The Next Step in Modern Aviation: Civil Application of Electromagnetic Aircraft Launch System

by

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Abstract

Two critical phases of flight have contributed to the majority of fatal accidents, takeoffs and landings. Aiming to improve one aspect, the takeoff, is the foundation of this project. Since the inception of sustainable flight, many iterations of assisted takeoff equipment have developed. In the 1950s, the steam catapult emerged as the premier technology for aircraft short-distance takeoff. Other experimented sources were deemed unreliable or inefficient. One was ahead of its time, using linear induction motors and electromagnets to generate acceleration. As other countries took to steam for plane launching, Japan took the linear induction technology and applied it to their trains and over time nearly perfecting the world's most efficient transportation system. Looking forward and being ready for the future's unknowns, the US Navy resurrected the forgotten catapult technology as a joint venture with General Atomics. The electromagnetic catapult was the Navy's solution for the future by achieving more efficient means of assisted takeoffs onboard its ships. Currently, the catapult is going through test trials onboard the newest aircraft carrier, CVN-78, and with plans for implementation on future iterations of Ford series hulls if it proves successful. Launching multiple sizes of manned and unmanned planes with minimal maintenance requirements is the most significant improvement over steam. As the system matures, it has the potential to expand beyond military use. Improving civilian aviation by implementing EMALS seems impossible, but the notion of safer and more efficient aviation justifies the viability of this technology in the future.

Keywords: aircraft, aviation, efficient, electromagnetic, maintenance, safety.

The Next Step in Modern Aviation: Civil Application of Electromagnetic Aircraft Launch System

Aviation has significantly evolved since World War II. Safety is the most contributing factor to its success through technological, mechanical and organizational improvements (Rodrigues & Cusick, 2015). Unfortunately, many of these improvements have developed from mishaps and near-misses. It could be said every practice and procedure in aviation is written in blood. Through the incorporation of safety management systems, major overhauls in security and integrating them into daily processes, traveling by air has become safer than by automotive (NTSB, 2015). The NTSB (2015) reported that all modes of travel totaled 34,678 fatalities in the United States, with .0128 percent of being aviation and highway travel at a staggering 97.23 percent.

A major organization that has influenced aeronautical science and dedicated a resounding commitment to improving aviation safety, the International Civil Aviation Organization (ICAO) (2016), has set its vision to “achieve the sustainable growth of the global civil aviation system.” Aviation safety is the core of ICAO’s fundamental objective; identifying ways to improve safety and increase the efficiency of operations requires innovation. With innovation, expanding upon what is done right and reinforcing the quality of standard operating procedures prevent the occurrence of defects and loss of life. Taking the ICAO’s vision and blending safety and efficiency inspires a strong look to improve aviation operations.

The takeoff is where it all starts and although humankind has made significant strides incorporating safety and control measurements, the phase suffers from 12 percent of all fatal aviation accidents between 2009 to 2015 (Boeing, 2016). To reduce or even eliminate fatalities during this phase requires looking at the past to move forward. Guiding aircraft until generating enough lift; carts, rails, and catapults have been around since the start of powered forward flight (Bilstein, 2001). The catapult existed since medieval times, often associated with warfare by launching stones and boiling oil (Columbia Encyclopedia, 2016).

Catapult technology increased significantly throughout the 20th-century. In the 1950s, the British Royal Navy conducted tests on launching heavier aircraft from aircraft carriers. Catapult propulsion used various sources such as gunpowder and rockets, but hydraulic systems were the most common used in World War II (Bilstein, 2001). Looking for a sustainable way to launch aircraft while reducing the stress of airframes, the Royal Navy's experiments resulted in the steam catapult becoming the solution. The steam catapult allowed fast turnarounds for between launches with the ability to launch four aircraft per minute increasing warfighting capability efficiency and sustainability; it eventually was adopted by the United States, Brazil, and France (Bilstein, 2001). Although the steam catapult emerged as the premier technology for aircraft launching dominance, another source was researched and proposed as an alternate way to propel aircraft but was limited to the technology of its time.

