Control system and experimental results on a PM maglev test bed

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ABSTRACT: The paper concerns a static EMS levitation test bed, with four six-pole levitation units: two equipped only with copper coils, the others with combined coil-permanent magnet excitation. The paper focuses both on the levitation control system architecture and on the experimental results.

1 INTRODUCTION

In a previous paper (Castelli Dezza, 2000), the results of levitation tests on a static platform were reported. This platform was raised up by means of four levitation units, each constituted by two poles, of classical electromagnetic type (copper coils wound on ferromagnetic cores). Later on, a new EMS static platform has been designed and constructed (Castelli Dezza, 2002a), again with four levitation units, but each unit has six poles, and two out of four units have a double excitation, with coils and permanent magnets (PMs). This papers deals with the description of the levitation control system architecture and of the experimental results gained about the levitation of this new platform.

2 THE STATIC PLATFORM

In the following figures, some photos and pictures of the platform are shown. We notice the four esapolar levitation units, two of coils-only (CO) type (on one side), and the other two with PMs (on the other side). We also notice that on the CO side, each pole has two coils, because the total magneto motive force (mmf) needed to produce the levitation force is assumed as divided in two components: one constant, equal to the mmf needed to balance the rated weight at the rated air gap, the other variable with the operating conditions; in such a way to maintain the levitation clearance (that is the magnetic air gap) constant; the constant mmf is called polarization, and acts as a PM, while the variable mmf is called regulation. The total mmf has been split, because we believe that, if just a portion of mmf is regulated, rather than the total amount, we can gain a better dynamic behavior; besides, the rms value of the regulation mmf will be lower, so reducing the Joule losses of the system. On the PMs side, the regulation coil only is needed, because the constant mmf is supplied by the magnet.

The main sizes and characteristics of PM, coils, and platform, are given in Table I

3 MODEL OF THE MAGNETIC CIRCUIT

A fundamental requirement of the control system is a linear relationship among current and magnetic flux; to this aim, the magnetic circuit design adopted a low flux density in the iron core (to avoid magnetic saturation in each operating condition). As a consequence, the iron magnetic potential drop is very low, and for this reason as a first fundamental hypothesis the iron permeability is assumed infinite.

Then, to the aim of the levitation control, the use of the sophisticated model proposed for the design stage (Figure 4, for the PMs levitation unit, Castelli Dezza, 2002b) is not needed. So, a simplified model is adopted, assuming that the 4 central poles are equal each other, and that the sum of the 2 lateral poles equals a central pole; with such assumptions, the levitation unit can be modeled by 5 central legs. Furthermore, the central points of each interpolar zone (e.g.: points P, Q, R, S in Figure 4) are equipotential for symmetry, so leakage reluctances can be split in two halves, and linked to upper and lower yokes: so the 5 legs are independent, and attention may be focused on the equivalent circuit of a single central pole (Figure 5). The expressions of the reluctances of Figure 5 are given in Castelli Dezza, 2002a, 2002b.

