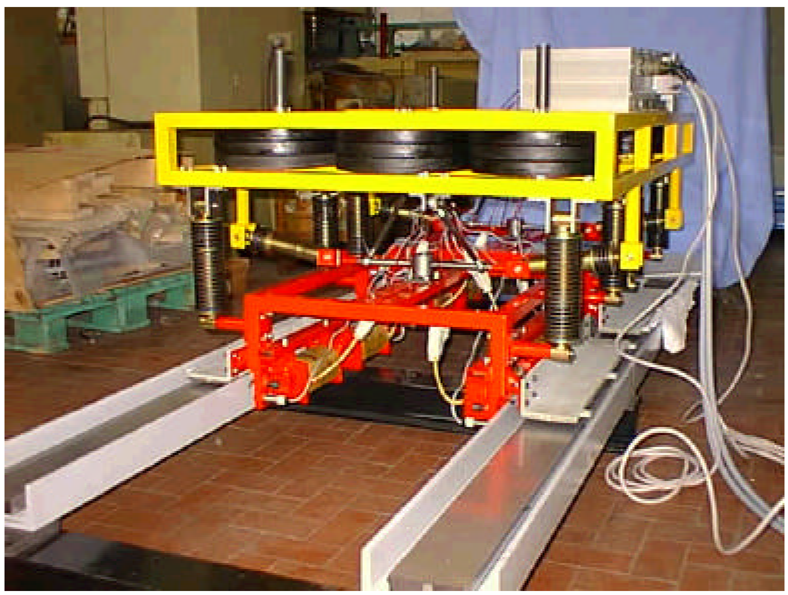

Figure 2: Prototype of the magnetic levitation system.

The welded steel platform (see Figure 2) has a mass of about 320 kg, which can be increased up to 500 kg by adding ballast and levitates on 10 m of magnetic rail made of permanent ferrite magnets. The permanent magnets have a composite structure with magnetic elements with different orientation of the field (Halbach array); for this prototype just two elements are sufficient to achieve a good distribution of field intensity (see Figure 3). Ferrite magnets were used for fixed elements and lighter rare earths magnets (NdFeB) are used for mobile elements on trolleys. The fixed magnets, glued on aluminium plates, are located in a U-shaped steel rail, whose wings protect the permanent magnets and constitute the ferro-magnetic rails for the guiding electromagnets.

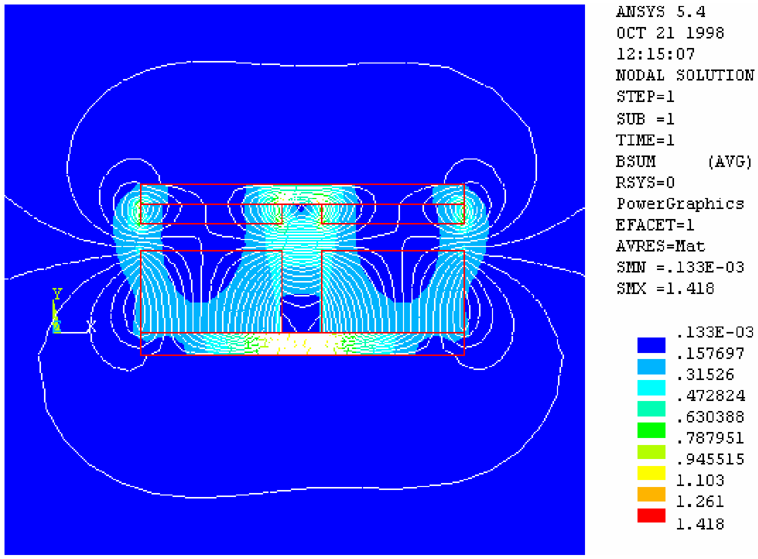

Figure 3: Magnetic field produced by permanent magnets in nominal conditions.

3.1 Secondary suspension

Main function of the secondary suspension is to reduce vibrations of the payload excited by track irregularities. For very fast displacements, it is required to damp the vertical oscillation of the system in order to eliminate risks of contact between vehicle and track and to reduce the r.m.s. value of the acceleration transmitted from the track to payload. In fact, vertical motions are completely undamped and since the suspension is passive and not controlled, any vertical oscillation persists for several seconds. An electromagnetic damper (passive or active) on the magnetic suspension can eliminate contact risks but it does not reduce effectively payload accelerations, besides it is bulky and it reduces the surface available for levitating magnets.

