AN ELECTRO-MAGNETIC CATAPULT FOR THE FUTURE CARRIER?

BY

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ABSTRACT

The announcement on the 25th July this year by the Defence Secretary, Des Browne, to confirm the decision to build two new 65,000 tonne aircraft carriers for the Royal Navy ended several years of speculation and uncertainty. The new carriers, to be named *HMS Queen Elizabeth* and *HMS Prince of Wales*, and designated CVF, are due to enter service by 2014 and 2016 respectively, and will deliver a step change to this nation's ability to project power. An aircraft carrier, however, is only as effective as the aircraft that it launches from its deck. For the future aircraft carrier, it has long been agreed that this aircraft will be the Short Take Off and Vertical Landing (STOVL) version of the Lockheed Martin Joint Strike Fighter, now known in the UK as the Joint Combat Aircraft (JCA).

FIG.1 – JCA PROTOTYPE STOVL VERSION

(www.armedforces.co.uk)

This article considers the facilities required to operate conventionally launched aircraft in the event of the UK withdrawing from the STOVL JCA project or the project itself being cancelled. It looks at the history of the catapult for aircraft launch before considering the various technologies as they might be exploited in CVF should the need arrive. In particular it considers electro-magnetic launch technologies, the development of US and UK catapult solutions and attempts to explain why it is felt that the UK version offers a potentially better and cheaper product.

Background

One of the principal drivers for the selection of the STOVL version of JCA (designated the F35B) was that it would enter service with the US Marine Corps (USMC) in time for its operation to be fully proven before the original in-service date of *HMS Queen Elizabeth* in 2012. Whilst the prototype STOVL version of the JCA (then known as X35B) first took to the air on the 23rd June 2001, development of this aircraft is way behind schedule and, despite a reduction in all up weight of some 1000 kg, it is still extremely heavy. Furthermore, if the scuttlebutt is to be believed, the USMC now appears to be under pressure from the US Navy to give up its indigenous fixed wing aviation in favour of support from the Navy's carrier-borne aircraft. Without buy-in from the USMC the future of the F35B would certainly need to be reviewed. In addition, whilst long-standing technology transfer issues with the US Government and the aircraft manufacturer now appear to have been resolved, the former Minister for Defence Equipment and Support, Lord Drayson, announced as far back as November 2005 that there had to be a 'Plan B'. There are no other viable STOVL alternatives thus, should F35B fail for any reason, whether technological or commercial, then 'Plan B' whatever the airframe would almost certainly require catapult-assisted launch.

History[1]

Early developments in catapult technology go back at least as far as January 1894; nearly a decade before the Wright brothers achieved powered flight at Kitty Hawk, North Carolina on the 17th December 1903. When Samuel Pierpont Langley, the secretary of the Smithsonian Institute, attempted to launch a 10-pound model aircraft, he employed a mechanical catapult in which the energy was stored in helical trolley-car springs. The result was a spectacular failure but it was the first step in the development of assisted aircraft launch that continues to this day.

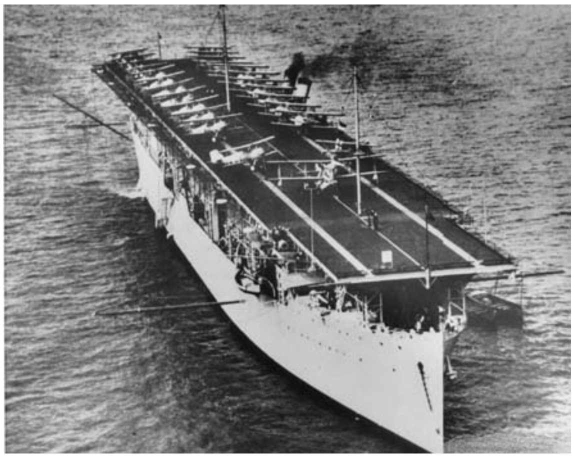

FIG.2 – USS LANGLEY

(www.nnsy1.navy.mil)

