Validation of a Linear Motor for Hyperloop Applications using a 3-axis Static Test Bench

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***Abstract*— In this paper, a static test bench to characterize the performance of a linear motor designed for a hyperloop system is proposed. This bench allows a 3D movement of the traslator in order to take measurements on all the states that the system can reach. The results from the conducted test have demonstrated a low deviation between the experimental and simulated value of the forces.**

Keywords—hyperloop, linear motor, static test, 3-dof

I. INTRODUCTION

Hyperloop, a new mode of transportation, is gaining significance. It consists of the use of a ground-based transportation system which includes a levitation system that avoids rolling friction forces, and which has been covered with a tube, controlling the inner atmosphere lowering the aerodynamic drag forces [1]. Thus, hyperloop is proposed as a solution to the current limitation in ground transportation due to rolling and aerodynamic problems.

Zeleros is one of the companies developing technology for hyperloop application worldwide. One of these technologies consists of linear motors to propel the capsules on certain parts of the route.

After designing the linear motor and simulating its performance, an experimental validation is required. One of the tests is described in this paper, in which a static bench has been developed to measure forces, currents and, losses before performing dynamic tests.

This bench includes a simplified model of the real scale lineal motor, using the same input power and dimensions, but with only one module. The actual power to propel the real hyperloop capsule will require several of these modules.

Several designs of static test bench have been published [2-5], but none of them allow measuring the three force components in the traslator, which is necessary to evaluate dynamic behavior of the vehicle.

The present work aims to describe the test bench used, to expose the results obtained and to compare them with results from electromagnetic simulations. Also, the values obtained from the test and the simulation will be discussed in order to expose the behavior of this machine.

This paper is divided as follows. In the second section the methodology for the test is described. Later, third section presents the results and its discussion. Finally, fourth section draws some relevant conclusions from the work.

II. METHODOLOGY

A conceptual sketch of the test bench presented in this manuscript is shown in Fig. 1. While the stator is attached to a structure, the traslator can move in the longitudinal (X), lateral (Y), and vertical (Z) directions. Using a 3-degree of freedom movement system, the traslator can be placed in an accurate XYZ space. Laser distance sensors of ±0.01 mm accuracy are used to calibrate the position of the system.

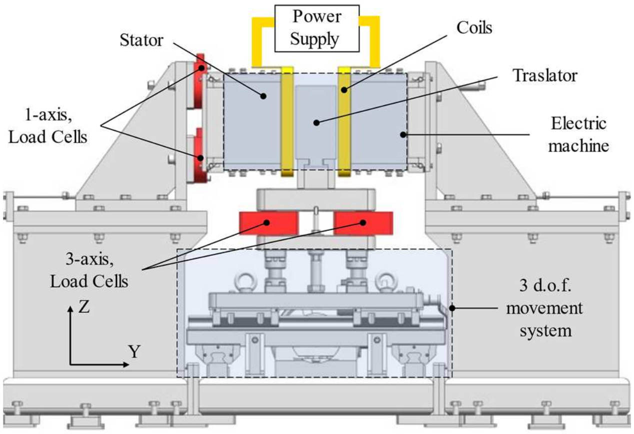

Fig. 1. Main parts of the static bench.

Regarding the energy supply, a power electronics circuit (shown in Fig. 2) allows discharging the electric current through the stator coils. Several supercapacitors are installed to reach the required currents, controlling them using IGBTs modules.

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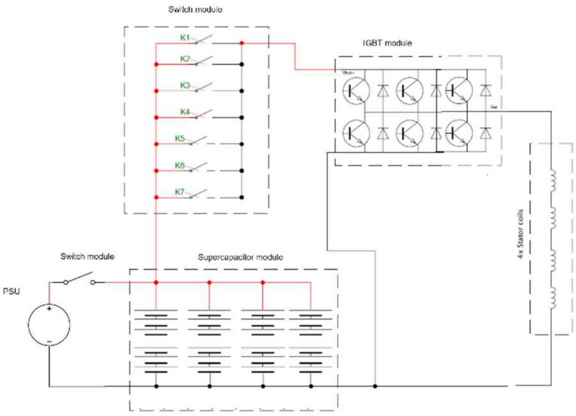

Fig. 2. Power electronics circuit diagram.