Launching through History

Catapulting aircraft from ships did not originate from the US or Royal navies, but around when the Wright Brothers were launching the *Flyer I*. Samuel P. Langley, an astronomer and the current head of the Smithsonian Institution, was determined to perfect the human piloted, engine-powered airplane (Bilstein, 2001). Armed with an investment of $50,000 from the US War Department, he worked with Charles M. Manly to develop a gasoline engine that was small enough to be mounted on Langley's designed *Aerodrome* (Bilstein, 2001). The *Aerodrome* required a small engine, so a steam engine was not feasible. Manly managed to create a gasoline engine weighing 125 pounds that outputted 53 horsepower to meet the requirement (Bilstein, 2001).

Once put together with Manley's engine, Langley attempted twice to launch his *Aerodrome* from his riverboat outfitted with a catapult. Both times it ended in disaster with a crowd of reporters watching in disappointment. The effort Manley put into the engine was not in question, but the *Aerodrome*'s design flaws along with the catapult design shortcomings ultimately contributed to Langley's failure (Bilstein, 2001). The grant of $50,000 and Langley's *Aerodrome*, unfortunately, did not meet the desired result from the War Department.

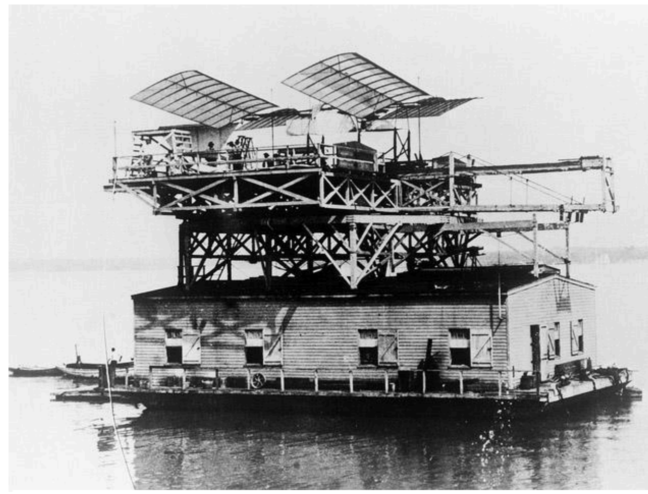


Figure . The Langley *Aerodrome* and Riverboat. From: http://www.theatlantic.com/technology/archive/2010/08/old-weird-tech-nasa-on-flickr-commons-edition/62249

On December 17th, 1903, Orville and Wilbur Wright did the impossible. Through the support Octave Chanute, who sent correspondence of developments in aeronautical science from Europe, the Wright Brothers solved several issues such as controllability, warping wings that assisted with banking and even developed the most efficient propeller at the time and powered it with their built 12-HP engine (Bilstein, 2001). Using a track-guided trolley, Orville took flight for twelve seconds and landed safely. Their effort resulted in the world's first human controlled, engine-powered flight and would captivate the minds of millions and bring aviation to the forefront of winning future wars and changing transportation forever.

The Wrights predicted that aircraft would see use as military reconnaissance and potentially prevent future wars by being a deterrent. The idea garnered interest from the US, Great Britain, France, and Germany. The US War Department awarded $25,000 to the Wrights after a successful demonstration. Wilbur went to Europe to demonstrate capabilities of their invention. Soon after, aviation started to develop beyond novelty, and American aeronautical science began to fall behind because of other nations investing into their respective laboratories. As a result, President Woodrow Wilson enacted the Naval Appropriations Act on March 3, 1915, to get military aviation progressing forward. The National Advisory Committee of Aeronautics (NACA) came from it, with the task of "to supervise and direct the scientific study of the problems of flight, with a view to their practical solution" (Bilstein, 2001). Although created to perform research, NACA did not have its own laboratory until 1920; most likely due to the focus on the World War I.