In the years following the First World War, pneumatic and pyrotechnic catapults were used to launch seaplanes from larger warships and even some merchantmen. In March 1922 the US Navy's experimental carrier the *USS Langley* was commissioned and was originally fitted with compressed air catapults but, after 3 years of disuse, these were removed in 1928. Despite the ship's low speed of 15.5 knots, take off by the relatively small aircraft of the time was simply no problem from the *Langley's* 159 metre flight deck. Operations from the 270 metre, 30 plus knots *USS Saratoga* and *USS Lexington* proved even less problematic and maritime catapult launch technology development effectively ground to a halt: no requirement so no development. With the exception of cruisers and battleships which often carried one or two catapult-launched seaplanes for reconnaissance purpose, at the outbreak of the Second World War only four aircraft carrying warships were fitted with catapults. *USS Enterprise* and *USS Yorktown* were both fitted with flush deck hydraulic catapults but these were rarely if ever used and, as late as 1943, the Commanding Officer of the *Enterprise* was asking to have the catapult removed. The Japanese heavy seaplane cruisers: *IJS Tone* and *IJS Chikuma* were each fitted with explosive catapults and could carry five Aichi E13A1 'Jake' scout planes. Ironically, it was a 'Jake' catapulted from *Chikuma* that preceded the Japanese attack on Pearl Harbour on 7th December 1941 and brought the United States into the war.

Despite an increase in aircraft weight and size, at the outbreak of the Second World War the large Fleet carriers of all nations such as the aforementioned Saratoga class, the Royal Navy's *HMS Ark Royal* and the Japanese *Akagi* class remained capable of launching their aircraft without assistance. As the growing understanding of the importance of maritime air power led to the requirement for more aircraft carriers, numerous smaller and cheaper escort vessels with 150 metre flight decks and top speeds of around 20 knots were built. Assisted launch thus became a necessity if these platforms were to launch aircraft with a viable payload. Development of the flush deck hydraulic catapult was rapidly reinvigorated and quickly put to sea in these relatively small ships. These catapults were not only successful in overcoming the shortfalls for which they were designed, they were ultimately retrofitted to many of the Fleet carriers and soon became a standard fixture in fixed wing maritime aviation.

With the introduction of jet aircraft and increasing demands in terms of aircraft weight and payload, hydraulic pressures were raised to ever-higher levels in order to provide the necessary launch energy. In May 1954, the port catapult hydraulic accumulator in *USS Bennington* burst releasing oil mist under tremendous pressure. The resulting explosion killed 103 men and injured 201 others, and it became clear to the major carrier-operating powers, specifically the United Kingdom and the US, that the hydraulic catapult had reached its limit.

FIG.3 – HMS PERSEUS SHOWING HER STEAM CATAPULT

(http://en.wikipedia.org)

The steam catapult was a British invention. The brainchild of Cdr Colin C Mitchell RNVR, it first went to sea in the early 1950s in the aircraft carrier *HMS Perseus*. So successful were these trials that by the end of the decade steam catapults were being installed in all new carriers. Over the following half century, steam catapults have been refined and improved, and the latest designs are capable of launching all the current types of carrier-borne aircraft. Nonetheless, 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.

The Electro-Magnetic Catapult

As hydraulic catapults gave way to steam in the 1950s, so the early years of the new millennium have seen the development of an alternative technology for launching aircraft, the electro-magnetic (EM) catapult. EM catapults are powered not by a steam driven piston but by linear induction motors or LIMs. Linear induction motors work on the same basic principle as all induction motors except that the motor is effectively unrolled to provide a linear stator and rotor. The movement of the armature or rotor through stator's electric field is thus linear rather than angular or rotational. This is well proven technology; the principle was first demonstrated in the military field in 1944 when the *Luftwaffe* tested a LIM-powered anti-aircraft gun. LIMs have since been used to power monorails at *Euro-Disney* in Paris and on Vancouver's rapid-transit system; they have also been used to drive roller coasters into the 160 kph range and an experimental LIM-powered train has achieved 400 kph.