Measures of traslator and stator forces are obtained via 3-axis (PM instrumentation K3D160) and 1-axis (AEP TC4) load cell sensors, respectively. Temperature, magnetic field, voltage, and current measures are also taken on the power supply, the IGBTs and the coils. The acquisition is performed by a NI compactRio FPGA through 16 bits NI-9220 and NI-9215 modules and logged at 100 Hz. It is important to highlight that the weight of the system is compensated via software to ensure accurate measurements.

Finally, a real image of the bench is shown in Fig. 3.

Fig. 3. Photo of the test bench.

Regarding the electromagnetic machine, the bench includes the minimum number of elements that can close the designed magnetic circuit, as shown in Fig. 4.

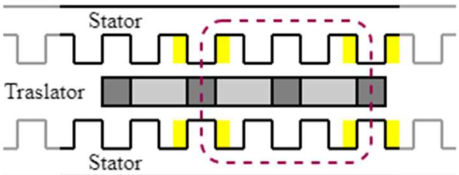

Fig. 4. Minimum number of elements to close the magnetic circuit.

In the present paper, only results moving the traslator in the longitudinal X direction are presented. This is named as the "displacement" and ranges in relative terms from 0 to 1. The displacement is referred to the position of the traslator tooth with respect to the stator one. The furthest separation corresponds to 0 displacement while, when both teeth are aligned, the displacement is equal to 1. This is graphically shown in Fig. 5.

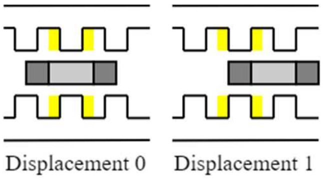

Fig. 5. Definition of the relative position of the traslator.

To have certainty on the results, electromagnetic simulations of the same set-up have been conducted using the software ANSYS® Electromagnetics Suite. Contours of the magnetic flux are shown in Fig. 6. The forces obtained from these simulations are discussed in the next section.

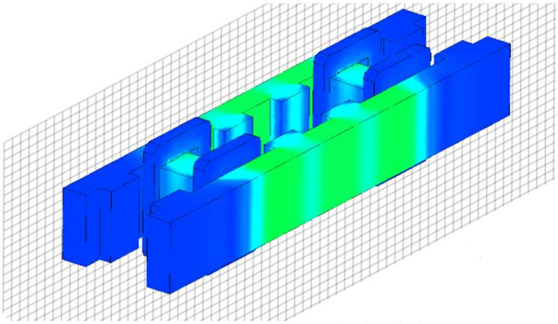

Fig. 6. Magnetic flux from the electromagnetic simulation.

III. RESULTS

Several tests have been performed. As stated previously, these tests are used to validate the simulation forces. They are also used to validate the assembly process and the geometrical tolerances of the whole system, as the performance of this machine is highly affected by the position of the traslator.

Firstly, for each one of the traslator displacements (named as x), the thrust (or longitudinal X force) is obtained for different input currents. The results from the simulation and the test are compared in Fig. 7.

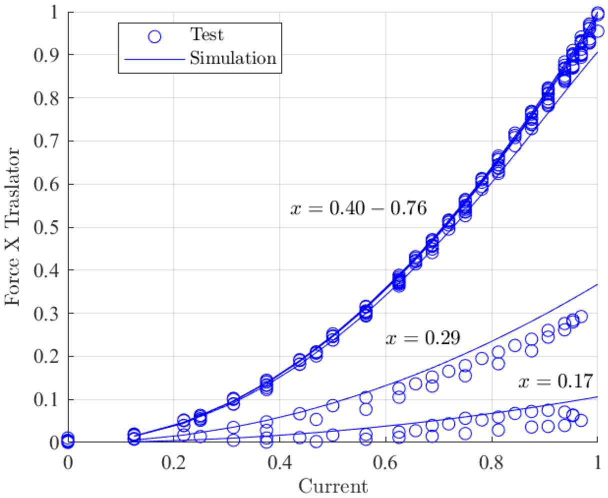

Fig. 7. Comparison of the force in X direction of the traslator.

From the figure, one can conclude that the accuracy of the simulation is larger when the thrust force increases, which corresponds to higher relative displacements. Lower values have larger experimental dispersion, mainly due to the lower accuracy of the load cells on this range. Also note that the non-linear increase of the thrust force with respect to the current is properly reproduced by both methods.