Moreover a secondary suspension allows shorter radius of curves for the vehicle. The payload can be suspended on an indefinite number of trolleys, bulky loads can be displaced easily using a sufficient number of trolley. Each trolley is an independent and complete vehicle, it can be used separately for displacing smaller loads. Since vertical position is not fed-back, the exact height of levitation depends on the total weight of the full system.

3.2 Power electronics

The lateral active suspension is actuated by four electromagnets, in opposite pairs to provide bi-directional displacement control for each axis. A DC bias current is required to linearise the force-current characteristics in the operating force range. From the electric point of view, each coil behaves as an impedance with a low resistance and high inductance. Such a load requires a sort of reactive transconductance amplifier, designed to minimise the energy spent for the control, which depends mostly on the amplifier efficiency, owing to the very low value of the resistance of the coils. The use of switching amplifiers is thus strongly advisable; the high inductance of the load acts as a filter reducing the high frequency components produced by switching amplifiers.

To further reduce electrical noise, due to the commutations of the active switches (MOS transistors), the bridge is driven to obtain a three level output voltage. Furthermore a double edge pulse width modulation (PWM) with triangular waveform, a common mode and a differential mode filters are used to reduce the output frequency contents. The reduced power losses, typical of switching devices, is so obtained together with noise levels not higher than those achievable with linear amplifiers.

The power amplifiers and the control for the stability of the levitation system are designed to minimise the energy consumption; for this reason it is important to design of the whole system reducing the lateral unstable forces.

3.3 Control design

From the signal of the proximity sensors, it is possible to estimate all the states of the system (position, velocity and current for each controlled axis) with a state observer built on a full mechanical model[3].

For this application it is important to minimise the energy consumption for the control and since the lateral unstable forces are critical for the solution here examined, it is important to minimise control forces. For this reason, in order to assure the zero average current control, the state space can be augmented with the states describing the cumulative error of the deviation currents from zero, i.e. each current from its bias value. In practice, when an external load is applied to the system the control will try to keep the current deviation to zero counteracting the external force with that produced by the permanent magnets and by the bias command moving the system toward the incoming disturbance.

In order to assure exact position regulation and tracking, the state space is also augmented with the states describing the cumulative error of the deviation positions from zero.

The control command is generated through a complete state feedback and the gain matrix can be obtained by direct pole placement or by means of a linear quadratic regulator. In this case the cost function to be minimised uses a complementary weight on each couple of current and position errors augmented states, thus it is possible to achieve the limit cases of zero error either for position or current, which corresponds to a number of null elements in the error gain matrix.

The current states are usually fed back inside the power amplifiers. As is usually the case, the current gains are sufficiently high, the current states dynamics is faster than all the others and may be neglected in the model used to estimate position and velocity states. In other terms, the voltage amplifier is transformed by the internal current feedback into a transconductance amplifier, its input being the desired current to be provided almost instantly to the coils. In the error gain matrix three effects due to the internal current feedback of the power amplifiers, to the mechanical effects, and to the cumulative errors can be evidenced.

3.4 Experimental tests

This prototype has been used to study the behaviour of the maglev system at standstill or in very slow motion, since the magnetic rails are very short [3]. The uncoupling between longitudinal motion and both lateral and vertical motion of the device makes the behaviour at standstill representative of the operational behaviour of the machine. Different control strategies can be implemented and different working conditions has been studied, investigating the stability and the robustness of the concept.

For each trolley, four inductive proximitor sensors are used for measuring the lateral position of the levitating system. Inductive proximity sensor were then used to measure the distance of the device from the ferro-magnetic rail with the aim of decoupling the position signal from the vertical displacement. Two sensors were used for each axis in a differential way, so that the ``zero reference'' was located where the resultant force due to the electromagnets is zero. In this case, vertical motions are decoupled from position signals and the system is stable also in case of large undamped vertical oscillations.

In case of zero position error strategy and in absence of external forces, the platform is in the central position but the current states are not zero due to the offset of the position sensors. In case of zero average current control strategy and in absence of external loads, the system is in equilibrium where the lateral component of levitation force is counteracted by the electromagnets force due to the bias current. When the bias current in electromagnet is very low, it is possible to find the equilibrium position where the lateral component of permanent magnets is zero and then to regulate the offset of position sensors.