The USN is currently developing the Electro Magnetic Aircraft Launch System (EMALS) for installation in the *USS Gerald R Ford* (CVN-78), the first of its new generation of super carriers. This is a particularly interesting development as the *USS Ford* will be nuclear powered and thus has abundant steam available for conventional steam catapults. Despite this, the USN has chosen to develop EM technology. An EM launch system offers the requisite higher launch energy as well as substantial improvements in areas other than performance. These include reduced weight, volume and maintenance, and increased controllability, availability, reliability and efficiency.[2] The ability of an EM system to vary speed and thrust to meet the needs of the vehicle being launched makes a single catapult suitable for a wide range of airframes, both manned and uninhabited.

FIG.4 – USS GERALD R FORD – FIRST CARRIER TO BE BUILT WITH AN ELECTROMAGNETIC CATAPULT

(www.defencetech.org)

Development of EMALS, however, has not been without problems. Recent reports by the US Government Accountability Office refer to the EMALS system for the *USS Ford* 'encountering technical difficulties in developing the prototype generator and meeting detailed technical requirements, which has led to increased programme costs and an over 15-month schedule delay.[3] EMALS is understood to utilise ‘vector control,’ a complex closed loop control system to manage the speed and thrust achieved from the system’s linear induction motors. The contractor developing this technology, General Atomics, appears to have had problems with earlier attempts at open loop control and consequently opted to develop this more complex and technically challenging solution. [4]To achieve closed loop control, extremely accurate position and speed sensing is required along with 3-phase voltage and current feedback from each of the LIMs. Though widely acknowledged as the theoretical ideal for motor control, the challenge lies in providing this accurately over the full length of the launch track. Small discrepancies can mean the difference between 0 and 100% thrust whilst the loss of a sensor could cause the entire system to fail, thus necessitating an extensive degree of high integrity redundancy. It appears likely that some the problems currently being encountered in developing EMALS may be linked to the vector control system.

Despite these difficulties, it is clear that the USN believes that the benefits offered by the EM technology greatly outweigh any disadvantages encountered with its development. As the pre-eminent operator of catapult-assisted launch for aircraft for the past three decades, anyone else aspiring to build and install catapults into aircraft carriers would be well advised to consider these developments in weighing up their options. Steam catapults, however, are a proven technology which has previously been used with a high degree of success in the Royal Navy, and is currently operated by both the United States and French Navies. Whilst the USN has opted for EMALS for its future carriers, it is understood that the French position is to fit steam catapults to their version of CVF known as *Deuxième Porte Avions* or PA2.

The UK Position

As previously stated, the STOVL version of the JCA carries with it a certain degree or risk; how high a risk is hard to define but Lord Drayson’s requirement for a ‘Plan B’ clearly requires alternatives to be considered. The official fallback position of the CVF Integrated Project Team (IPT), which is charged with developing this capability, is currently believed still to be to use steam should a catapult launch system be required, the reasons for which are understood to be:[5]

- Steam is viewed as a low risk solution – PA2 will have steam catapults thus the UK could simply follow the French lead.

- Any catapult system would need to be qualified for aircraft launch – steam catapults are well understood and such qualification is believed to be a much more straightforward business than for a new technology.

The first assertion that steam is low risk is open to challenge on the grounds that this would be the first time that a steam catapult would be paired at sea with a source of steam that was entirely separate from the propulsion system, whether conventional or nuclear. Additionally, qualification of an EM catapult may not only be less difficult and time consuming than the current assumptions would appear to indicate, but the qualification of a steam catapult driven by steam from a dedicated source could well deliver a whole new set of challenges.

Steam

The fundamental difference between CVF and other carriers with steam catapults is that these other carriers all have steam propulsion and thus the steam required for the catapult is bled from the main steam raising plant. For CVF, auxiliary boilers would have to be installed to provide the steam for the catapults, which would be the principal, if not the only user, of the steam produced. Whilst there is space in the main machinery spaces set aside for steam raising plant, this potentially gives rise to significant issues. In effect, the steam raising plant would operate as large ‘donkey’ boilers, cycling rapidly between high and low fire, reacting to short periods of high demand with extensive periods of low demand in between. This would undoubtedly cause problems, possibly major, with boiler availability and reliability, with consequential effects on the availability of steam catapults and the costs of operating them. Furthermore, although these boilers would be cycling frequently between high and low fire, when launching aircraft a very large volume of steam would be required. When conducting flying operations, approximately one quarter of the steam generated by the US Navy’s *Nimitz* class carriers is used for the steam catapults.

