Design and Simulation of an Electromagnetic Aircraft Launch System

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Abstract- Electric actuators are increasingly supplanting or replacing mechanical actuators (steam or hydraulic) in ship systems. This trend started in commercial shipping, especially cruise ships, and there is now a move to adopt the benefits in military systems [1]. This paper describes the design and analysis of a very large actuator for a military ship system -- an Electro-Magnetic Aircraft Launching System, or EMALS, which will accelerate aircraft to flight speeds in very short distances.

The aim is to replace the steam catapult currently used on aircraft carriers with a linear electric motor. The entire system should fit within the confines of the existing steam catapult. The advantages of such a system are increased operational availability, lower airframe stress due to programmable acceleration profiles, and reduced maintenance (and hence reduced manning). The goal of the study described here is to investigate the many feasible solutions and to use simulations to compare their performance.

This paper reports on the initial stages of the work which uses the Virtual Test Bed (VTB) as the simulation and virtual prototyping environment. This yields substantial side benefits because the EMALS research program represents a meaningful test case for the VTB itself. Models of the different parts of the systems are being built up from the specifications and the characteristics required by the U.S. Navy, and will be refined with increasing detail as the project is developed.

I. INTRODUCTION

The design of an EMALS has many intriguing challenges. The desired specifications and technical features include:

Goal velocity:	200 kt	102 m/s
Power stroke:	310 ft	94.5 m
Goal energy:	122 MJ	
Goal thrust:	1.29 MN	

A typical launch might be for a 25000 kg aircraft accelerated to 150 kt in 2.7 s, at an acceleration of 2.8 g. This represents a total energy of 70 MJ.

Acceleration to the goal velocity represents a 2 s stroke, at a constant acceleration of 5 g.

Optimal solutions have not yet been determined, but many general characteristics of the system have been explored, and productive regions bounded. For the purposes of the study, the overall EMALS has been partitioned into the following subsystems:

- The primary electromechanical energy converter. This is the “motor“ itself where forces are generated by the interaction of electro-magnetic fields.
- Energy storage: This subsystem must deliver power at up to 61 MW for 2 seconds, and must accept power at a maximum rate of 7.5 MW over a minimum recharge time of 50 seconds. Likely candidates are ultracapacitors or flywheels. SMES is also being considered. [2]
- The energy storage interface system. This provides the connection with the ship power grid to charge the energy storage subsystem.
- The power conditioning subsystem: This power electronics system directs the stored energy to the launch motor in conjunction with a feedback control system
- Peripheral subsystems: These include a tensioning subsystem, a brake subsystem, a retraction subsystem, a launch control/interface sub-system which is the user interface and directs the system control to meet the performance requirements of EMALS).

Currently the authors are developing several different versions of this system and conducting simulation tests in the VTB environment. In the rest of paper some elements of the design and the innovative approach adopted for modeling the linear motor system will be introduced.

II. MODELING IN VTB

The VTB software is an infrastructure that supports virtual prototyping of next generation electric systems such as the propulsion systems for an all electric ship [3]. The aim of this work is to use VTB to answer a wide range of questions such as:

- Among all the possible motor technologies (induction, super-conducting coil, permanent magnet), and geometries , which best fits the technical requirements?

- What is the ideal layout of the magnetic field components and the current carrying components? Which part should move and which should be stationary?
- What topologies, devices, and redundant structures should be used in the power conditioning subsystem?
- What are the detailed parameters of the machine, including physical dimensions, number of phases?, and so on

The VTB enables construction of simulations via a modular architecture. This allows rapid exploration of many system configurations, with many permutations of linear machine types, converter types, and energy storage types. The project will take advantage of all the main features of the VTB environment, i.e.:

- multiformalism: the possibility to describe any model using the most appropriate input language (such as ACSL, Simulink, SPICE, etc.)
- high level graphic visualization (see Figure 1)
- object-oriented system definition and connectivity

