Electromagnetic Aircraft Launch System - EMALS

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***Abstract*—With the proliferation of electromagnetic launch systems presently being designed, built, or studied, there appears to be no limit to their application. One of the intriguing applications is electromagnetically catapulting aircraft from the deck of an aircraft carrier. The U.S. Navy had foreseen the substantial capabilities of an electromagnetic catapult in the 1940's and built a prototype. However, it was not until the recent technical advances in the areas of pulsed power, power conditioning, energy storage devices, and controls gave credence to a fieldable electromagnetic aircraft launch system. This paper presents the U.S. Navy's Electromagnetic Aircraft Launch System (EMALS) being developed in partnership with Kaman Electromagnetics (Hudson, MA). It addresses the EMALS's present design and the technologies involved, as well as the ship and operational impacts, advantages, disadvantages, and compatibility issues for today's and tomorrow's carriers.**

I. Introduction

The U.S. Navy is presently pursuing electromagnetic launch technology to replace the existing steam catapults on current and future aircraft carriers. The steam catapults are large, heavy, and operate without feedback control. They impart large transient loads to the airframe and are difficult and time consuming to maintain. The steam catapult is also approaching its operational limit with the present complement of naval aircraft. The inexorable trend towards heavier, faster aircraft will soon result in launch energy requirements that exceed the capability of the steam catapult. An electromagnetic launch system offers higher launch energy capability, as well as substantial improvements in areas other than performance. These include reduced weight, volume, and maintenance; and increased controllability, availability, reliability, and efficiency.

II. Present Steam Catapults

The existing steam catapults currently installed on U.S. carriers consist of two parallel rows of slotted cylinders in a trough 1.07 m deep, 1.42 m wide, and 101.68 m long, located directly below the flight deck. Pistons within these cylinders connect to the shuttle which tows the aircraft. The steam pressure forces the pistons forward, towing the shuttle and aircraft at ever increasing speed until takeoff is achieved.

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While the catapult has many years of operation in the fleet, there are many drawbacks inherent in the steam system. The foremost deficiency is that the catapult operates without feedback control. With no feedback, there often occurs large transients in tow force that can damage or reduce the life of the airframe. Also, extra force is always added due to the unpredictability of the steam system. This tends to unnecessarily overstress the airframe. Even if a closed loop control system was added to the steam catapult, it would have to be highly complex to significantly reduce the thrust transients to a reasonable level.

Other drawbacks to the steam catapult include a high volume of 1133 m^3, and a weight of 486 metric tons. Most of this is top-side weight that adversely impacts the ship's stability and righting moment. The large volume allocated to the steam catapult occupies "prime" real estate on the carrier. The steam catapults are also highly maintenance intensive, inefficient (4-6%), and their availability is low. Another major disadvantage is the present operational energy limit of the steam catapult, approximately 95 MJ. The need for higher payload energies will push the steam catapult to be a bigger, bulkier, and more complex system.

III. EM Aircraft Launch System - EMALS

The requirements of the EMALS are driven by the aircraft, the carrier, and the operational requirements of the carrier's airwing. These requirements are:

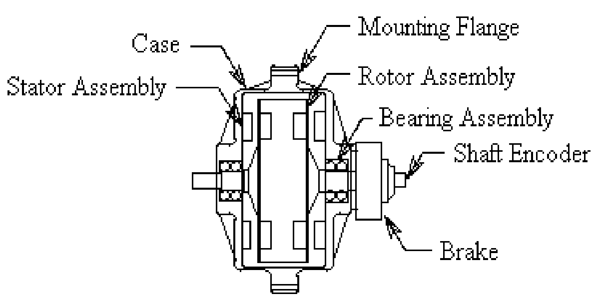
TABLE I
EMALS Requirements

Endspeed	28-103 m/s
Max Peak-to-Mean Tow Force Ratio	1.05
Launch Energy	122 MJ
Cycle Time	45 seconds
Weight	< 225,000 kg
Volume	< 425 m^3
Endspeed Variation	-0 to +1.5 m/s

The present EMALS design centers around a linear synchronous motor, supplied power from pulsed disk alternators through a cycloconverter. Average power, obtained from an independent source on the host platform, is stored kinetically in the rotors of the disk alternators. It is then released in a 2-3 second pulse during a launch. This high frequency power is fed to the cycloconverter which acts as a rising voltage, rising frequency source to the launch motor. The linear synchronous motor takes the power from the cycloconverter and accelerates the aircraft down the launch stroke, all the while providing "real time" closed loop control. The details of each component's design are presented in the following paragraphs.