Beyond Reconnaissance, an Instrument of War

The United States did not declare war on Germany until April 6, 1917. US aviators found their way to support the war beforehand by joining Canadian, British, and French units. Flying for Allied squadrons, these Americans were some of the first engage in significant plane-to-plane combat. Because the US acceded to the war three years late, their aircraft manufacturing and production were well behind the European effort. Meeting the demands of Allied countries and the war effort proved difficult, but funding from the US government inspired much-needed growth for manufacturing and production. The war pushed aviation beyond expectations;

manufacturing processes matured exponentially and war tactics expanded with planes mounted with machine guns and bombs. As the war drew to a conclusion, Orville Wright wrote to a friend, "The Aeroplane has made war so terrible that I do not believe any country will again care to start a war," (Bilstein, 2001). WWI brought many applications of planes, but the US Navy grew tired of its primary roles of patrol and reconnaissance. Observant naval officers watched British carriers go through trials which inspired adopting aircraft that provided offensive and defensive capabilities onboard future ships.

Seeing the power of launching planes by ship, the US Navy converted the collier *USS Jupiter* in 1919 to its first aircraft carrier, christening the name *USS Langley*. With its catapult system, the crew launched Commanding Officer Kenneth Whiting off the deck (Underwood, 2015). The ship was capable of housing 36 aircraft and contained a single catapult. Two other ships started out as battle cruisers but were converted into carriers thanks to the confidence inspired by the USS Langley. The observations noted by the Navy were finally coming to fruition for an aircraft carrier launching aircraft in multiple roles. The US Navy practiced tactics with its new carriers, proving the superiority of air power that would prove to be crucial in the next war.

Through Darkness, Light Pierces through

World War II introduce the sheer strength of carrier-based air power, with the war in the Pacific beginning with the Japanese skillfully planning a preemptive strike on the US Pacific Fleet in Pearl Harbor, Hawaii, on December 7, 1941, that heavily damaged many ships in port (Bilstein, 2001). Three aircraft carriers: the *Saratoga*, *Lexington*, and *Enterprise* along with their respective battle groups were out to sea performing various missions, so the response time to battle the Japanese was quicker than Japan anticipated (Rice, 1979). The Japanese missed opportunities to take out fueling supplies and repair facilities in Pearl Harbor enabling the US to repair and send ships out to sea (Bilstein, 2001).

In response to the attack on Pearl Harbor, the United States entered World War II. The Pacific Fleet gathered its resources to combat the Imperial Fleet although the American carriers were outnumbered. Two significant naval battles took place, the battle of Coral Sea, and the Battle of Midway. The Battle of Coral Sea marked the first naval battle where neither opposing carrier saw each other; the battle was waged entirely by air (Navy, 2016). The attack left the Imperial Fleet in disarray with 39 planes out of 125 returning and many of the seasoned pilots for Japan dead. Although the USS Lexington's crew had to abandon ship, Yorktown was repaired and steam forward with the Hornet and Enterprise. The Japanese enticed the US to follow the Japanese to an unfavorable position so they could strike, but the US deciphered the Japanese code and used the information strike back. On June 4-7, 1942, US Navy achieved an upset victory by sinking four Japanese carriers and gaining the upper hand in the Pacific (Navy, 2016). The United States and allied forces made headway to the Japanese mainland. The crippled Imperial Fleet and heavy losses of personnel and ships ultimately led to the surrender of Japan in Tokyo Bay on September 2, 1945; nearly one month after the atomic bombings of Hiroshima and Nagasaki (Bilstein, 2001).

Air superiority was the key factor to the success of the war in the Pacific. Logistic capabilities improved getting supplies and troops to strategic locations. New technology brought with it the most destructive force created by man. WWII was the deadliest war ever with 50 million fatalities (Philip's Encyclopedia, 2008). The conflict brought with it tremendous sacrifices of people but also many technological advancements such as pressurized aircraft and axial-flow jet engines were derived over the period of the war (Bilstein, 2001). Industrial production during the war demonstrated efficiency improvements such as person-hours required for assembly on the B-17 decreased from 55,000 to 19,000 hours in over three years (Bilstein, 2001).