FIG.5 – LAUNCH OF AN F-14 (TOMCAT) FROM THE *USS CARL VINSON*

(http://encarta.msn.com)

Assuming the practicalities of raising steam could be resolved, the UK has had no experience of operating steam catapults since *HMS Ark Royal* was decommissioned in 1978. Whilst this can, no doubt, be overcome through working and training alongside the French and Americans it all adds to the risk of this solution. In view of the almost total shift away from steam at sea and in wider industry, there must also be some doubt as to the very availability of appropriate non-nuclear steam raising plant, not just within the UK but throughout Europe as a whole. Overall, fitting steam-raising plant solely to supply the steam for catapults would appear to be a less than ideal solution.

An Alternative to Steam or EMALS?

Development of EMALS in the United States has cost in the region of $305M. For the UK to buy in retrospectively to this system for use in CVF would undoubtedly incur a proportion of these costs in addition to the materiel costs of the system. There is, however, a potentially viable alternative that would not only cost considerably less than EMALS to develop but would offer what is technically probably a better solution. This solution is EMCAT, the UK MOD's own development in partnership with Converteam Ltd of an electro-magnetic catapult. Like EMALS, the launch energy for EMCAT utilises LIMs, but these are advanced LIMs (ALIMs) specifically developed by a British company, Force Engineering Ltd, to have very low operating slip. This has enabled a sensorless open loop control system to be successfully developed, which has been demonstrated to provide an excellent degree of control.[6] This may well prove to have significant advantages over the closed loop vector control favoured by General Atomics for EMALS.

Inevitably there is a problem with EMCAT and this is that the system does not actually exist at this time. What has been developed, however, is a smaller, low voltage version of an EM catapult known as the Electro Magnetic Kinetic Integrated Technology or EMKIT. EMKIT was born out of the original UK EMCAT programme, which was being developed by the CVF Integrated Project Team before the decision was made to select the STOVL version of JCA. In essence, EMKIT is merely a scaled down version of EMCAT but uses low voltage ALIMs to launch an Uninhabited Air Vehicle (UAV) of up to 500 kg. The full scale version of EMCAT would have been capable of generating burst energy in the region of 80 to 100 MJ for accelerating a full scale manned aircraft such as the F/A-18 E/F (Super Hornet) or F35C (Lightning II) up to launch speed. It would also have been possible to turn down the power to enable EMCAT to launch reconnaissance aircraft or UAVs.

FIG.6 – EMKIT TECHNOLOGY DEMONSTRATOR SHOWING LAUNCH TRACK IN FOREGROUND

(Photograph: Lt Mick Thomson RN)

The EMKIT facility as currently configured comprises a launch track into which the ALIMs are set, the test load / launch vehicle built around the armature or reaction plate as it is known, and an additional length of track which incorporates the friction braking system. This is served by a diesel generator, 2 rotating pulsed energy stores, control room, and an equipment hall containing 2 transformers, 2 high power converters and the switchboard. This facility, along with temporary domestic offices, has been built on a green field site leased from Bruntingthorpe Aerodrome and Proving Ground in Leicestershire.

EMKIT trials to date have been extremely successful, proving the technology required for electro-magnetic launch and demonstrating its feasibility in a fully integrated system. The 500 kg test load has achieved speeds of 50 ms^{-1}, more than enough to launch the current generation of UAVs of this weight, whilst a 1 MJ launch of a 1030 kg test load equivalent to a Predator A UAV was also demonstrated. With a longer track, lower speeds may also be used to deliver the necessary launch energy. Converteam estimates that with a longer launch track the levels of thrust achieved could potentially be used to launch considerably larger UAVs of up to 4.5 tonnes. With larger energy stores and a longer track, it is estimated that a maximum launch energy close to 6 MJ could theoretically be achieved, sufficient to launch a fully loaded MQ9 Predator B (Reaper) similar to those now in service with the Royal Air Force in Afghanistan.