A. Disk Alternator

The average power from the prime power is rectified and then fed to inverters. With power from the inverters, the four disk alternators operate as motors and spin up the rotors in the 45 seconds between launches. The disk alternator is a dual stator, axial field, permanent magnet machine (see Fig. 1). The rotor serves both as the kinetic energy storage component and the field source during power generation and is sandwiched between the two stators. There are two separate windings in the stators, one for motoring and the other for power generation. The motor windings are placed deeper in the slots for better thermal conduction to the outside casing. The generator windings are closer to the air gap to reduce the reactance during the pulse generation. The use of high strength permanent magnets allows for a high pole pair number, 20, which gives a better utilization of the overall active area. The rotor is an inconel forging with an inconel hoop for prestress. The four disk alternators are mounted in a torque frame and are paired in counter-rotating pairs to reduce the torque and gyroscopic effects. The rotors operate at a maximum of 6400 rpm and store a total of 121 MJ each. This gives an energy density of 18.1 KJ/KG, excluding the torque frame.



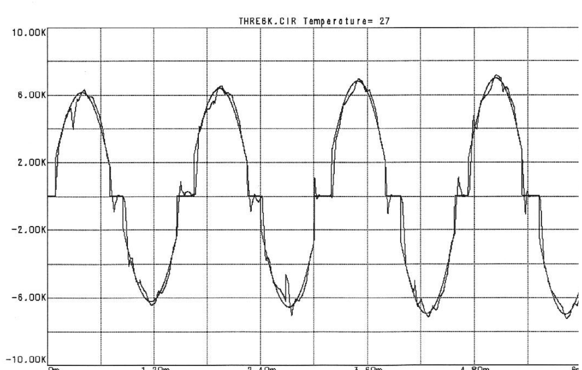


Fig. 1. Disk Alternator - Cross Section.

Each disk alternator is a six phase machine with phase resistance and reactance of 8.6 mΩ and 10.4 μH, respectively. At max speed, the output of one of the disk alternators would be 81.6 MW into a matched load. The frequency of this output is 2133 Hz and drops to 1735 Hz at the end of the pulse, for a max launch. Machine excitation is provided by the NdBFe 35 MGOe permanent magnets, which are housed in the rotor. These magnets have a residual induction of 1.05 T at 40 ^{o}C and create an average working air gap flux density of 0.976 T, with tooth flux densities approaching 1.7 T. The stator consists of a radially slotted laminated core with 240 active slots and liquid cold plate. The maximum back EMF developed is 1122 V. Maximum output voltage is 1700 V (L-L) peak and current is 6400 A peak per phase.

The disk alternator's overall efficiency is 89.3%, with total losses of 127 KW per alternator. This heat transfers out of the disk alternator through a cold plate on the outside of each stator. The coolant is a WEG mixture with a flow rate of 151 liters/minute. The average temperature of the copper is 84^{o}C, while the back iron temperature is 61^{o}C.

B. Cycloconverter

The cycloconverter, or power electronics in general, is the pivotal technology allowing EMALS to become a reality aboard ship. With a 103 m long motor, power electronics permit efficient operation by turning on only the coils that can affect the launch at a particular time rather than the entire motor at once. It also permits EMALS to operate at its most efficient point at all speeds by allowing for a variable voltage, variable frequency supply.

The cycloconverter is a naturally commutated 3ϕ-1ϕ bridge circuit. The output of one bridge is paralleled/seriesed with outputs of other bridges to attain the power levels required. By paralleling/seriesing the bridge outputs and not the switches themselves, the design eliminates the current sharing reactors and the series capacitors. The output of a cyclo is 0-644 Hz and 0-1520 V(L-L). Simulations of the operation of the cycloconverter have been completed. Fig. 2 shows the results of a typical output waveform of the cycloconverter. As can be seen in the figure, the peak current output is 6400 A for a max launch.

