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Laboratory Prototype of Double Frequency Longitudinal Electromagnetic Levitator for Levitation Melting

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Abstract

Longitudinal electromagnetic levitators (LEL) have been proposed and studied for many years. In spite of these studies the configuration with double frequency supply has been taken into consideration only in few papers. Aim of this work is the presentation of some new results obtained at the Laboratory for Electroheat of Padua University by numerical calculations and experiments on a double frequency LEL prototype.

Introduction

Longitudinal electromagnetic levitators consist of a set of exciting conductors, parallel to the axis of a non-magnetic cylindrical levitating load, carrying large high-frequency currents [1,2,3]. The exciting conductors are constituted by copper tubes appropriately end-connected in order to give rise to a convenient alternating electromagnetic field distribution. The currents induced in the cylindrical load by this field, interacting with it, generate Lorentz forces that support the sample against gravity and at the same time produce its heating due to Joule losses. The two phenomena (levitation and heating) are closely coupled together, but different optimum frequency values exist for each of them corresponding to their maximum intensity [4]. The existence of these distinct optimum values offers the possibility of designing levitation systems with separated heating and levitating coils excited at two different frequencies which optimise the heating and the levitation effects respectively.

At the Laboratory for Electroheat of Padua University (LEP) longitudinal electromagnetic levitators have been studied in the last years. A single frequency laboratory prototype has been first analysed and constructed and preliminary studies of a double-frequency LEL have been developed [5,6,7].

This prototype has been now modified in order to be able of supplying different levitation and heating conductors with two frequency values with the aim of verifying by experiments the reliability of the calculation models for LEL design purposes and obtaining general guidelines for the design and optimisation of a new prototype with double-frequency excitation.

1. Laboratory prototype and geometry used for calculations

The laboratory prototype available at LEP, already described in [5], corresponds to the basic geometry of the exciting conductors and the experimental set-up shown in figure 1; they are made of water cooled copper tubes 6x6x2 mm cross-section, whose barycenter positions – with reference to an origin placed on the symmetry axis and the upper surface of the lower conductors – are given by the coordinates given in table I.

This prototype has been modified in order to be able of using conductors 1-1’ and 2-2’ for levitation and 3-3’ as heating coil. According to the frequency converters available in the laboratory, during the tests the levitation coil has been supplied with currents up to 3000 A at 10 kHz and the heating one up to 1000 A at 450 kHz. However, different current and frequency values have been also considered in the calculations in order to optimise the levitation force.