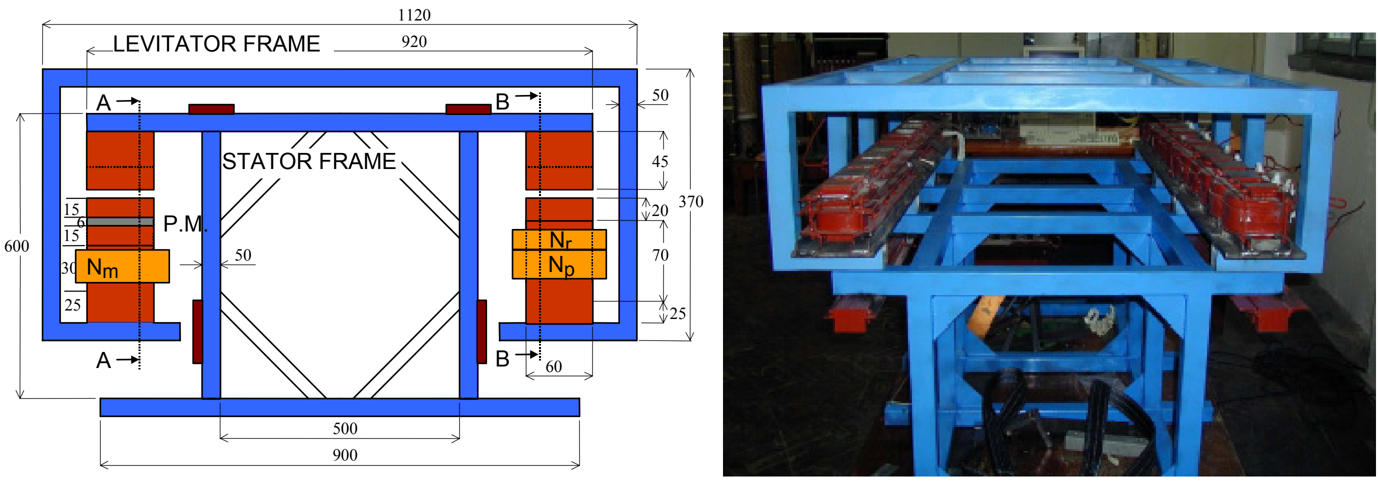

Figure 1: scheme and photo of the platform; the blue bars are the stator and levitator frames, the dark red rectangles represent the ferromagnetic cores and yokes.
Left: picture of the frontal view; sizes are in [mm]; the dark grey rectangles are the PMs, the orange rectangles represents the coils (N_p = polarization, N_r = regulation, N_m = magnet)
Right: photo of the platform; the levitator frame has been unthread and placed over the stator frame.

Table 1: main sizes and characteristics of PMs, coils, and platform

PM sizes [mm]	Height (magnetizing direction)	6	Width	60	Length	76, 38 (central, lateral poles)
PM characteristic	Material	NdFeB	Coercitivity [kA/m]	870	Remanence [T]	1.18

Pole shoe sizes	Width [mm]	60	Length [mm]	80, 40 (central, lateral)	Area [m^2]	$A_\delta = 4.8 \cdot 10^{-3}$
Platform	Rated mass [kg]	$M_r = 1000$	No-load mass [kg]	250	Rated levitation air gap [mm]	$\delta_r = 4$
	Equivalent central pole shoe number	$p = (4 + 2\cdot 0.5) \cdot 4 = 20$				
	Rated air gap flux density [T]	$B_\delta = \sqrt{\frac{2 \cdot \mu_o \cdot M_r \cdot g}{A_\delta \cdot p}} = 0.5$				

Coils	Polarization	Regulation	Magnet
Turns per coil	$N_p = 80$	$N_r = 24$	$N_m = 90$
Wire diameter [mm]	3.15	3.15	2.12
Rated current [A]	$\frac{B_\delta}{\mu_o} \cdot \delta_r \Big/ N_p \approx 20$		

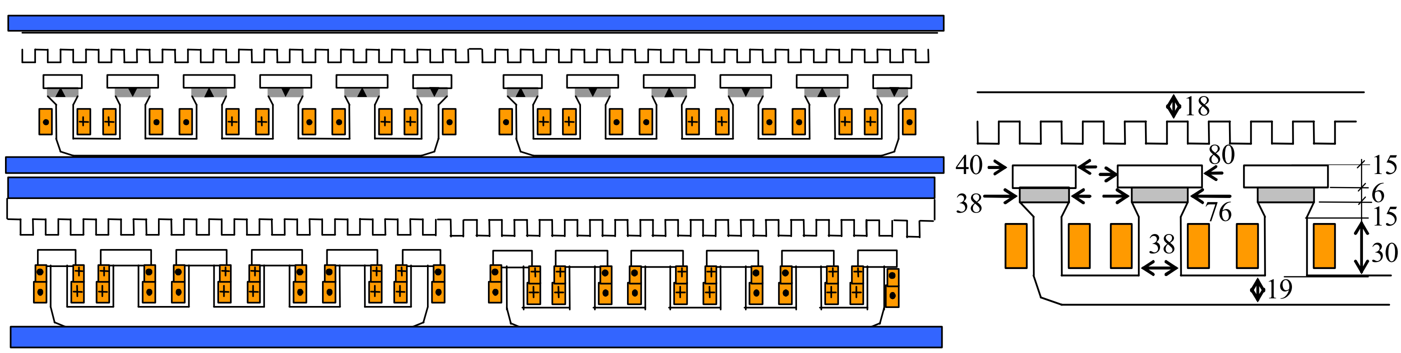

Figure 2: pictures of the lateral sections of the platform: each side has two esapolar levitation units.
Upper, left: section AA of the platform (PMs side); the arrows indicate the magnetization verse of PMs.
Lower, left: section BB of the platform (CO side); plus sign indicates incoming current, dot outcoming.
Right: main dimensions of the levitation units (sizes in [mm]).