The cooling for the switching assembles takes place through liquid cold plates to which the components are mounted. The medium is de-ionized water at 35^{o}C input, 100 psig max, 1363 liters/minute. This is required to dissipate 528 KW lost in the cycloconverters.

Fig. 2. Cycloconverter Simulation Results.

C. Linear Synchronous Motor

The launch motor is a linear synchronous "coilgun", as shown in Fig. 3. The trough is the same as the steam catapult trough to allow for backfit capability. The motor itself is a dual, vertical stator configuration with the active area facing outwards. The rotor, or carriage, sits over the stators much like a saddle and protrudes through the flight deck to be attached to the aircraft. The carriage contains 160 full permanent magnets, the same type used in the disk alternator, NdBFe. The carriage is restrained in two axes by rollers. The rollers run in channels welded to the stator frame. This allows both the stator and trough to flex with the ship and the carriage to follow this flexure while maintaining a consistent air gap of 6.35 mm. The stator consists of 0.640 m long segments, which are 0.686 m high and almost 0.076 m thick. These segments turn on and off as the carriage passes. The position sense system is based on Hall Effect sensors, much as in today's rotary brushless commutated motors. As can be seen in the figure, the stators are protected by offsetting them from the slot in the flight deck. This is due to the contaminants, typically jet fuel, nuts, bolts, wrenches, hydraulic oil, etc., that constantly invade the trough through the slot and could, over time, affect the stators. Between the stators, in an environmentally sealed housing, are the busbars and the static switches,

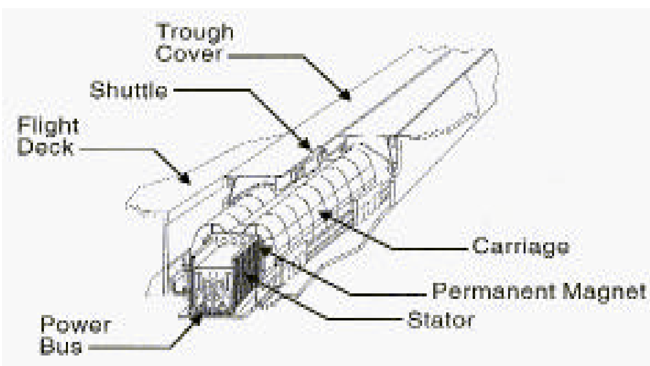


Fig. 3 EMALS Launch Motor

which are SCRs used to control the power to the stator segments.

The launcher stator is based on the modular unit called a segment. There are a total of 298 segments, 149 per side, for the entire launch motor, each 0.640 m long. The segment is wound as a three phase lap winding with 6 turns per slot and a total of 24 slots. This translates to 8 poles per segment and a pole pitch of 8 cm. These coils are epoxied into a slotless stator structure with G10 separating the coil legs. The slotless stator design keeps the phase inductance low at 18 μH. The phase resistance is 41 mΩ while the bus resistance is 0.67 mΩ. The air gap working flux is 0.896 T with the armature reaction of approximately 0.24 T. At full thrust, the permanent magnets experience a shear stress of 38 psi. At the end of the 103 m power stroke, the front of the carriage enters the brake. This brake consists of shorted stator segments, which act as eddy current brakes. At the same point in time, the carriage is still covering a number of active stator segments. Two phases are switched in these segments so that reverse thrust is initiated to help with the braking force.

With a projected efficiency of 70% and peak losses of 13.3 MW in the stator, active cooling will be necessary. Maximum coil action is 4.36e6 A^2s, resulting in a maximum copper temperature delta of 118.2^{o}C. The launch motor has an aluminum cold plate to remove this heat from the attached stator windings and back iron. The cold plates consist of stainless steel tubes in an aluminum casting. The peak temperature reaches approximately 155^{o}C and, after cooling for the 45 second cycle time, cools to 75^{o}C. The carriage that houses the permanent magnets will be cooled by convection, since there will be only slight heating from eddy currents in the carriage structure and magnets.