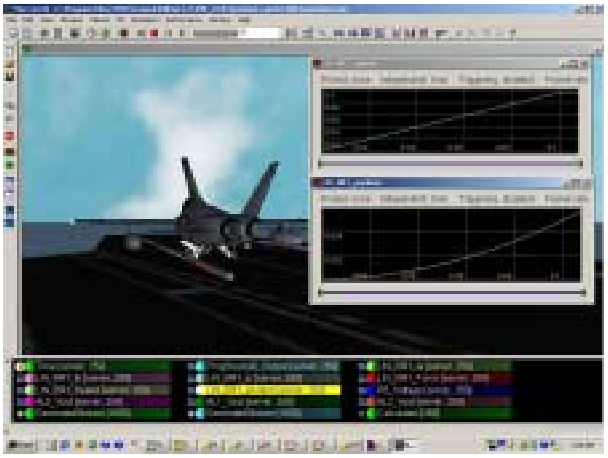

Figure 1: A simulation result from VTB

III. LINEAR MACHINE DESIGN

The generic format considered is a transverse flux linear machine having a double sided stator [4]. A significant early choice is to have the armature or current carrying windings stationary and the field or induction grid on the moving part, referred to as the shuttle. This design avoids sliding contacts, but implies that either the complete winding or large sections of the winding must be energized at the same time. This has a serious impact on the power electronics system since large inductances must be driven.

Two basic shuttle geometries were considered, an "inverted U" and a "blade" (see Figure 2). Either shuttle geometry can be implemented using an induction grid, a permanent magnet array or an array of wound field coils. These last would need a cryogenic cooling system. Thus the motor can have any of three configurations:

- a linear induction motor,
- a permanent magnet motor, or
- a wound field synchronous motor.

In the "inverted U" configuration the shuttle must provide the return path for the magnetic flux.. The overall system weight is low, but the steel that closes the magnet circuit is on the shuttle so the moving mass is high. This mass presents problems with respect to stopping the shuttle from the speed of ~ 100 m/s, in only 10 meters. Ideally this would be done electrically, but eg with permanent magnets, the shuttle mass is ~ 10 tonnes so a substantial friction brake is required to absorb the 50 MJ of stored energy in 10 m..

In the blade shuttle configuration the return steel is on the stationary part of the motor. The total system mass is higher, but the steel mass provides a wonderfully effective thermal reservoir, which suits the intermittent nature of this system in operation. No active cooling is required. Further the blade is relatively light (~1 tonne) so the braking system can be electrical.

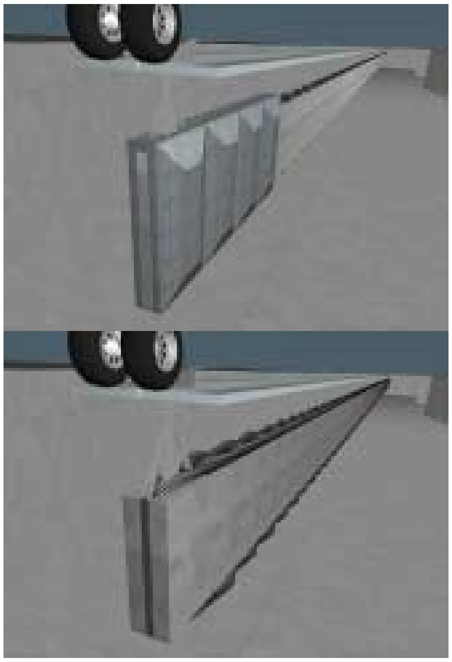

Figure 2: the two options for the linear machine in the simulated 3D environment: a) inverted U and b) blade

The machine design used for the first simulations is detailed elsewhere. [5] [6] The important parameters for this discussion are however that a 3 phase system is used, wound at one slot per pole per phase, with a pole pitch of 150 mm, and a slot length of 1 metre. The slots are 25 mm wide by 50 mm deep, which results in an inductance in the slot for a single conductor of 2.6 µH / metre. Current ratings of available semiconductors dictate a 4 turn winding. The available semiconductors, and likely bus voltages are not capable of driving the complete 100 metres of such a 3 phase winding at the speeds required. This results in a modular design where the track is sectioned, initially into 12 sections, where the first section is 15 metres in length and the last 5.

IV. POWER ELECTRONIC SYSTEM

The power electronic system will be modular, as discussed above, with an individual 4 kV 4.5 kA H bridge for each turn in each phase in each section Thus a total of 12 H bridges is required to drive a section. This has the extra benefit of guaranteeing reliability through a very high level of redundancy. The possibility of using separate energy storage for each H bridge or subgroup of bridges is also under consideration. An inner current control loop will guarantee the actuation according to the information coming from the torque (force) reference and the position sensors.