The war also required some ingenious ways to get heavy aircraft up in the air. Jet-assisted takeoff (JATO) enabled heavy transports and bombers to liftoff from saturated fields and naval flying boats to launch from the deck of ships during poor sea states (Bilstein, 2001). Launching bombers and flying boats with a rocket was not the safest choice. Several years after the war, the British developed a practical way to launch heavier, more sophisticated aircraft from the brow of a ship with steam power. The US Navy took the best of what the British did and incorporated many key features into its new supercarriers such as angled flight decks and steam catapults that allow four aircraft to takeoff per minute (Bilstein, 2001). Although the steam catapult emerged as the premier aircraft launcher, a forward thinking design was in work in the US and was patented soon after the war.

The Electric Car Catapult

The electromagnetic catapult derived from linear machines that produce linear force and generation of motion throughout the length of the machine (Yan, Zhang, Peng, Zhang & Jiao, 2016). The linear motor was studied by Charles Wheatstone back in the 1840s but was limited to batteries and permanent

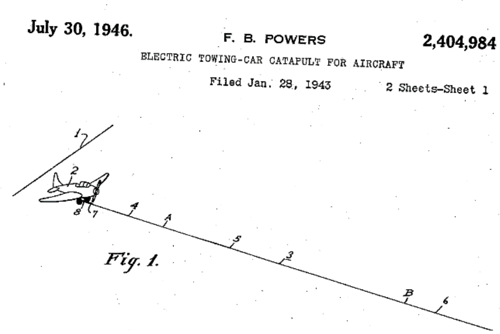


Figure . Electric towing-car catapult for aircraft (Sheet 1). Patent filed with US Government, January 28, 1943, Powers, B., retrieved from: https://www.google.com/patents/US2404984 magnets (Bowers, 2001). The Westinghouse Company took the idea further and applied it to launching aircraft. The idea was patented as the electric towing-car catapult for aircraft by Frank B. Powers in 1946 and even today is cited by multiple companies such as Central Japan Railway Company and Exhaustless, Inc (Powers, 1946). Powers' design utilized a self-moving towing-car that moved down the runway using an induction motor that generated acceleration by magnetic field attraction between a primary and secondary members. Because the design was flat and low, it would act more of a carriage than the catapults today with a launch bar and could be adapted to various types of the landing gear (Powers, 1946). The design was also known as the "Electropult" and utilized a quarter mile track to accelerate an aircraft to 100 MPH in just 4 seconds (Bowers, 2001).

Powers (1946) referenced that the catapult would be beneficial for land-based aircraft and locations that required significant lengthening for larger, heavier aircraft would see the best use of his design. Also, for flight planning purposes, he noted that it was desirable to know the velocity and direction of gusts along with the weight of aircraft to predetermine liftoff (Powers, 1946). Although assumed, the patent did not reference limited to no friction between the primary and secondary members of the system created by electromagnetic fields. The idea of launching aircraft through linear induction motors was confined to its time because of the lack of useful computer technology, multi-megawatt power systems utilizing generators, means for energy storage and power conversion (Bowers, 2001).

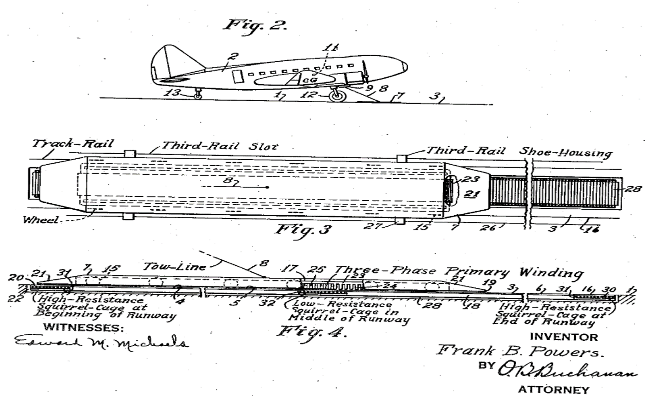
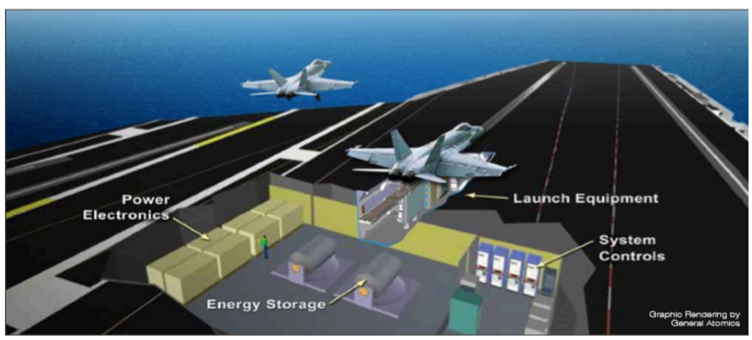