Figure 3: photos of the esapolar levitation units. Upper: CO type. Lower: PMs type.

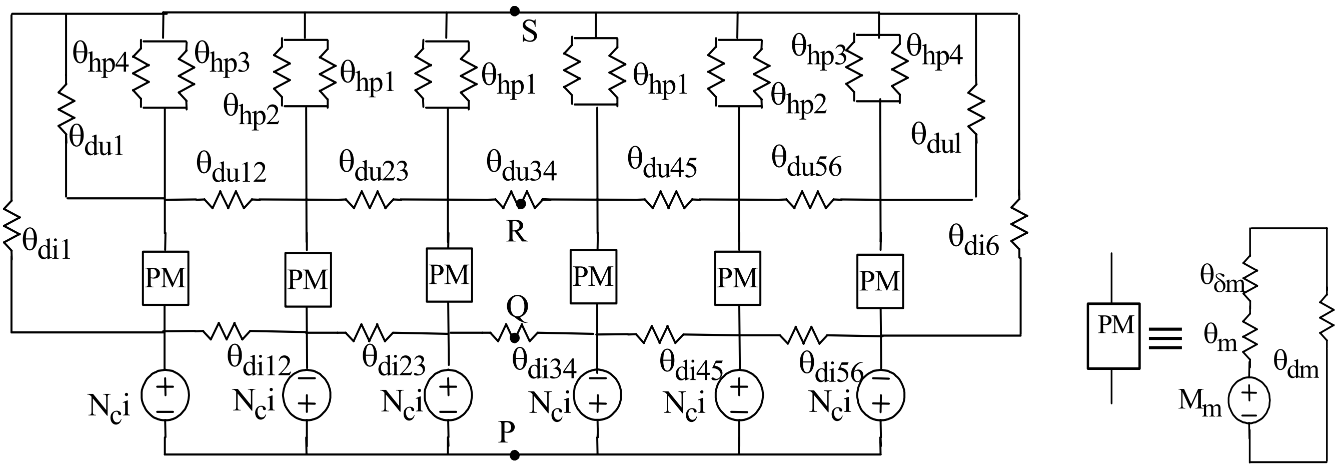

Figure 4: equivalent net for the magnetic circuit of the PMs levitation unit.

θ_{hpj} = air gap reluctance of half pole j: all central half poles are considered equal among them, while the three lateral half poles are different each other; θ_{dujk} = leakage reluctance between upper pole shoes of poles j and k; θ_{dijk} = leakage reluctance between lower pole shoes of poles j and k; $N_c i$ = coil mmf ; M_m = PM mmf; θ_m = PM reluctance; $\theta_{\delta m}$ = reluctance of the air gap between the PM and the polar shoe; θ_{dm} = PM leakage reluctance.