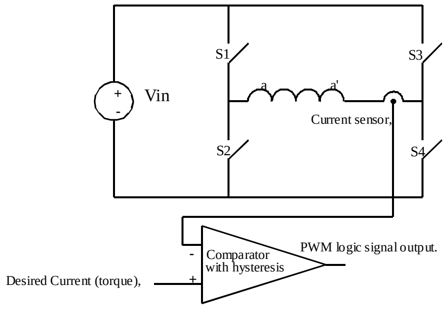

Figure 3: The H bridge for individual coil current control

V. MODELING ACTIVITY

The authors are currently developing models for all of the individual system components. Some preliminary simulation results are already available as well as a simulation-driven animation of the 3D system showing the obtainable performance. Effort is currently being concentrated on the permanent magnet brushless motor case.

A. *Machine modeling*

A standard d-q model was developed [7]. For such a machine. In order to replicate the modularity of the motor in the modeling structure an original approach to the model formulation was adopted.

The model architecture has two separate parts:

- The stator winding model
- The shuttle model

The system is designed so that any set of independent stator models can be connected to a single shuttle.

The stator model represents the current in a single winding and it defines the force contribution of that stage to the overall system force.

The superposition theorem is applied in the shuttle model to sum the force generated by each module and then to solve the mechanical equations for speed and position. This information is sent back to the stator modules in order to evaluate the electromotive force.

The equivalent circuit of the stator model is illustrated in Figure 4.

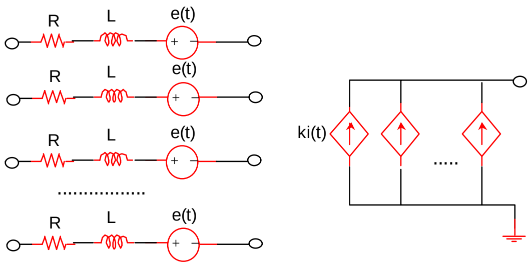

Figure 4: The equivalent circuit of the stator model

Each winding is represented with its equivalent circuit: considering that the design suggested 4 turns for each phase, the model is able to represent 12 independent circuits for any single module.

The evaluation of the electromotive force and the mechanical force coefficient is based on the mechanical position and velocity. First of all a check is performed to evaluate if the slider is over the module, so that the action of the permanent magnet is present, and then a check of the position within the module determines the specific values.

The mechanical system is modeled through the equivalent circuit shown in Figure 5.

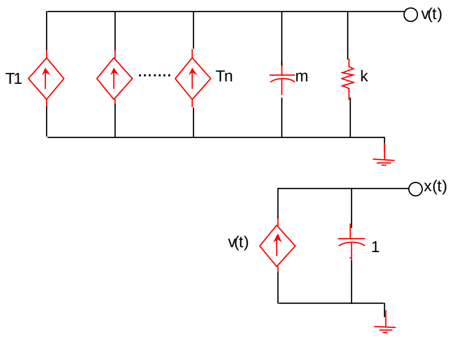

Figure 5: The equivalent circuit of the mechanical part

In this circuit we have two separate sections: the speed calculation obtained by summing the force from all the modules and the position calculation obtained as a pure integration.

A set of tests were performed to validate the modeling approach.

The results of the first test are illustrated in Figure 6.

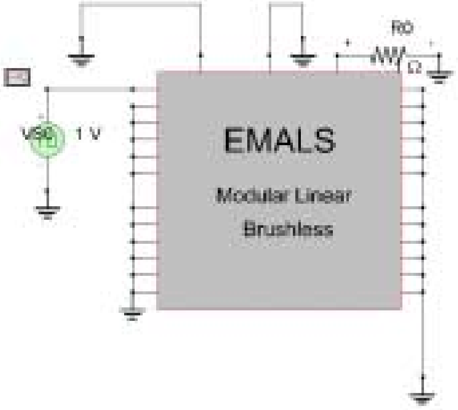

Figure 6: A first simulation test

The pins on the sides are the electrical terminals, while those on top are for the mechanical interface. In this case the speed and position are fixed to zero (the two pins on top are grounded – equivalent to a locked-rotor test), while a square wave voltage feeds one winding. This test verifies the correctness of the electrical subsystem and a classical R-L transient is the computed result (see Figure 7).