Whilst EMKIT has been developed to launch a UAV of up to 500 kg (for example, Hermes 450 / Watchkeeper) there has never been an endorsed requirement for this capability. A number of potentially interested authorities within the Equipment

Capability (EC) area of the UK MOD have been approached to see if they had any interest in this technology but none has been forthcoming. Arguably the real value that the EMKIT project has delivered is to derisk the technology required for a full scale EM Catapult. Not only has EMKIT proved the launcher technology, it has proven to be extremely reliable and has demonstrated excellent repeatability. Distance of travel, launch velocity and launch energy have invariably remained constant during repeated tests under similar conditions. This is an important factor should a full scale catapult eventually be built which would require to be qualified in terms of availability, reliability and maintainability, as well as overall performance, before it could ever be approved for the launch of manned aircraft.

In simple terms the qualification process involves a very large number of launch operations using an equivalent dummy load to prove the launch system and its support services. If the UK were to use the same steam catapult system as the French then presumably the costs involved could be shared. Nonetheless, it seems inevitable that a full set of qualifications would still need to be undertaken owing to the potentially uncertain nature of the steam supply and the different safety regimes. Should the decision ultimately be made to develop an EM Catapult, however, there would appear to be no reason why the shore test facility that would inevitably be required could not be used to qualify the system for aircraft launch. It is understood that *HMS Queen Elizabeth* is likely to be built as a STOVL carrier anyway, and will enter service in 2014 with a ski jump and no catapult whatever the current state of the JCA project. Although challenging, should a decision ultimately be made to fit a catapult launch system to CVF it would appear to be feasible to build and qualify EMCAT for *HMS Prince of Wales* in time to meet her in-service date of 2016.

How Much Would It Cost?

Technology development, design, construction and operation of the EMKIT facility have cost a total of £2.6M thus far. On top of this, there are two further pieces of development work which need to be carried out if a fully viable UAV launch capability is to be achieved. An EM arresting system is required to permit safe recovery of the launch vehicle, and additional work may be required to improve the design of the existing ALIMs by reducing the thrust end effects and smoothing the thrust profile. As a rough order of magnitude (ROM), the total cost of these two pieces of work is estimated to be in the region of £1M. In addition, a further £625k is required to develop super capacitor energy stores which potentially offer a substantial improvement in capability over the current rotating energy stores as installed at EMKIT. Whilst these are being developed in part to optimise EMKIT’s capabilities, improving energy storage has a wider applicability elsewhere for both the surface ship and the submarine communities, and this is currently the principal driver for its development.

The ALIMs employed within EMKIT operate on low voltage whilst generation of the energy required to launch a full sized aircraft necessitates the development of high voltage motors. The ROM cost for this activity to include the design, modelling, manufacture and test of an HV LIM is about £0.5M as the necessary, mature HV converter technology already exists at Converteam. Successful development of an HV LIM, which takes full account of the proposed LV LIM improvement programme, development of an EM arresting system, and the planned work on super capacitor energy storage, would provide all the building blocks required for a resurgent EM Catapult. Overall, developing the technology necessary to derisk an EM Catapult will cost in the region of £5M of which more than half has already been committed. Derisking the technology through this work would then enable a full size EMCAT to be built as a Shore Test Facility (STF) for around £30M.[7]

How does this Compare with the Alternatives?

Of the $305.6M that the US Government has invested in the EMALS project to date, some $160M was spent on programme definition and risk reduction up to April 2004; the remaining $145.6M is scheduled for payment over 5 years for system development and demonstration.[8] This total sum equates to some £167M at the current Government accounting rate.[9] The estimated £35M to achieve the same level of technology readiness and proving in the UK for EMCAT thus looks highly cost effective. Quite how much it would cost to buy in to EMALS is not known as the Information Exchange Agreement with NAVAIR has now expired and a replacement is yet to be agreed with NAVSEA, which has now taken on responsibility for the project. There is also the issue that it is understood that the only fast jets for which EMALS will be qualified are the F/A-18 E/F and the F35C, which will form the backbone of the US Navy's air power now that the F14 (Tomcat) has been withdrawn from service.