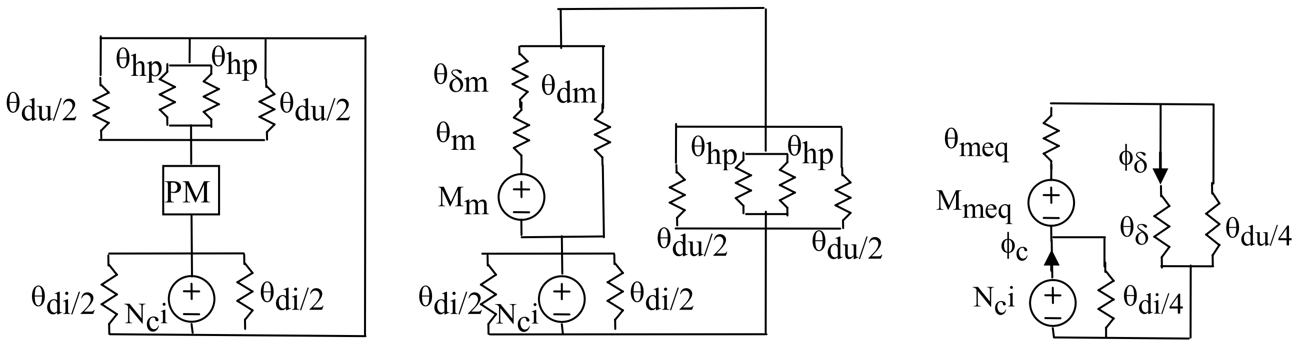

Figure 5: equivalent circuit for a central pole; M_{meq} and θ_{meq} are Thevenin's equivalent of the PM circuit; $\theta_\delta = \theta_{hp}/2$.
ϕ_δ = magnetic flux in the air gap; ϕ_c = magnetic flux in the coil.

4 SYSTEM EQUATIONS

Let we call v = coil supply voltage, i = coil current, R = coil resistance, p = time derivative operator, N_C = coil turns number, ϕ_C = magnetic flux in the coil, ϕ_δ = magnetic flux in the air gap (see Figure 5), m = platform mass (per levitation unit), δ = air gap width, A_δ = air gap area, $F = \phi_\delta^2 /(2 \cdot \mu o \cdot A_\delta)$ = magnetic attractive force, g = gravity acceleration, $a = p^2\delta$ = vertical acceleration. The model equations are the electric circuit voltage law $v = R \cdot i + N_C\,(p\,\phi_C)$ and the mechanical equation $F - m \cdot g + m \cdot a = 0$. The system has three state variables: the air gap δ, its time derivative $\dot{\delta}$ and the coil flux ϕ_C. The control aim is to maintain the levitation force constant, and this requires a constant air gap flux ϕ_δ; the coil flux ϕ_C can be considered constant too, so the state variables are reduced to two. Through the equivalent circuit of Figure 5, the air gap flux ϕ_δ is solved for the coil current, and the state equations are:

$$p\delta = \dot{\delta}$$

$$p\dot{\delta} = g - k_1\left(\frac{N_C \cdot i + M_m}{\delta + k_2}\right)^2$$

where k_1 and k_2 are constants obtainable by solving the magnetic equivalent circuit.

By linearising the equations in the rated working point (δ = 4 mm), and applying Laplace transform, the equations needed for the control system design are as follows:

$$s\delta = \Delta\dot{\delta}$$

$$s\dot{\delta} = -k_3 \cdot \Delta i + k_4 \cdot \Delta\delta$$

The model and the equations have been developed with reference to the PM levitation unit, but in a very similar way the CO unit can be analyzed; in fact, the polarization mmf is maintained constant by a devoted power supply, so it acts as a PM.

5 CONTROL SCHEME OF A SINGLE LEVITATION UNIT

The control scheme is similar to classical industrial schemes, used for motor drives, with two nested loops: an inner loop for force control (magnetic levitation force) and an external one for position control (magnetic levitation gap), Figure 6.

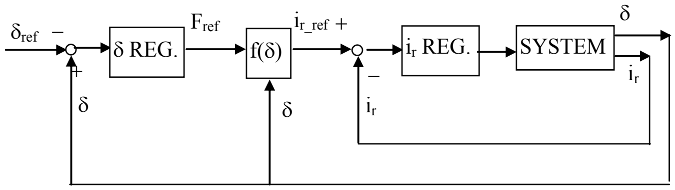

Figure 6: control scheme of a single levitation unit.

The position regulator compares the reference air gap δ_{ref} with the actual one δ, and calculates the reference force F_{ref}.

The force regulator is in fact a current regulator, because the force is kept constant by varying the regulation current: given the reference force F_{ref}, the system (function $f(\delta)$ in figure) calculates the regulation current i_r needed to produce this force (at the actual air gap), and this is the reference value i_{r_ref} for the current regulator.

The current regulator is a PI, and the coefficients K_p and K_i were found to obtain in the closed loop system a phase margin of 90° (to avoid overshoot) and a bandwidth of 1500 rad/sec (the converters switching frequency is 20 kHz).