Figure . Electric towing-car catapult for aircraft (Sheet 2). Patent filed with US Government, January 28, 1943, Powers, B., From: https://www.google.com/patents/US2404984

Powers' system did not see significant investment until garnering interest from the military, nearly 50 years later.

Resurrection of the Electric Catapult

In 2004, the US Navy announced that San Diego, California-based General Atomics was awarded a System Development and Demonstration (SDD) contract to design and integrate a full-scale electronic catapult system at NAVAIR Lakehurst, located at Naval Air Engineering Station Lakehurst, New Jersey (Navy, 2004). The US Navy intended to replace aging steam catapults on its future aircraft carriers, with the newest class of carrier employing the system in 2014. The system became known as Electromagnetic Aircraft Launch Systems (EMALS). The new technology would allow for aircraft to be launched with graded acceleration, reducing stress on airframes (General Atomics, 2016). Naval Air Systems Command (2016) claimed other benefits included:



- Increased system reliability and efficiency;
- Cost reduction over time due to decreased manning and maintenance requirements;
- Launching wider array of aircraft, to include unmanned and heavy fighter aircraft;
- Reduced volume and weight of equipment;
- And cooler, quieter operation.

The benefits of the system are ideal for compact spaces aboard carriers and launching different types of aircraft. The technology has not been without a few shortcomings. In January

2010, a software error hindered progress and delayed testing with a cost to the US Navy estimated at $52,000 (Frost, 2011). As the kinks were worked out of the system, the Navy kept steam catapults as the backup plan; if faced to enact it, development of CVN-78 would be extended 15 to 18 months and cost millions. Fortunately, General Atomics was able to demonstrate the capability of the system and inspired confidence that the project would achieve its estimated time of completion (Frost, 2011). Several years later, the Congressional Research Service reported that the US Navy did not fully understand the maintenance requirements of the system and that system maintenance could only be performed during non-flight operations (O’Rourke, 2016). For steam catapults on the Nimitz class, flight operations could still meet mission requirements while maintenance was performed on the non-operating catapult. EMALS requires a complete shutdown, cutting power from all four electric catapults, a significant downside that affects warfighting capability. The point of the system was to increase warfighting capability by increasing launches through advanced electronics.

In theory, the idea of using electricity to generate acceleration to launch aircraft sounds like the best direction. Using the system creates possibilities that aren’t possible with steam systems. What can be certain is the approximate 340 Mean Cycles Between Critical Failure (MCBCF), which means one launch per aircraft, is not going to cut meet the demands of the military service (O’Rourke, 2016). The goal of 4,166 MCBCF is going to require the system to go through major changes before it inspires confidence as a true solution.

Electromagnetic propulsion has gone through rigorous usage and has demonstrated that it requires less maintenance time and is more efficient than traditional means of oil, coal and even steam. EMALS enables the Navy with a capability to adjust its catapult system on the fly with the same benefits that other transportation systems have enjoyed. Powers' design was limited by the technology of its time and Britain showed the world the effectiveness of steam power. At the start of 21st century, the US Navy looked for its replacement and its decision of electromagnetic propulsion was truly forward thinking, but with any new technology brings new hurdles to overcome. In 1962, the Japanese started train operations using magnetic levitation and propulsion technology are still trying to perfect it today (Suyama, 2014).