IV. Ship Impact

The introduction of EMALS would have an overall positive impact on the ship. The launch engine is capable of a high thrust density, as shown by the half scale model that demonstrated 1322 psi over its cross section. This is compared to the relatively low 450 psi of the steam catapult. The same is true with energy storage devices, which would be analogous to the steam catapult's steam accumulator. The low energy density of the steam accumulator would be replaced by high energy density flywheels. These flywheels provide energy densities of 28 KJ/KG. The increased densities would reduce the system's volume and would allow for more room for vital support equipment on the host platform.

Another advantage of EMALS is that it would reduce manning requirements by inspecting and troubleshooting itself. This would be a significant improvement over the present system, which requires substantial manual inspection and maintenance. The EMALS, however, will require a transition of expertise from mechanical to electrical/electronic.

EMALS eliminates the complexity of the present system's conglomeration of different subsystems. The steam catapult uses about 614 kg of steam for a launch, it uses hydraulics extensively, water for braking, and electromechanics. These subsystems, along with their associated pumps, motors, and control systems tend to complicate the launch system as a whole. With EMALS, launching, braking, and retraction would be achieved by the launch motor, thereby reducing all the auxiliary components and simplifying the overall system. The hydraulic oils, compressed air, etc. would be eliminated as well as the cylinder lubricating oil that is expelled into the environment with each shot. The EMALS would be a stand alone system, completely independent of the ship's main plant. This will allow greater flexibility in the design of the ship and more efficient ship propulsion schemes.

One of the major advantages of electromagnetic launch is the ability to integrate into the all electric ship. The Navy has directed substantial research into its Advanced Surface Machinery program that is developing electric derived propulsion schemes for the next generation of surface combatants. There has also been a good deal of work in high power electric weapon systems [1]-[3]. As such, more and more of a ship's systems will evolve into the electrical counterparts of old mechanical systems. This is true of the launch, and eventually, the arresting gear. The average power required by EMALS is only 6.35 MVA. Taking these power levels off the grid should not be a problem in an all electric ship, considering multi-megawatt pumps already exist on carriers for various applications.

Perhaps the most interesting aspect of electromagnetic launch is the flexibility it offers in the way of future aircraft and ship designs. An electromagnetic launcher could easily be sized down to perform as a launch-assist system, augmenting the short takeoff of a STOVL aircraft. It can also be easily incorporated into the contour of a ramp, which provides a more efficient fly-away angle for the aircraft being launched. This reduces the required endspeed, the commensurate energy supplied, as well as the stresses on the airframe. Overall, an EM launcher offers a great deal of flexibility to future naval requirements and ship designs.

On the other hand, there are drawbacks to the EMALS. One of these is that high power electromagnetic motors create electromagnetic interference (EMI) with electronic equipment. As in the case of an electromagnetic launcher, there would be sensitive aircraft equipment sitting directly above the launch motor. Along with the aircraft equipment is the ship's own equipment, which may be affected by the electromagnetic emissions. Through proper EMC design and a "magnetically closed" motor design, EMI will be minimized.

Another drawback of an electromagnetic launcher is the high speed rotating machinery associated with pulsed power applications. The disk alternator rotors are spinning at 6400 rpm, each storing 121 MJ, for a total of 484 MJ. In a laboratory, this is not a problem, but put these rotors on a heaving, jarring platform and it becomes more complicated. In order to ensure safe operation, the flywheel and bearings are to be a stiffer design than conventional.

V. Operational Impact

Due to the inherent high level of elegant control of electronic equipment, it is possible to reduce the stresses imparted to the aircraft. The present steam catapult has relatively high peak-to-mean acceleration profiles (nominally 1.25, with excursions up to 2.0). This results in high stresses in the airframe and generally poor performance. With an electromagnetic system it would be possible to correct for deviations in the acceleration profile in typically hundreds of milliseconds, which would result in low peak-to-means. A simulation was conducted that analyzed the level of controllability of the proposed design. As shown in the simulation results in Fig. 4, the acceleration profile is smooth and flat, compared with a typical steam catapult profile shown in Fig. 5. The simulation shows that for various load conditions, the EMALS is capable of operating within the 1.05 max peak-to-mean acceleration requirement. The result of this reduced peak-to-mean is reduced stress on the airframe. To quantify the effects of a reduced peak-to-mean, a Fracture Mechanics analysis was conducted on the airframe [4] with both the steam catapult and EMALS peak-to-means. The results from this analysis show a peak airframe life extension of 31% due to the reduced stresses on the airframe. This is becoming more important as tight budgets are forcing the Navy to procure fewer aircraft. This also has the benefit of a safer operational environment, since when the EMALS experiences any unforeseen problems during a launch, it has the capability to quickly adjust and correct for them, even if a component fails during the launch.