The air gap regulator is a PID, and the coefficients K_p, K_i, K_d were found by a pole placement technique, to gain a good closed loop response in simulations. The coefficient values used to simulate the system in Matlab are shown in Table 2.

In the real control system, digital regulators have been implemented, by microcontrollers (μCs).

We notice that the CO levitation units require another current regulator for the polarization current i_p, which acts alone (it is not coupled to any air gap regulator). The polarization reference current i_{p_ref} is constant during the normal operation (and is equal to the current needed to balance the rated weight at the rated air gap), while it changes as a step-wise function during the lifting and descent stages, to avoid overloading of regulation coil (if i_{p_ref} were always constant, during the lifting stage all the defective mmf should be supplied by the i_r regulator); the total air gap is divided into determinate intervals, and each interval matches a fixed i_{p_ref} value.

Table 2: values of the PI and PID coefficients, used to simulate the system operation in Matlab

	K_p	K_i	K_d
PM levitation units			
PI current	35	1073	-
PID air gap	4.51	12.52	0.36
CO levitation units			
PI polarisation current	14.5	357	-
PI regulation current	1.41	180	-
PID air gap	8	12.5	0.2

6 LEVITATION CONTROL SYSTEM ARCHITECTURE

Each of the 4 levitation units is independently controlled by a devoted μC; a fifth μC acts as a master, which coordinates the four slaves and schedules the operations.

The μCs devoted to PM units operate in a bit different way with respect to CO ones: the former implement exactly the control scheme of Figure 6, while the latter implement just the i_r regulator, whilst the δ regulator is implemented by the master, which also calculates the i_{r_ref} value, and provides it to the μCs of the CO unit. Such choice is due to two reasons: 1) in addition to the i_r and δ regulators, the CO μCs has to implement the i_p regulator too, while the master should just schedule the operation; so, to the aim of a proper allocation of operations, it is better to assign one out of the three regulators to the master; 2) a plane of a rigid, planar boy is identified by 3 points, so if the air gap is measured and regulated in 4 points, the fourth control may clash with the other; to avoid this, only 3 air gap sensors are used; two sensors are placed in the corner of the PM levitation unit, and the third sensor is placed in the middle between the two CO units: in this way, two air gaps have to be evaluated, in the corner of the two CO units (Figure 7). If such evaluation is performed by the master, we have a good reason to assign him the δ regulator of the CO unit.

Finally, as the master knows the air gap of the CO units, it also chooses the related value of i_{p_ref}, and send this information to the i_p regulator of the CO units. We notice that during the lifting and descent stages the i_p variation is monotone (rising up or down), so if the slaves know the i_{p_ref} step-wise function waveform, the master does not need to send the value of i_{p_ref}, but only the command to change its value: this is useful to reduce the data flow.

A scheme of the overall control architecture is shown in Figure 8. Such scheme seemed to minimize the data flow between master and slaves, which is a very important goal, to the aim of a good performance of the control system.

7 CAN BUS COMMUNICATION

The master communicates with slaves not directly, but by means of a communication bus: this allows a contemporaneous sending and receipt of the data and the commands for all the slaves.
The adopted bus is industrial protocol CAN (Controller Area Network): it is robust (because some bits are devoted to the data check and to the verification of correct transmissions), and versatile (because an identifier exists -ID-, which characterizes not the node but the message, so a message could be sent to many nodes -multi-master-multi slave access-); besides, there are no clashing problems in the bus access, because if two nodes require contemporaneous access, the ID defines the priority (the lower the ID, the higher the priority).

The transmission time depends on the transmission speed, and on the message length. The standard CAN applications (for automotive) work at 500 kbit/s, even if the rated speed is 1 Mbit/s: we chose this value, corresponding to 1 μs per bit. The CAN message is formed by 44 system bits (ID, check, etc.), plus N bytes, with N ≤ 8; in our application, the master send at the most 5 bytes (2 for the i_{r_ref} value of one CO unit, 2 for the i_{r_ref} value of the other CO unit, 1 for the “change the i_{p_ref} value” message), so the longest messages are 84 bits long, and require 84 μs at the rated speed.