4 Linear motor

The key point in the motor design was the necessity to keep the motor normal force very small (in fact the motor itself has negative stiffness that means lateral instability). In fact, a symmetrical structure allows to reduce the normal force by a two opposite normal forces generation. A large airgap with a low flux density and an ironless structure involve a low specific magnetic energy stored in the airgap and a very low energy stored changing with the cursor disalignement.

The motor is a Double Side Ironless Linear Motor (DSILM) with a long induct and a short inductor. It is a brushless linear motor with a double induct and an ironless inductor. This topology of motor allows to get very high Thrust/Normal Force ratio and a very low normal negative stiffness as it is required by the magnetic suspension adopted.

Other advantages of this topology are low thrust ripple, linearity between current in the quadrature axis and the thrust, and insensibility to the cursor disalignement in the direction normal to the moving direction (these peculiarity is important when the motor is associated to a levitation system).

An additional advantage is that the power is completely allocated on the stator and there are not electric contacts in motion.

The main drawback is the big amount of copper losses due to the long stator and the consequent reduction in the system efficiency. This drawback can be attenuated splitting up the stator winding in different block and integrating an electronic device devoted to fed the electrical power only to the blocks where the cursor is running. Different strategies to realise this kind of subdivision have been proposed in the past for similar motor topology designed for high speed transportation.

Linear motor technical specifications are shown in Table 2

Parameters	Value	Unit
Rated Thrust	250	N
Rated Normal Force	0	N
Rated Lateral Stiffness	<100	N/mm
Rated Vertical Stiffness	<100	N/mm
Rated Speed	5	m/s

Table 2: Linear motor technical specifications.

The rated normal force is equal to zero when the cursor is perfectly located in the middle of the double stator. If a little disalignement is present the force increases as will be described in the next section.

4.1 Motor design

The Double Side stator with and an internal IronLess cursor Motor (DSILM) has been designed, integrating traditional formulas and 2D and 3D FEM simulations. In particular, the evaluation of the normal force generated by the motor can only be done performing 2D FEM analyses [7,8,9] in the plane orthogonal to the moving direction. The key point in the motor design was the necessity to keep the motor normal force very small (in fact the motor itself has negative stiffness that means lateral instability). This necessity drove to some a "priori" choices on the motor design: symmetrical structure, large airgap, low airgap flux density, ironless structure for the moving part.

In fact, a symmetrical structure allows to reduce the normal force by a two opposite normal forces generation. A large airgap with a low flux density and an ironless structure involve a low specific magnetic energy stored in the airgap and a very low energy stored changing with the cursor disalignement. In order to validate these choices, specific FEM simulations finalised to get the optimum ratio between the highness and the thickness of the permanent magnets assembly have been done. The overall machine preliminary design has been carried on the basis of the conventional sizing equations [10]. Because of the motor structure, it was necessary to perform the motor design in two stages: the middle part and the endings part of the inductor of the motor separately. In fact, in the central part of the inductor, the magnetic flux created by one magnetic pole flows through the stator joke divided in two parts in opposite directions (like in a rotating machine). On the other hand, at the extremities of the inductor the magnetic flux of one magnetic pole flows through the stator joke in only one direction.

As a consequence, at the endings of the inductor, the magnetic field intensity is higher than that in the central part. This fact causes the so called "end effects", influencing the thrust ripple, the magnetic field distribution, the inductance values and the power losses. As a consequence, in the design stage, it was necessary to find a trade off between overloading the magnetic circuit at the beginning and at the end of the inductor and underloading the magnetic circuit in the central part of the inductor.

In the first case, the produced specific thrust (the thrust referred to the motor weight) is higher, but the power losses in the iron are high, as the motor lateral instability and the thrust ripple. In the second case, the produced specific thrust is lower, but the power losses in the iron are reduced, as the motor lateral instability and the ripple thrust. As discussed in [4], for the motor under study, it was selected a low airgap magnetic induction value to allow that the stator joke is underloaded.

After the preliminary design, the linear motor has been optimised using 2D and 3D FEM simulations. In particular, with this method, the following aspects have been studied: ratio between tooth and slot thickness, ratio between pole pitch and magnet length, stator joke dimensions. In Table 3 the motor main data are listed.