The Electromagnet Bullet

In Japan, the Shinkansen line, better known as the "Bullet Train" line (Suyama, 2014), uses electromagnetic propulsion to accelerate forward while also suspending itself by induced magnetic levitation, preventing contact with the rails. Levitating above the rail creates limited friction and increases the ability to accelerate faster (Gao, Zhou, Fang & Smith, 2016). Also with limited friction, the amount of maintenance required to upkeep the rails and train is lower compared to conventional trains touching the track by an estimated cost of 50.4 percent less per mile (TEMS, Quandel & GBSM, 2010). It was created with a focus to replace traditional trains by providing faster, cleaner travel connecting Tokyo to Osaka (Suyama, 2014).

In 2014, the Tokaido Shinkansen celebrated its 50th-anniversary since the commencement of operations. During its many years of existence, it has maintained an unblemished safety record of no train accidents, without loss of life or even injury. The train system is committed to consistency, with less than a minute of delay reported in the fiscal year of 2013 (Suyama, 2014).

The Japanese have created the most efficient train system with their Shinkansen train lines (Gao et al., 2016). The Life Cycle Energy Consumption (LCEA) research performed by Gao et al. (2016) reported that the carbon footprint from air and road transportation, to include operation, flight and driving, and infrastructure, produce roughly 95% more CO2 when compared to high-speed maglev rail transportation. Understanding the added value of magnetic levitation and propulsion seen in maglev trains can pave the way to improving not just existing train systems outside of Japan, but taking this concept and applying it other modes of transportation.

Implications on Flight Operations

The beginning of catapults to assist takeoffs at short distances has been attributed to Samul P. Langley. Although his experiment wasn't successful, the concept of guiding planes to forward flight has rigorously improved since then. Launching planes off of ships has been the primary benefactor of catapult technology. The US Navy has used this technology to project its sea power and capability across the world. It has pioneered the doctrine of flight operations out to sea, but it shares common procedures that need to be practiced for the overall safety of the pilots, crew and the people onboard and down below.

When performing flight operations, management of human error is key to preventing accidents (Rodrigues & Cusick, 2012). A sound way to implement crew resource management (CRM) is to brief with the entire crew to get everyone on the same page, especially if the flight is complex or outside of the normal scope of operations (Rodrigues & Cusick, 2012). Understanding external factors that affect takeoff performance and the length of the flight must be known and accounted for safely conducting operations.

When it comes to taking off, the gross weight of the aircraft is a key part when predicting takeoff distance (Dole & Lewis, 2000). So as the weight increases, more speed is required to generate enough lift for takeoff; the weight of the aircraft is proportional to takeoff speed, meaning as one increases, so the other also does. The effect of wind is another factor and must be considered for takeoff distance. A strong headwind provides the ability to takeoff at a lower ground velocity, while a strong tailwind allows an aircraft to generate takeoff velocity faster (Dole & Lewis, 2000).

For flight operations out to sea, Rosenthal and Walsh (1993) concluded that the safest way to conduct flight operations was for aircraft carriers to turn into the wind. The carrier would have to turn into the wind, adjust the speed if required, to create the safest way launch aircraft (Rosenthal and Walsh, 1993). Takeoff velocity is most critical during short runway lengths, so determining the takeoff distance is the most important factor for safely taking off (Dole & Lewis, 2000). Additionally, pressure altitude and ambient temperature affect density altitude, which can cause several effects on takeoff performance such as an increase in takeoff velocity and can also decrease thrust, reducing the acceleration rate (Hurt, 1965). Density altitude will not affect supercharged reciprocating engines until reaching critical altitude (Hurt, 1965).