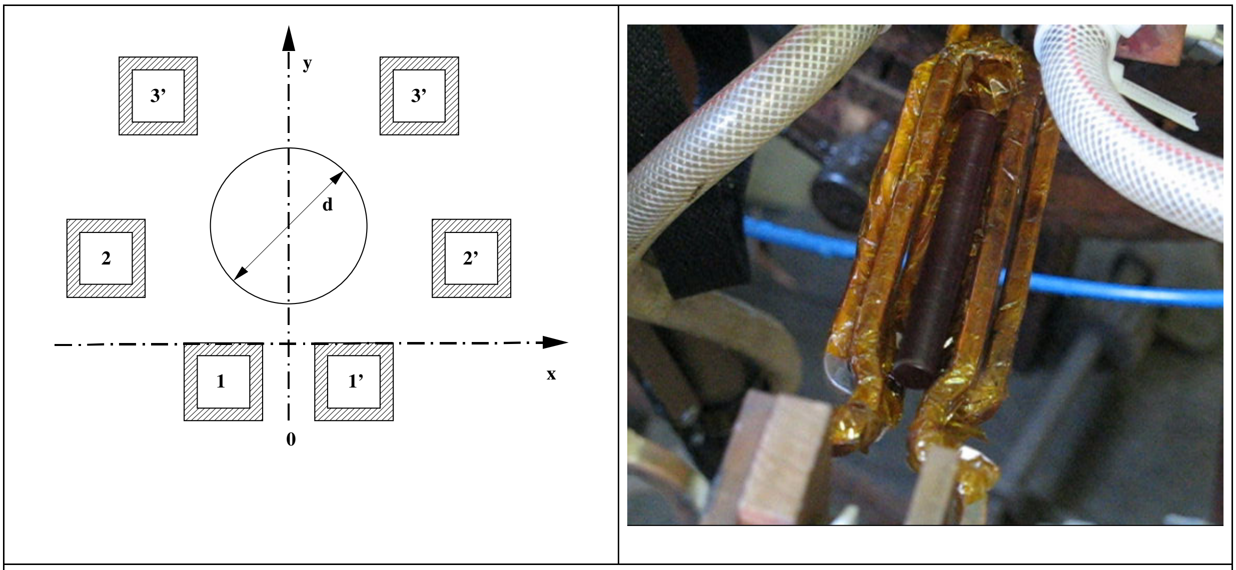

Fig. 1 – *LEL prototype: basic geometry and experimental set-up*

Table I – *Coordinates of exciting conductors*

Conductor barycenter	1	1’	2	2’	3	3’
x [mm]	- 6.0	+ 6.0	- 17.0	+ 17.0	- 12.0	+ 12.0
y [mm]	- 3.0	- 3.0	+ 6.0	+ 6.0	+ 18.5	+ 18.5

Moreover, due to the original LEL construction, tests have been performed with the current directions in the levitation coils indicated in fig. 2-a); but other exciting conditions are being also analysed.

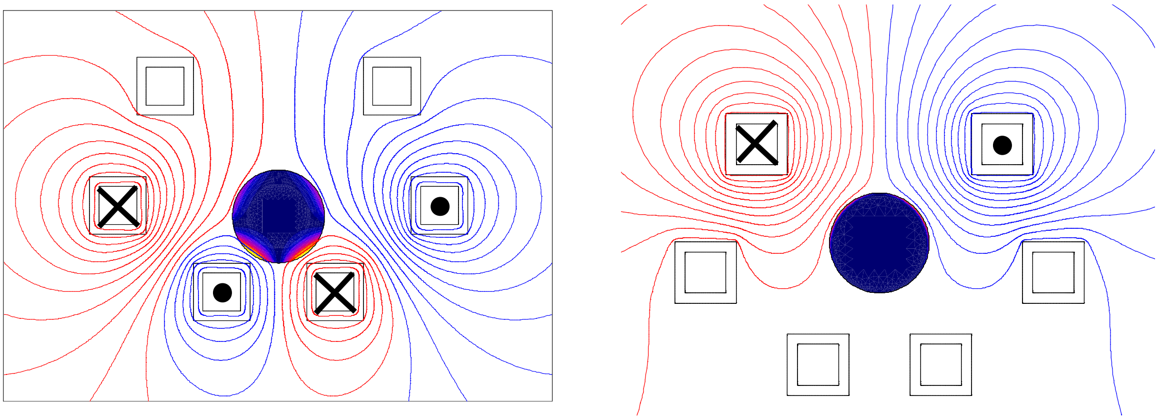

Fig. 2 – *Typical magnetic field pattern in the levitation (a) and heating (b) coils*

2. Calculation and test results

The calculations have been performed neglecting the levitator and billet end effects by a 2D FEM programme. The eddy current problem has been solved assuming that the currents flow in a direction normal to the study domain and consequently that the magnetic field has a negligible component on that direction.

The finite element method applies vector magnetic potential coupled with electric scalar potential to solve the electromagnetic problem. The computation of the average value over a time period of the electrodynamic forces has been made by means of virtual work method, and consequently the ‘x’ and ‘y’ components have been computed through:

$$\vec{F}_x = -\frac{\partial Wm}{\partial x}\vec{u}_x \qquad\qquad \vec{F}_y = -\frac{\partial Wm}{\partial y}\vec{u}_y$$

where Wm is the magnetic energy stored in the system, ∂x , ∂y are the virtual displacements and $\vec{u}_X$, $\vec{u}_Y$ are the space unit vector.

Tests and calculations have been done with reference to a specimen constituted by a aluminum cylindrical specimen 10 mm diameter, 80 mm length.

The lifting force has been calculated, with exciting currents in the levitation coil of 1000 – 2000 - 3000 A and 800 – 1000 A in the heating one, as a function of the position of the billet, the resistivity variations of aluminium with temperature and the frequency of the LF levitation currents.