Parameters	**Value**	**Unit**
Poles Number	8	-
Pole Pitch	60	mm
Stator Length	3'000	mm
Cursor Length	480	mm
Airgap (each side)	10.5	mm
Airgap Induction	0.4	T
Stack Height	84	mm
Stack Width	27	mm

Table 3: Linear motor main design data.

At the end of the design stage the motor overall performance has been verified, including the produced forces, as well as their variations, depending on the cursor position. In particular, it was studied: the motor parameters (to be used in the equivalent circuit) and the generated forces. The generated forces are the thrust and the normal forces. The thrust is the main motor target and the normal forces can be considered as the undesired second effect.

The developed thrust can be calculated in the design step by the traditional formulas and the FEM simulations. The thrust has been measured by laboratory test using a load cell. To describe the overall procedure for the simulations and the tests, it is necessary to introduce the following variable: the d [°] angle, that is the electric angle between the main magnetic field and the reaction magnetic field due to the stator currents. The thrust has been evaluated for different d values and different current values.

4.2 Experimental results

The motor prototype has been realised as shown in Figure 4 and Figure 5, and the experimental results are quite interesting.

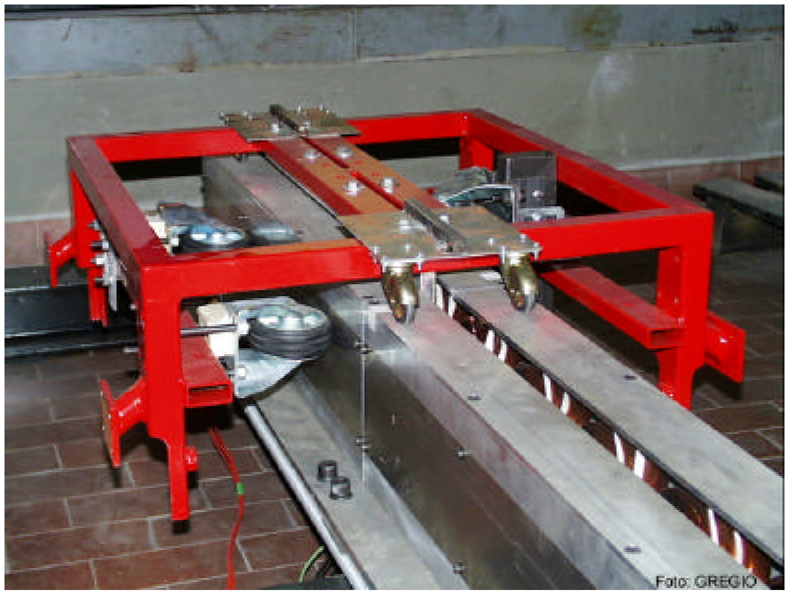

Figure 4: Overall assembly of the linear motor prototype.

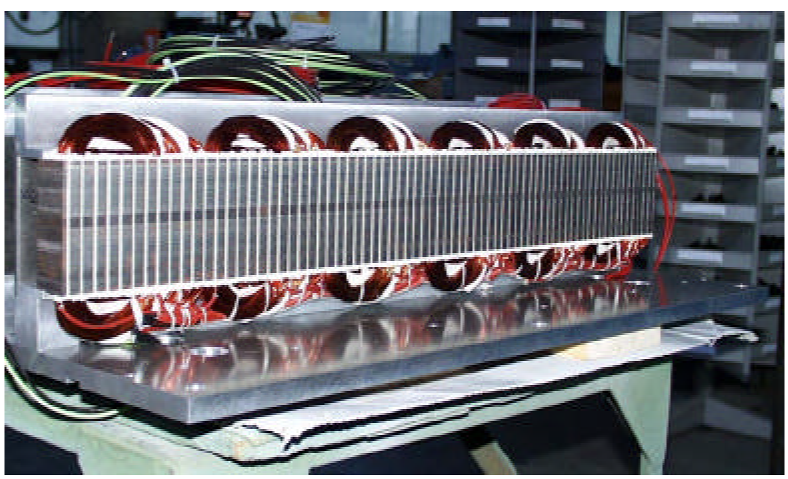

Figure 5: One stator side of the linear motor during the construction.