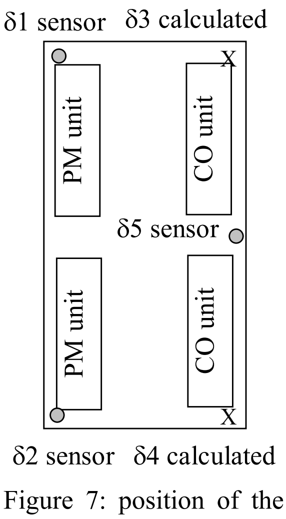

Figure 7: position of the levitation units and of the air gap sensors.

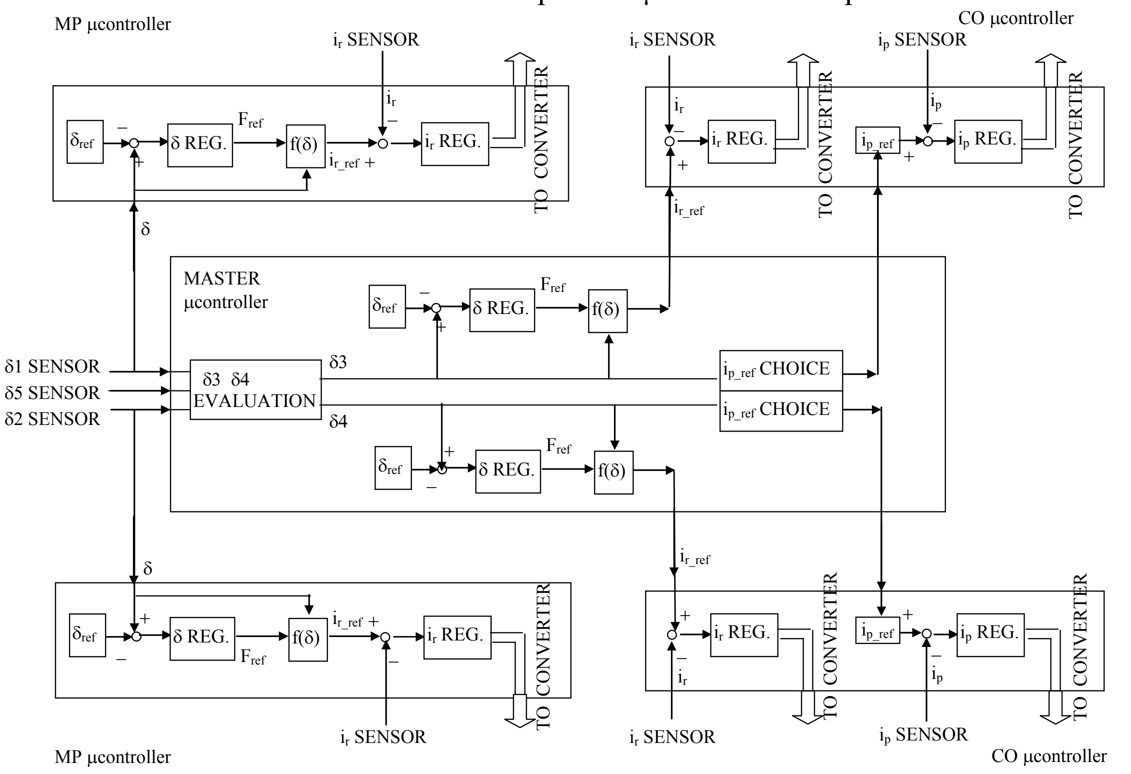

Figure 8: Levitation control system overall architecture.

8 MICROCONTROLLERS

The fundamental micros requirements are:
- computational capability adequate to implement two regulators each one;
- A/D converter with 1÷3 channels;
- capability to drive the converters switches;
- CAN facility.

A micros family that satisfies such requirements is the dsPIC30F family, of Microchip, which is intended for real time motor control applications. The digital signal processing (DSP) features allow multiplications of variables as long as 17 bit, and sums of 40 bit variables. The internal clock is 40 MHz, and with an external oscillator can be brought up to 120 MHz. For our application, we chose a working frequency of 60 MHz, to avoid overheating of the chip.