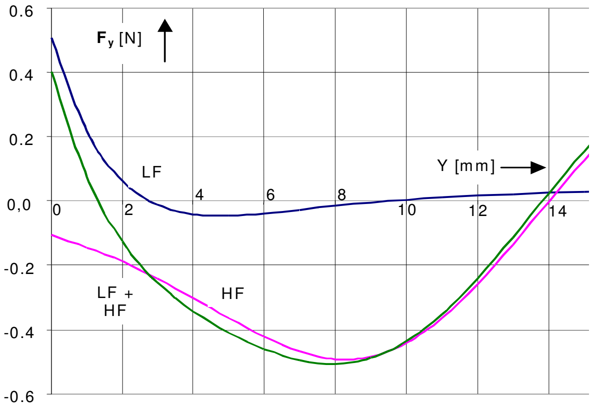

Fig. 3-a – *Vertical components of LF and HF forces as a function of the specimen vertical position [I_{LF}=I_{HF}=1 kA; ρ=5 $\mu\Omega$·cm]*

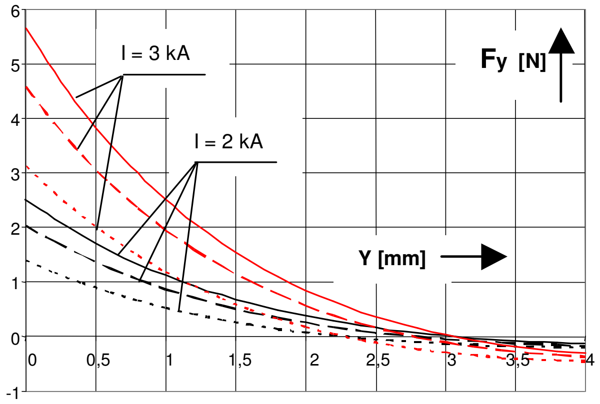

Fig. 3-b – *Vertical component of LF force as a function of the specimen vertical position, for different resistivity values [I_{LF}=2-3 kA; ρ=2.7-5.0-9.77 $\mu\Omega$·cm]*

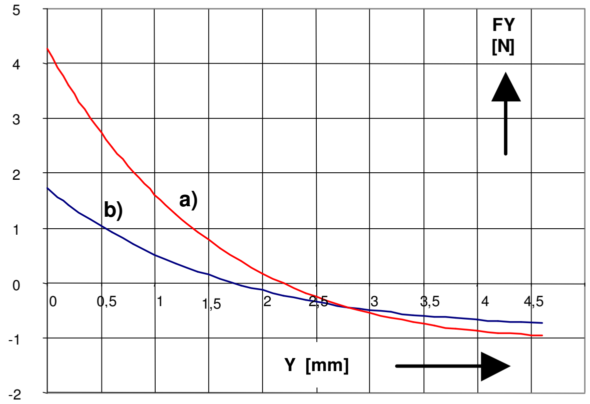

Fig. 3-c – *Resulting vertical force (sum of LF, HF components and specimen mass) as a function of the billet vertical position [I_{HF}=1 kA; I_{LF}=2 kA (curve b) - 3 kA (curve a); ρ=5 $\mu\Omega$·cm]*

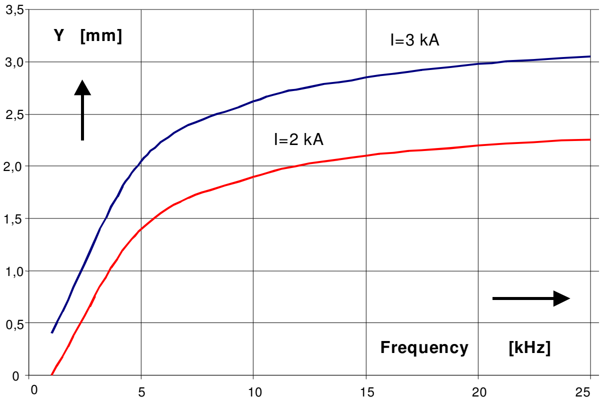

Fig. 4 – *Equilibrium position of the specimen as a function of frequency of the LF current [I_{HF}=1 kA; I_{LF}=2-3 kA; ρ=5 $\mu\Omega$·cm]*

The diagram of figure 3-a shows the variation of the vertical component of forces acting on the billett, due to the levitation (LF) and the heating currents (HF) respectively, as a function of the vertical billet position. The curves refer to LF and HF current intensities of 1000 A; they show that at these current values the resulting force gives an equilibrium levitation position too low, very near to the lower exciting conductors.

For this reason, only levitation current intensities in the range 2000÷3000 A have been considered; the corresponding vertical component of the LF force is given in figure 3-b, for different resistivity values (corresponding to different billet temperatures), as a function of the specimen vertical position.

Taking into account the HF component of the force (given in figure 3-a) and the specimen mass, this means that the equilibrium position will change in a very narrow range during heating also with relatively high variations of the LF current (figure 3-c).