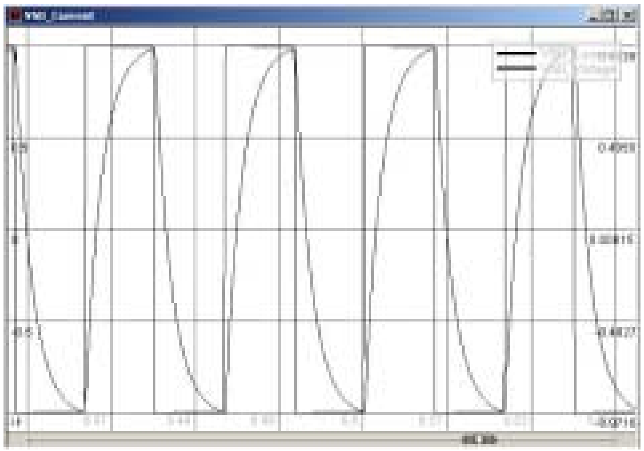

Figure 7: The results of the first test

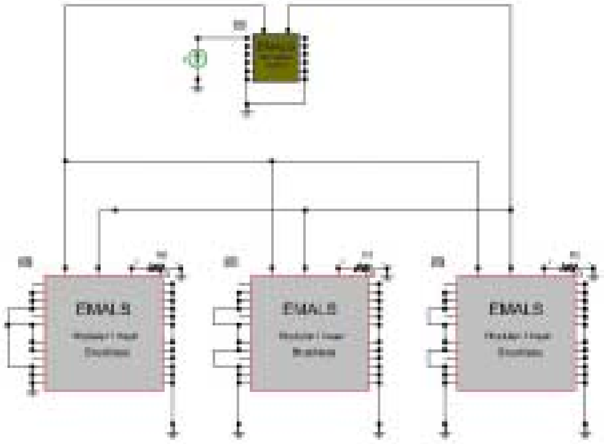

Figure 8: The second test

A second test as described in Figure 8 validated the mechanical model. In this case we have three stator models and one slider model. A force is applied to the slider and then we measure the voltage across the open-circuited stator electrical windings. In this case we see the classical trapezoidal waveform that appears only for those sections that are under the slider (see Figure 9).

B. *Converter modeling*

All the switching alternatives are considered. A completely separate drive circuit for each coil is seen as the best solution, and as suggested above the ideal energy storage system may well consist of an energy storage unit for each bridge circuit. Averaged models of PEBB-like converters have been used to speed up the simulation; but switched versions also can be used.

In the first simulation an H bridge configuration for each phase was adopted: This means that a single converter was connected in parallel to 4 different windings. Since we are using ideal switch models at this stage, this is a reasonable thing to do.

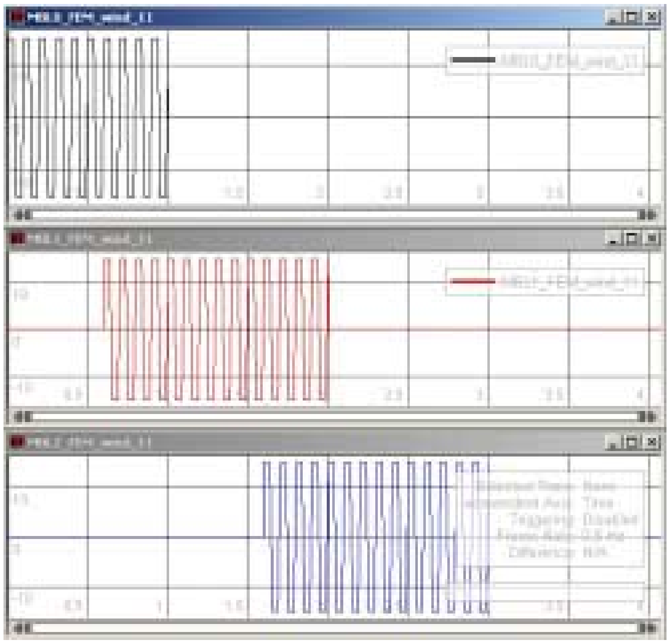

Figure 9: The results of the second test

C. Control modeling

The controller was modeled by using the VTB-Simulink interface. The controller is designed to fulfill the following requirements:

- each independent coil is fired by shuttle position sensors located along the stator.
- preset current (thrust) levels in each coil are known.
- open loop operation is possible if communication fails or is damaged.
- If communication exists, each coil thrust is adjusted as it is firing, so as to ensure adherence to the required thrust/ velocity profile.