9 THE SUPPLY SYSTEM

As above explained, the CO levitation units need both a polarization and a regulation mmf, while the PMs units need the regulation mmf only, so (linking in series all the coils of a levitation unit) two power supplies are needed for each CO unit, and one power supply for each PMs unit. As the control scheme shows, all the power supplies operate as current controlled sources: the current regulators operate in such a way to impose the desired current to the coils. The power supplies consist of static converters, fed by a common DC bus, driven by PWM techniques; the polarization current is DC, so a chopper is used; the regulation current can reverse (if the air gap became too small, the regulation coils need to give an opposite mmf respect to the PMs or to the polarization coils), so a two-leg DC-DC converter is used. The switches are IGBT (valves SKM 100 GB, of Semikron), with proper driver (chips IR21844 of International Rectifier), and the switching frequency used is 20kHz. The DC bus is obtained by a three-phase diode rectifier, and DC bus voltage is 60 V. All the supply system (both hardware and software) has been realized in our laboratory.

10 SENSORS AND MEASUREMENTS

Currents are measured by LEMs, whose output (0-5 V) can be directly send to the A/D converter of the microcontrollers.

Air gaps are measured by inductive proximity sensors, which produce a current proportional to the distance, in the range of 5-15 mm; with an adequate shunt resistance, or a proper conditioning, a voltage signal can be obtained in the range of the A/D converter input (0-5 V). To improve the signal stability, both the air gap and current signals have been filtered with a low pass filter.

11 EXPERIMENTAL RESULTS

Up to now, the levitation tests have been carried out separately in each of the two sides of the platform (the PM and the CO side), with the other side mechanically locked. In the PM side, good results were gained: the platform levitates, and has a good response to noise, as shown by the following oscillograms. Figure 9a shows the air gap and its reference, during a start up test: the air gap rise down from 8 to 4 mms in 3 seconds; Figure 9b shows the regulation current and its reference, during the same start up process; in both cases, the reference value is well followed, and the rated value is stable. Figure 10 shows the air gap and the regulation current during a step variation of the weight (a mass is put on and taken away) and some pulses (the platform is hit by a rubber hummer): in both cases, the reference air gap value is quickly restored and is stably kept.

In the CO side, difficulties were found in stabilizing the levitation, due to the mutual coupling between the two coils per pole (polarization and regulation), and/or to the delay introduced by the CAN communication; further tests will be carried out, to investigate the problem: in particular, we want to improve the robustness of the polarization (in such a way that it is not influenced by the variations of both air gap and regulation current), and to adopt a faster communication system.

12 CONCLUSION

A static EMS Levitation test bed has been described, with four six-pole levitation units: two equipped only with copper coils, the others with combined coil-permanent magnet (PM) excitation.

In the coils-only (CO) levitators, two types of coils exist: one with a constant current, which acts as a permanent magnet, and is called polarization coil; the other with a variable current, regulated with the operating conditions, in such a way to maintain the levitation clearance (that is the magnetic air gap) constant; this second type is called regulation coil, and is the only existing in the permanent magnet levitation unit.

The levitation control system has been analyzed. The control loop of a single levitation unit is similar to classical industrial schemes, with two nested loops: an inner loop for force control (magnetic levitation force) and an external one for position control (magnetic levitation gap).