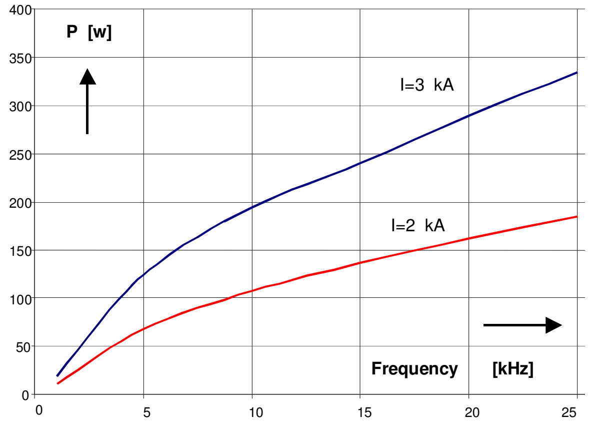

Fig. 5-a – *Power induced in the specimen by the LF currents as a function of frequency at equilibrium positions [ρ=5 $\mu\Omega$·cm]*

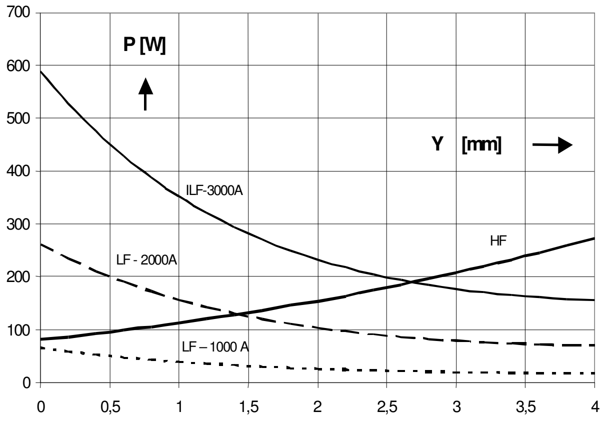

Fig. 5-b – *Power induced in the specimen by LF and HF currents as a function of the vertical position [I_{HF}=1 kA; I_{LF}=1-2-3 kA; ρ=5 $\mu\Omega$·cm]*

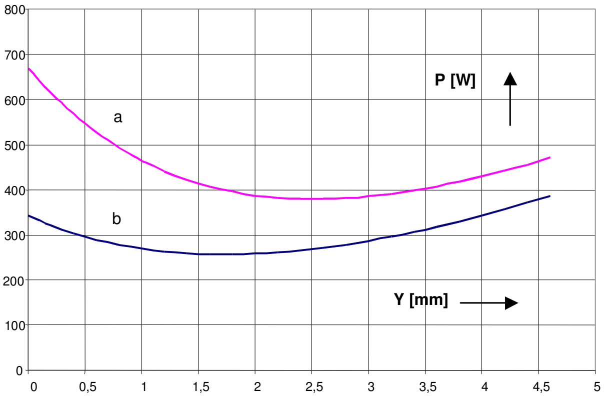

Fig 5-c – *Total induced power as a function of the billet vertical position [I_{HF}=1 kA; I_{LF}=2 kA (curve b) -3 kA (curve a); ρ=5 $\mu\Omega$·cm]*

This is confirmed by the curves of figure 4, which give the equilibrium position of the specimen as a function of the frequency of the levitation currents.

Moreover, the choice of the frequency of the levitation current - also if dictated by the frequency converter available at LEP - appears to be appropriate since, as indicated by the curves of figure 5-a, it gives a substantial contribution to the power transferred to the workpiece.

The diagrams of figure 5-b, show the relative contributions of the HF and LF currents to the power induced into the billet, as a function of the billet vertical position, at different LF current intensities: as the vertical position increases, the LF power decreases but a higher HF power is dissipated in the load. There is therefore a region where – at constant LF current - a low variation of the equilibrium position will not influence significantly the total power induced into the specimen (see figure 5-c).

These values of induced total power have been checked by tests comparing calculated and experimental values of the melting times of the billet.

The experimental data, given in table II, refer to the total induced power and melting times obtained with I_{HF}=0.8 kA; I_{LF}=1-2-3 kA and specimens with normal or blackened surface.