In considering the alternatives, it should be noted that steam catapults are inherently high maintenance, which adds significantly to the through life costs of such a system, not only in terms of materiel but also for the manpower requirement. Using the illustrative figures provided by Converteam and based on a ship life of 30 years, whole life costs (WLC) for steam catapults for 2 CVFs come out at £415M whilst the costs for equivalent EM catapults are £284M.7 The shore test facility for an EM catapult, comprising one catapult system capable of launching an aircraft, is more expensive than the equivalent steam STF as are the unit production costs for the 4 operational systems, 2 per ship. Operating costs, however, are significantly less whilst support costs over the 30-year period are in the order of only 25% those for steam. For a ship life of 50 years, therefore, the WLC benefits are likely to be even more significant than those illustrated for a 30-year life.

Moving Forward or Stepping Backwards?

CVF will have integrated electric propulsion, generating some 112.6 MW of power from 4 Diesel Generators and 2 Gas Turbine Alternators. Additionally, the ability to bleed or trickle power into the energy stores between launches means that there is an abundance of installed power readily available to support aircraft launch without fitting additional power plant in the form of auxiliary boilers. The Marine Engineering Development Strategy of the mid 1990s, recently taken forward in the 2006 Marine Systems Development Strategy, focuses on the delivery of the true electric ship. There has been much progress in implementing this vision across the surface fleet and CVF is the next stage in this process. The re-introduction of steam technology to service what would be the ship's primary weapon would undoubtedly be an undesirable and retrograde step, and its inclusion in an 'electric ship' does not appear to demonstrate a coherent systems approach.

Conclusions

There would thus seem little doubt that should the requirement arise, the arguments for selection of an EM launch technology are convincing; anything else simply does not stand up to scrutiny. The real question is thus probably not whether one goes for steam or EM but whether to buy in to EMALS or do it ourselves. EMALS has the advantage that it is a reality; despite the very real problems that its implementation is currently facing there can be little doubt that the US Navy will overcome and the system will ultimately go to sea as planned. On the other hand, EMCAT would appear to be potentially very much cheaper, both in its short-term development and over the life of the ships into which it might be installed. Moreover, early indications are that is likely to be simpler, more reliable and offer greater capability than EMALS. Rear Admiral Kevin M McCoy USN, NAVSEA's Chief Engineer for the Naval Systems Engineering Directorate and thus a key player in EMALS future development, recently visited the EMKIT test facility where he expressed real interest in the technology being demonstrated.

Development thus far has been funded through Output 6 (Technology in the Supplier Base) of the Research Programme, however, this funding has now run out following completion of the EMKIT test and trials programme. The new Technology Development Channel (TDC), effectively an amalgamation of Outputs 6 and 7 (Innovative Solutions to Defence Problems), appears to be an entirely appropriate source for funding further research and development and the intention remains to seek funding through this route. Unfortunately, competition with other programmes is fierce and when the allocation of Channel C funding was last considered in June this year, none of the four EM launch proposals made the cut. Alternative sources of funding are being considered but, whilst highly supportive in principle, the Sponsor for Carrier Strike within the EC area, the Director of Equipment Capability (Above Water Effects), is not minded to fund the work at this time. Similarly, until a clear need to implement 'Plan B' is identified, funding is unlikely to be forthcoming from CVF IPT unless the case can be made to spend the money for risk mitigation.

Nonetheless, should the funding be made available in the near future then all the derisking work: super capacitor based energy storage, EM arresting system, LV LIM enhancements and HV LIM development could be completed by around 2010. Whilst undoubtedly challenging, this should enable the STF to be built and the system qualified in time for installation to meet the in-service date of *HMS Prince of Wales.* On the other hand, if this money is not forthcoming then we are in serious danger of finding ourselves in a position where it is simply not possible to resurrect the project in time for its implementation in *Prince of Wales*. Unless a further requirement can be found for the EMKIT facility at Bruntingthorpe in the near future then it is likely to be dismantled and the site returned to its owners. Should this happen then the Royal Navy could potentially not only lose the opportunity to fit world class technology into its new carriers, but UK plc will miss out on the opportunity to be the world leader in this area.

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