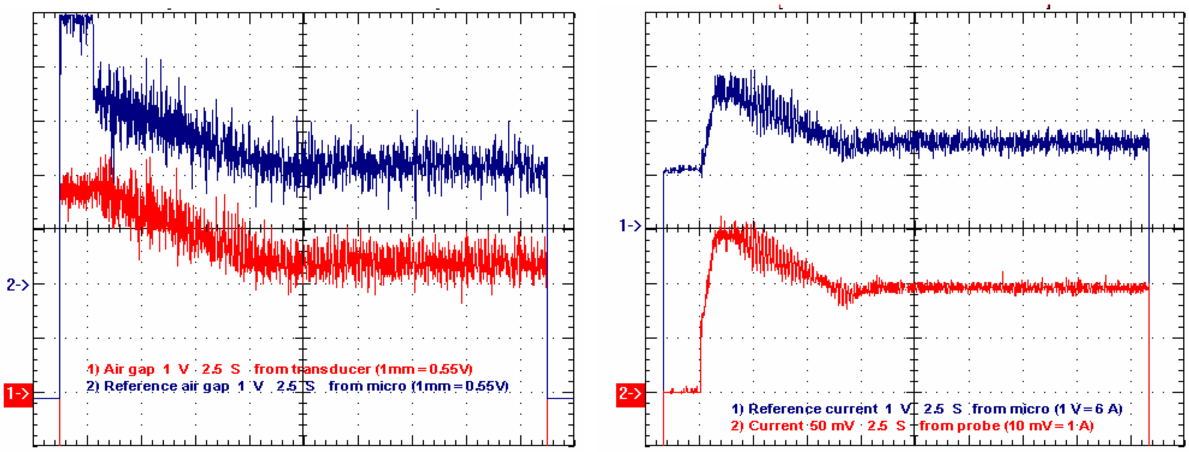

Figure 9: air gap and its reference (left), current and its reference (right), during a start up test

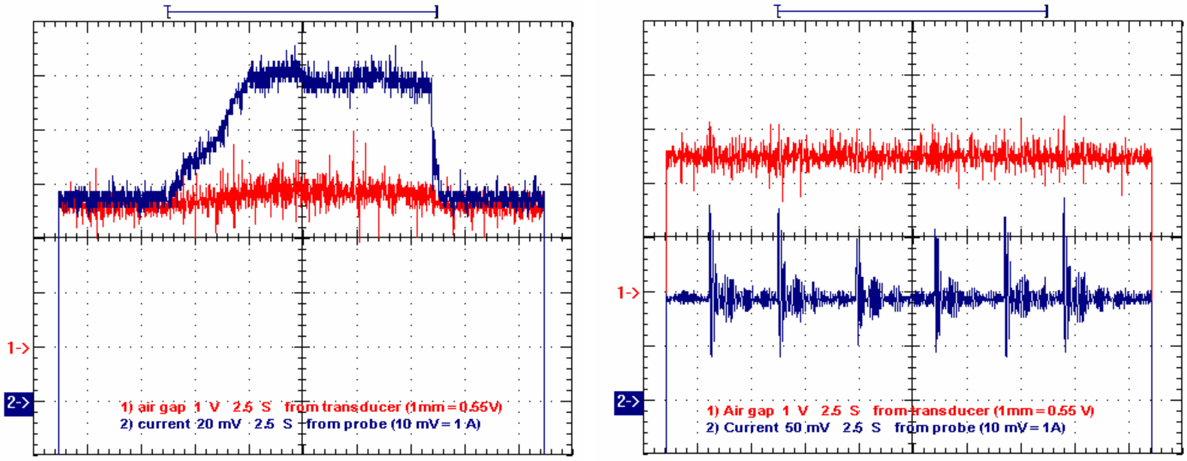

Figure 10: air gap and regulation current during a step variation of the weight (a mass is put on and taken away), left, and during some weight pulses (the platform is hit by a rubber hummer), right.

The force control is gained by regulating the coils current.

The levitation control system architecture is based on 5 microcontrollers (dsPIC30F family), one master and four slaves.

Two slaves implement the whole control loop of the two PM levitators (both air-gap and regulation current regulator), the other two slaves implement both the current regulators (polarization and regulation) of CO levitators; the master implements the air gap regulators for the CO levitators, defines the whole system operating times (start and end of levitation process) and gives the right reference values related to the different operation phases (at start and end of levitation process, air gap varies as a ramp, current varies as a step-wise function).

Such scheme seemed to minimize the data flow between master and slaves, which is a very important goal, to the aim of a good performance of the control system. The master and the slaves communicate via CAN bus.

All the current regulators act directly on static converters, which operate as current controlled sources.

Many experimental tests have been carried out. Up to now, the levitation test have been carried out separately in each of the two sides of the platform (the PM and the CO side), with the other side mechanically locked. In the PM side, good results were gained: the platform levitates, with a good response to noise. In the CO side, difficulties were found in stabilizing the levitation, and other tests are planned to investigate the problem. Then, the next step will be to gain the levitation of the whole platform.

In the future, we want to compare the two excitation solutions (coils alone, and combined coil-permanent magnet), in terms of control performance and power losses.

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