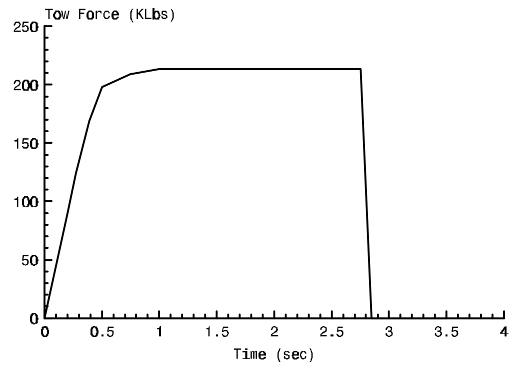


Fig. 4. EMALS Force Profile

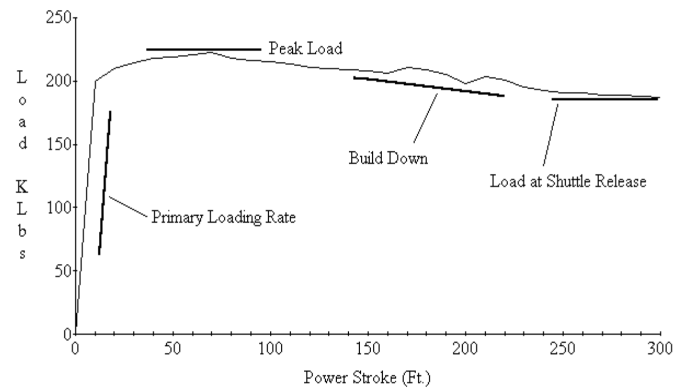


Fig. 5. Steam Catapult Force Profile

The EMALS offers the increased energy capability necessary to launch the next generation of carrier based aircraft. The steam catapult is presently operating near its design limit of approximately 95 MJ. The EMALS has a delivered energy capability of 122 MJ, a 29% increase (see Fig. 6). This will provide a means of launching all present naval carrier based aircraft and those in the foreseeable future.

VI. Present Work

The program is now in DEMVAL in a Critical Component Demonstration (CCD) phase. It is fundamentally a risk reduction phase, in which components, subsystems, and systems which pose the greatest amount of technical risk will be researched and developed to ensure that the technical issues are manageable before proceeding to full scale design. The components being developed are the cycloconverter, the stator, permanent magnets, and control system. These components are required to individually demonstrate their full design capability. For the cycloconverter this means power density, waveform generation, thermal management, and all the per unit electrical parameters the design requires. For the stator section, thrust density, thermal management, and all the per unit design parameters must be demonstrated. The permanent magnets must be able to withstand the harsh environment of the present catapult trough. This includes

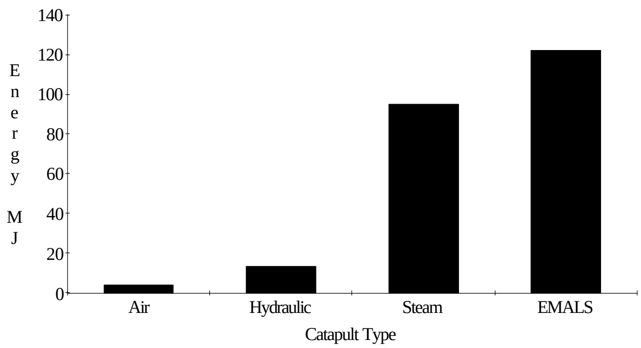


Fig. 6. Progression of the Catapult

heat, cold, corrosive agents, shock, etc. Once these components demonstrate their design requirements, they will be integrated with each other in a test fixture. This complete launch test fixture will enable the components to mimic a launch system. It will verify the operation of the EMALS, at all speeds and thrust levels, to the required specifications of the overall launch system.