To test the motor without the magnetic levitation a bogie with wheels has been realised, adapting the one designed for the magnetic levitation. This bogie, has realised integrating the load cells in the moving structure, to get a test bench suitable to measure forces in any direction. The experimental tests have been focused on the measurement and verification of the quantities previously computed through simulation and formulas: motor parameters and generated forces.

4.2.1 Comparison Between Design and Test Results

The simulations and the experimental results have been compared. It seems that, in general, the motor behaviour has been predicted with a good precision. Considering the equivalent circuit, the difference is less than 10% (Table 4) and this result can be considered very good.

Parameters	Phase Resistance	Phase Inductance
Designed Value (by formulas)	2.4	11
Designed Value (by FEM)	2.45	12
Experimental Designed Value	2.53	12.9

Table 4: Linear motor parameters.

The measured and calculated thrusts have been compared in [10]. In Figure 6 the calculated and measured thrust for two conditions are shown: rated stator current and d= 90 ° (nominal electric angle).

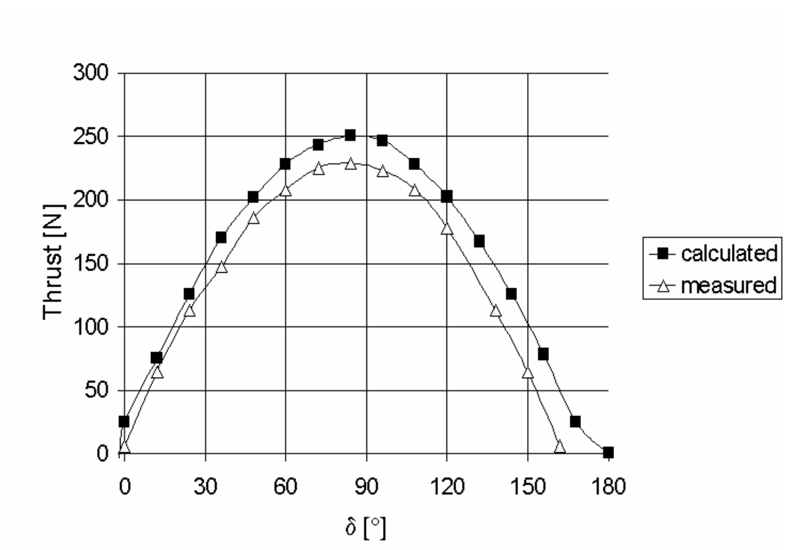

Figure 6: Calculated and measured thrust at rated stator current.

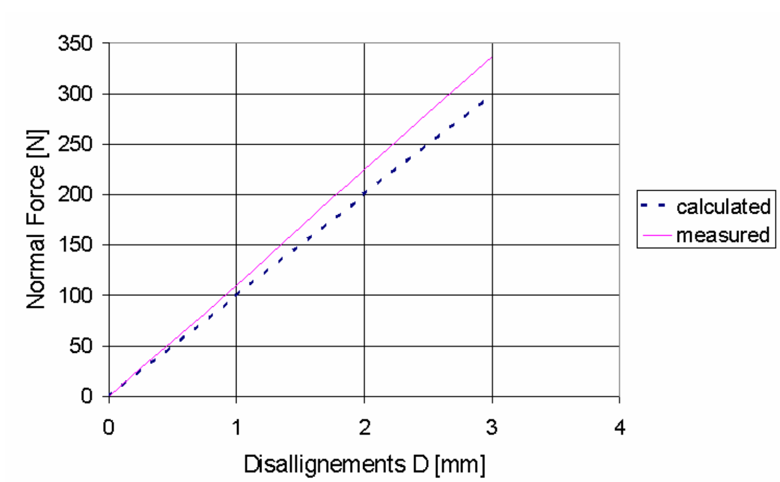

Figure 7: Calculated and the measured thrust for d= 90 °.

In Figure 7, the measured and the calculated normal force are shown: the agreement between the two results is quite good.

5 Conclusions

Two test benches equipped with the prototypes of the two subsystems have been constructed and an experimental validation of the design results has been performed. The design procedure and the comparisons between the design predictions and the experimental results is be exposed. The experimental results are in good accordance with the numerical ones obtained from the developed mathematical models showing the ability of the models to predict the behaviour of the actual systems and their suitability for designing levitation devices of this type.

6 References

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