Rosenthal and Walsh's concept of conducting flight operations out to sea is not easily replicated on land. If the envelope for takeoff isn't safe, especially during crosswinds, it's important to postpone taking off and wait for a safe condition to exist. Applying the land-based catapult can introduce both positive and negative implications. If there is only one runway utilizing a catapult, the headwind or tailwind should be in a beneficial direction. If there's a crosswind, it's be safer using a catapult to guide the aircraft to lift off, preventing crosswinds from affecting the aircraft until released by the catapult to prevent runoff. Another beneficial use is during icing, which the NTSB (Weener, 2011) listed the FAA to apply current research improve the way aircraft are designed, to safely guide the aircraft down the runway until the velocity for takeoff is reached.

Airports that have multiple runways could have designated runways non-equipped catapult aircraft, so they would be funneled to these runways to minimize the impact of departing aircraft. It could also provide an incentive for airlines to retrofit their aircraft with a launch bar or applicable technology to take advantage of EMALS. Retrofitting aircraft with a launch bar would seem to be difficult to engineer, but EMALS utilizes gradual acceleration that is computer controlled (Naval Systems Command, 2015). It is not feasible with a steam catapult because the pressure is released instantaneously, with the sudden impact putting more stress on the airframe and the gear. Gradual acceleration would create a minimal impact to the airframe with a properly incorporated system. A concern of retrofitting a launch bar to the nose section of an aircraft is an additional stress to that location. Utilizing Powers' (1946) original concept of using a carriage under the aircraft could bypass the launch bar requirement and minimize impact to landing gear and airframe. To minimize the impact of using catapults on runways, arriving aircraft would not have to worry impacting the system. Only during launches, the launch system would appear. When not activated, the system would retract into the runway. If aircraft were launching in clusters, the system would return to its starting position, with the next aircraft aligning to the system and its takeoff path.

Updating Future Aircraft and Retrofit

The GABRIEL Project was a forward-looking project that investigated using maglev technology to assist not only with takeoff but landing (Rohacs & Rohacs, 2014). The GABRIEL Project (2014) estimated that removing landing gear would save an estimated 9.3 percent of total weight of an aircraft and reduce takeoff fuel consumption by 79.6 percent. The project borrows Powers' concept of using a sled or cart but completely replaces the landing gear with ground-based equipment. The biggest problem with this concept is addressing emergency landing and certification of the technology. If EMALS can be properly implemented by the US