The control algorithms are designed in Simulink, tested interactively, and finally compiled for better simulation performance.

The modular structure of the motor requires a hierarchical structure for the speed control.

Only one speed control (System Manager or SM in the following) is used, and as many current controllers as the number of modules (Hardware Manager or HM in the following). According to the position, the SM will decide which modules have to activate the current control.

Figure 10 shows the structure of the SM. A simple PI control performs the speed control task while the reference for each section is generated by a “section selector” block. Each HM receives a current reference and implements the current strategy as shown in Figure 11.

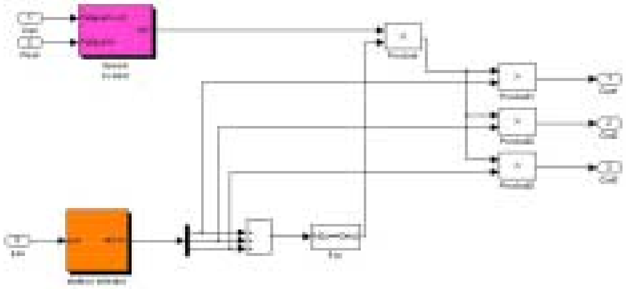

Figure 10: The SM structure in Simulink

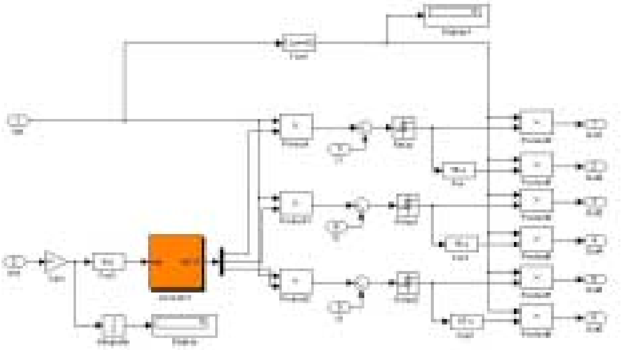

Figure 11: The HM structure in Simulink

Figure 12 shows part of a simulated aircraft launching event. The waveform represents the current in one of the windings of the first module. At the beginning the current ramps up and the control performs the classical square waveform. After a while, the slider leaves the first module and the current reference is set to 0.

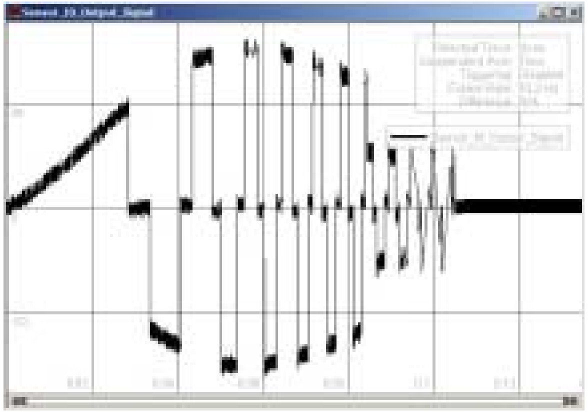

Figure 12: Current during the starting transient for first module

D. 3D Visualization

In parallel with the mathematical development of the model, a 3D view of the system was implemented in the Visualization eXtension Engine of VTB (VXE). This allows for interesting system analysis, and will be especially valuable when the whole system model is completed . An example of a close view is shown in Figure 13.

Figure 13: An animation of the EMALS system

VI. SUMMARY AND CONCLUSIONS

Most commonly, promising research directions are deduced from data from existing operation systems. Without operational systems to guide research, recourse must be had to very powerful cross disciplinary system simulators. VTB is an ideal tool to explore the very broad range of combinations of the many possible variants for an EMALS, and to be able to converge on optimal systems. The project is enabling experience in machine design and simulation to be applied to a very detailed study focusing on a range of important criteria including total system mass, total system volume, thermal management, reliability, robustness, survivability via redundancy, and also acoustic, magnetic, and electromagnetic signatures of this very large pulsed power application.

VII. ACKNOWLEDGEMENTS

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