Also, electromagnetic interference (EMI) is an issue that must be addressed early on in the design process. It must be fully understood and manageable before proceeding to the next phases of development. The high fields occur in relative close proximity to the aircraft, which houses sensitive avionics, weapons, and magnetic anomaly detection gear. It is, therefore, of prime importance to ascertain the probability of EMI between the EMALS and its neighboring systems. CCD offers a chance to address the issue of EMC. Using an electromagnetic FEA code, the shielding effectiveness of the catapult trough will be determined, as will the effects of various trough geometries. This model will be verified with hardware at low power levels. Once there is good agreement between the simulation and the empirical data, the simulation will be scaled up to the levels of EMALS.

The simulation model takes advantage of the symmetry of the trough and launch motor in the Y-axis. Since the major area of concern of the EMI issue is the fields on the flight deck, only the end turns are modeled. The coil legs running in the vertical direction will contribute little to the fields on the deck. This simulation is run at the complete spectrum of frequencies that the launch motor will produce, and the fields above the deck will be compared to the sensitivities of the various aircraft equipments. Fig. 7 shows the magnetic vector potential *A* for a 100 Hz, 10,000 A source. This is just a representative source to show the shielding effectiveness of the trough. As can be seen from the figure, little energy is escaping the trough structure. The magnetic fields are 0.07 mTat 10 cm above the deck at the center of the slot. Along the flight deck, the fields reach a maximum of 0.3 mT within 2.5 cm above the deck right over the coil. They fall to the Earth's ambient level at 5 cm above the deck.

VII. Conclusion

Electromagnetic motors for both launching and recovery of aircraft aboard a carrier are now possible due to a myriad of technical advancements. The advantages of electromagnetic motors are their improved performance capability over present systems and the resultant reduced weight and volume because of the high power, force, and energy densities possible. These savings are especially important on a carrier where they are precious commodities. In the future Navy, weight and volume may be of even

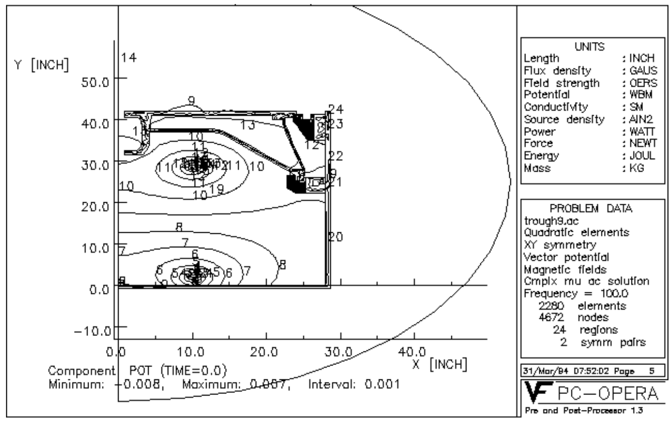


Fig. 7. Magnetic Vector Potential *A*, 10,000 A, 100 Hz source

higher importance as smaller budgets may demand smaller ships, and future design will require, just as in automobiles and space vehicles, etc., more performance out of smaller boxes. Electromagnetics offers this advantage. These systems would also provide the inherent controllability that comes with electrical machinery allowing for safer, less mechanically stressing operations. This will lead to extended life of airframes, nose-gear, and tail-hooks. Most importantly, electromagnetic motors will provide high level forces and greater efficiencies, which will permit the future generations of heavier, faster aircraft to operate off a carrier. Systems need to be developed that can produce the necessary performance. Electromagnetics offers a viable option.

References

[1] Fish, S., Cherry, J., "Dynamic Simulation of Capacitor-Based Electric Gun Systems for Naval Applications," IEEE Transactions on Magnetics, Vol. 29, No.1, January 1993.

[2] Emad, F.P., Borraccini, J.P., Waltman, D.J., Fiske, T.H., Ruby, W.R., Superczynski, M.J., Whitestone, R.C., "DTRC Electromagnetic Launcher with Feedback Control,"

[3] Grater, G.F., Doyle, T.J., '"Propulsion Powered Electric Guns-A Comparison of Power System Architectures," ibid.

[4] Peoples, J.E., "EMALS Aircraft Structural Fatigue Life Prediction," Report NAWCADLKE-DDR-05-PD-0008, October 1992.