Another test has been conducted is to compare the traslator forces in X and Y direction for the maximum thrust displacement. This is plotted in Fig. 8, which shows that the accuracy of the lateral Y force is slightly lower. Equivalently to the thrust force, the lateral one follows a parabolic trend.

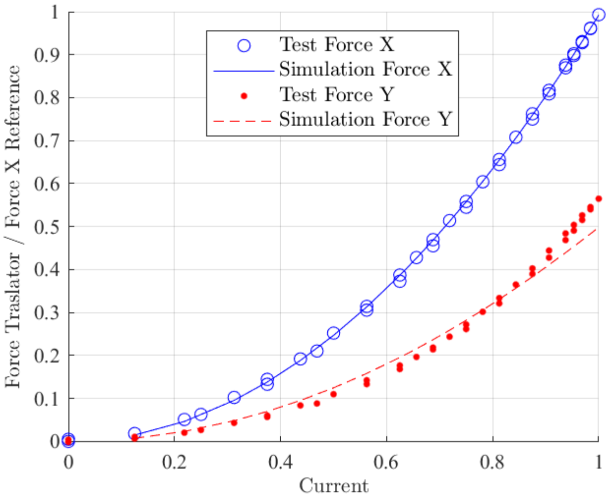

Fig. 8. Traslator forces for maximum thrust displacement.

Then, for the maximum input current, Fig. 9 compares the X and Y force in the whole displacement range.

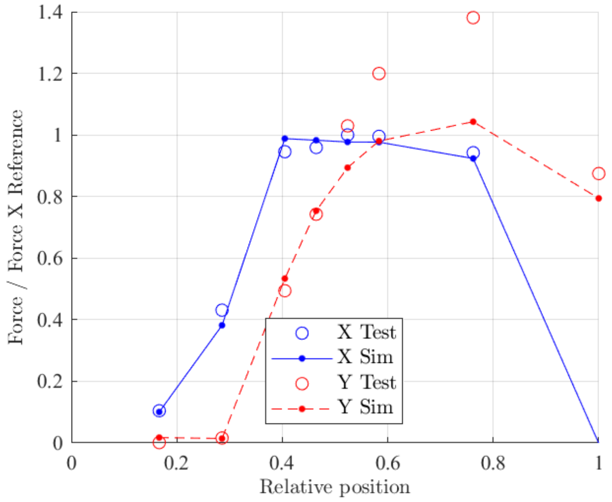

Fig. 9. Traslator forces with respect to displacement.

It can be seen that the force in Y direction is similar to the one in the X direction, although the simulation does not fit properly the results. This is due to tolerances on the assembly that provoke a difference on the traslator position from the one on the theoretical simulation. This difference on the airgap affects significatively more the force on the lateral direction rather than the thrust.

Another effect that can be appreciated is that, during approximately 40% of the displacement range, the value of the thrust is approximately constant, which considerably helps to reduce the ripple of the coupled force when operating this system dynamically, as in this case several coils have to be activated in sequence in order to provide a net thrust to the traslator. Also note that the lateral force is less planar than the former, having its maximum at a 0.8 displacement.

Then, it is compared the forces on the stator in the only direction that the load cell allows measuring, the Y axis. This magnitude is plotted in Fig. 10. For the stator, the test and simulation predict similar values. As it can be seen, the trend of this force is different from the one on the stator, as, instead of a sinusoid, this force follows a double parabola whose maximum occurs when the teeth are aligned.

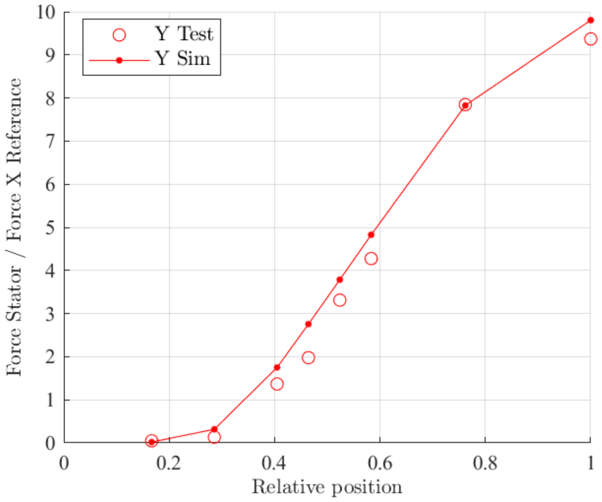

Fig. 10. Stator force with respect to displacement.