Table II – *Melting times and induced power for different LF currents [I_{HF}=0.8 kA]*

I_{LF} [A]	T_{NORMAL} [s]	$T_{BLACKENED}$ [s]	P [w]
1000	50	54	≈ 235
2000	36.2	38.5	≈ 300
3000	31.0	32.5	≈ 380

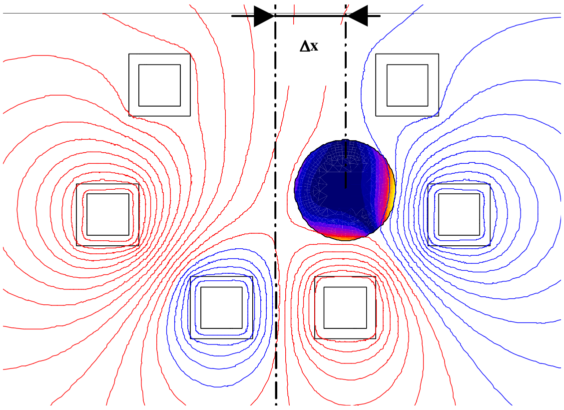

Fig. 6-a – *Example of magnetic field pattern and induced power with billet shifted laterally in x direction of Δx from the y axis*

The variation of melting times corresponds to the different surface emissivity conditions of the specimens.

Taking into account the approximations introduced by the use of a 2D model and the specimen vertical oscillations around the equilibrium position experienced during tests, the agreement between theoretical and experimental data can be considered very good.

The horizontal stability has also been analysed, calculating the component F_x of the force acting on the specimen when it is shifted laterally in x direction of a quantity Δx, as sketched in figure 6-a.

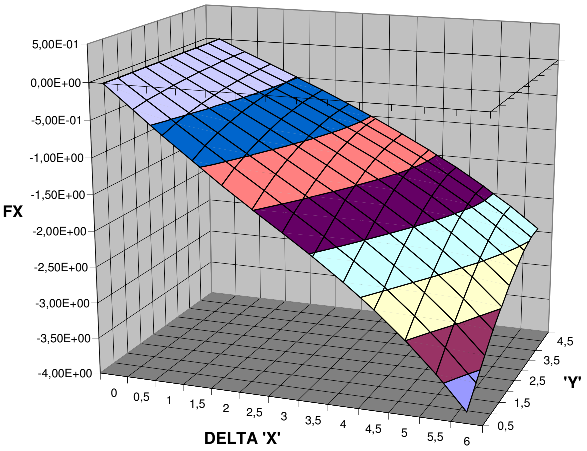

Fig. 6-b – *Force component F_x as a function of the displacement Δx from the y axis and the billet vertical position y [I_{HF}=1 kA; I_{LF}=2 kA; ρ=5 $\mu\Omega\cdot$cm]*

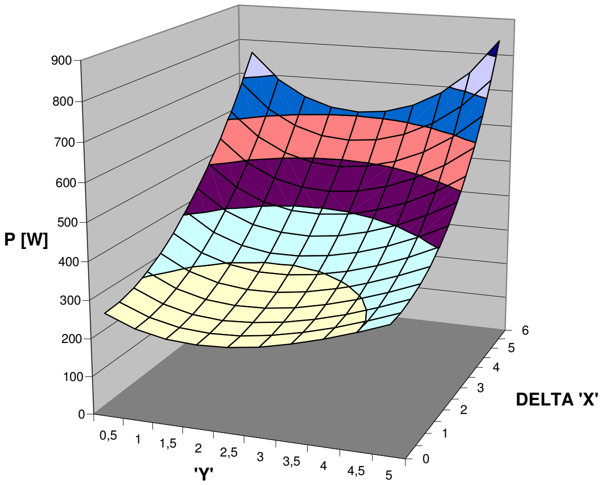

Fig. 6-c – *Total power P induced in the billet as a function of the displacement Δx from the y axis and the billet vertical position y [data as in fig. 6-b]*

As shown in figure 6-b, calculated with LF current of 2 kA and HF current 1 kA, the force is always negative for every value of y, pushing the billet towards the y axis with a force intensity increasing as Δx increases.

The corresponding total power values induced in the billet for the same conditions are given in figure 6-c: for Δx=0 the diagram gives the same values of the curve a) of figure 5-c. Moreover, it shows again the different influence of the LF and HF coils as the position y varies.

Conclusions

In the paper the characteristics of a laboratory prototype of a double frequency longitudinal electromagnetic levitator for metals levitation melting have been analysed. The levitator is characterised by separate levitation and heating coils excited with currents at two different frequencies.

A FEM calculation model has been developed and used for predicting the lifting forces and the induced power in the levitating load.

A number of laboratory experiments has been performed for testing the reliability of the model for the design of such kind of electromagnetic devices.

The model is presently used for the theoretical analysis of different LEL geometries and the design of a new LEL capable of melting higher mass loads.

References

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