Finally, the Y force on the stator with respect to the one on the traslator are compared in Fig. 11. It can be seen that the double-side configuration of the motor allows decreasing considerably the lateral forces. Around the position of maximum thrust, the force on the traslator is 40% the one on the stator. This ratio is reduced to even less than an order of magnitude (10%) when the teeth are aligned. This effect helps reducing the loads on the vehicle that mounts the traslator.

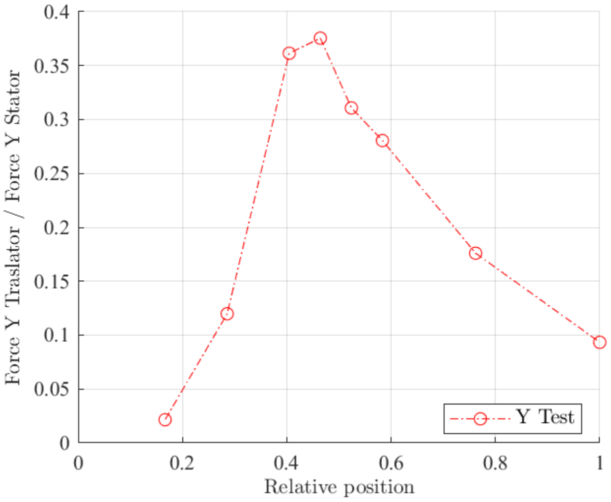

Fig. 11. Stator and traslator Y force comparison for the test.

Apart from discussing the measures from the load cells, the losses due to Joule effects will be inferred. The heating of the coils when they are activated means that their resistance increases, enlarging even more the heat losses. Also, it is important to know if the design voltage is enough to obtain the current due to the increase in the resistance during the process, and not only in the initial state. Furthermore, to reduce the overall weight of the system, aluminum wires are employed which implies higher resistances. During the tests, the closed loop current control compensates these effects.

On the other hand, the way the coils are connected affects the overall system. A large number of magnets means numerous points in which electrical losses can be significant. It is important to check these connections, minimizing voltage drops. The tests conducted show that the voltage drops are within the expected limits, therefore, validation of the connections is achieved.

By his part, the inductance is one of the key parameters of the system. The dynamics of the coils will determine if the target current can be achieved in the required times. The tested coils have small inductances around 17 µH at 1 kHz. However, due to the high input currents and circuit capacitances, phenomena such as back EMF among others, must be taken into account in the power electronics design.

On the other hand, the mechanical tolerances are also a relevant part of the system as they directly affect the performance. Particularly, the airgap affects the inductance and the value of the measured forces. A maximum deviation of 0.35 mm of the airgap compared to the one set on the simulation has been measured, which ensures the validity of the results.

It is important to highlight that the forces in Z direction, although they are measured, they are not relevant unless the traslator is moved vertically. This is the reason why these forces have not been presented in this paper.

IV. CONCLUSIONS

Different tests on a 3-dof static test bench for a linear motor have been successfully completed.

The tests have been focused on measuring the thrust and lateral forces on the traslator and the stator. The main conclusion is that, overall, the fitting of the numerical forces with the experiments is quite satisfactory. The only magnitude that has not been accurately reproduced on the whole range is the traslator force in the Y direction due to the geometric tolerances of the assembly. Also, for lower values of the forces, the dispersion on the experimental values is quite high as the resolution of the load cell on this region is not acceptable.

One phenomenon checked is that the thrust force on the traslator is unaffected by the mechanical tolerances of the assembly, opposite to what happens on the lateral ones.

The thrust force has a more planar shape with respect to the longitudinal displacement than the lateral one, having its maximum between 0.4 and 0.8 displacement. This helps to reduce the ripple in the X direction.

Several differences are appreciated on the lateral force. Firstly, the double-side configuration allows reducing the magnitude on the traslator with respect to the stator at least a 60% at the maximum thrust displacement. It can be reduced even more than a 90% when the teeth are aligned or completely misaligned. Also, the maximum value of this force occurs at 0.8 on the traslator and at 1.0 on the stator.

Finally, the successful completion of the tests means that the linear motor has reached a TRL-4 state in a laboratory environment. This demonstrates the feasibility for a hyperloop application, as the expected forces in simulation have been obtained. Further testing characterizing the dynamic behavior of the system will be conducted to reach TRL-5 or further.

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