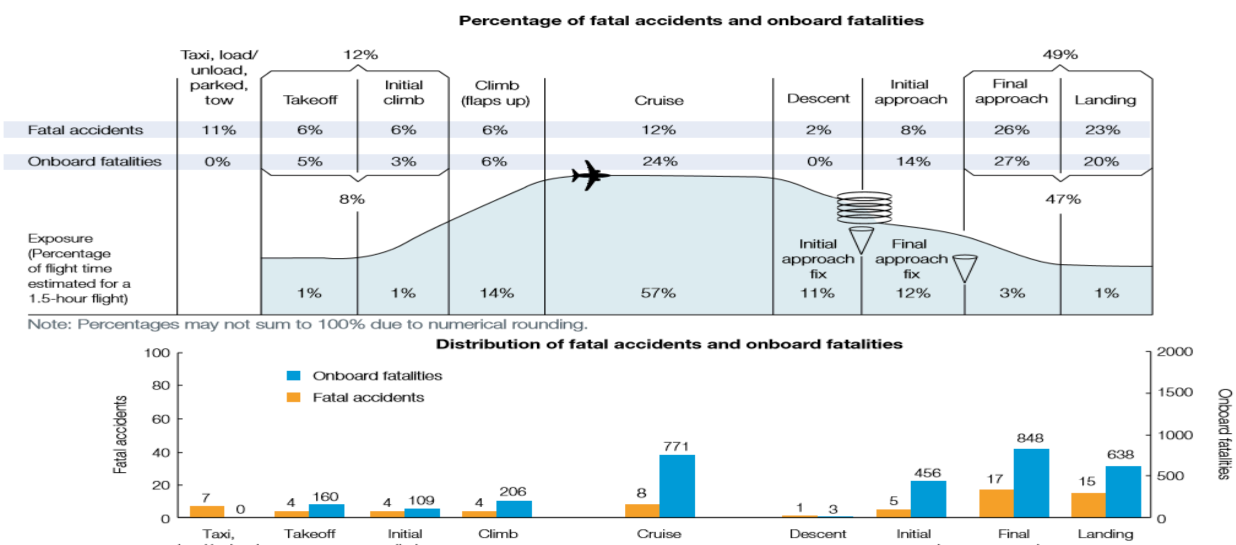


Figure . Fatal accidents and onboard fatalities by phase of flight (2006-2015). From Statistical Summary of Commercial Jet Airplane Accidents, July 2016, Boeing, retrieved from: http://www.boeing.com/resources/boeingdotcom/company/about_bca/pdf/statsum.pdf

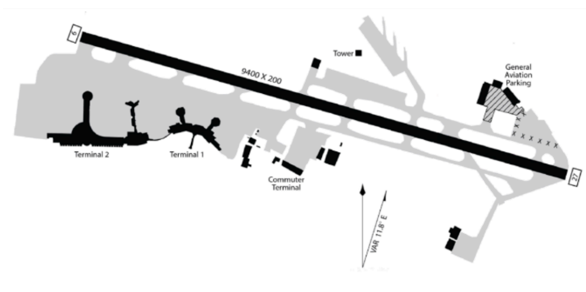
Navy, it may inspire confidence in applying technology such as GABRIEL and EMALS for civilian use. Advanced electronics and sensing technology would also need to be implemented with onboard flight control system to guide aircraft safely to the landing gear on the runway. The development of EMALS and implementation into daily flight could inspire detachable landing gear, accounting for both sides of the most critical phases of flight. Boeing (2016) accounted for 47% of fatalities onboard during final approach and landing, resulting in the loss of 1,486 lives from 2006 to 2015.

Aligning the collaboration effort from General Atomics (GA) and the US Navy with improving civil aviation can provide a solution to preventing thousands of pounds of fuel burnt during take-off. Boeing (2008) reported that the 777-200 Extended Range used an estimated 3,605 to 3,730 pounds of fuel during each takeoff (depending on the setting of flaps). Also,

AIRPLANE MODEL	TAKEOFF GROSS WEIGHT Pounds (kilograms)	PROFILE TYPE	TAKEOFF FLAP SETTING	FUEL USED Pounds (kilograms)	FUEL DIFFERENTIAL Pounds (kilograms)
717-200	113,000 (51,256)	1	18	4,061 (1,842)	-
		2	5	3,859 (1,750)	202 (92)
737-800 Winglets	160,000 (72,575)	1	15	5,273 (2,392)	-
		2	5	5,069 (2,299)	204 (93)
777-200 Extended Range	555,000 (249,476)	1	20	14,710 (6,672)	-
		2	5	14,018 (6,358)	692 (314)
747-400	725,000 (328,855)	1	20	21,419 (9,715)	-
		2	10	20,532 (9,313)	887 (403)
747-400 Freighter	790,000 (358,338)	1	20	23,558 (10,686)	-
		2	10	22,472 (10,193)	1,086 (493)

during takeoff and the initial climb phases, Boeing (2016) reported that 12 percent of fatal accidents occurred. If there's a way to save fuel and increase safety, the electromagnetic catapult system appears to be a solid solution.

The amount of fuel spent (burnt and in costs) during takeoff appears to be initially negligible but can change depending on airfield elevation, runway slope, air temperature, wind, runway length and the flap configuration (Hurt, 1965). During shorter takeoffs at locations such as San Diego International Airport, San Diego, CA, and Midway International Airport, Chicago, IL, flap angles have to be increased to account for the shorter takeoff distance (FAA, 2016). In a 747-400, Boeing (2008) reported that with a flap setting of 10 degrees burns an estimated 5,633 pounds of fuel and when set at 20, it burns an estimated 5,772 pounds of fuel. It leaves us with fuel differential of 139 pounds of fuel or 20.32 gallons if using Jet A as the base fuel. The weight of Jet A is 6.84 per US gallon (e2Energy, 2011). In August 2015, Aviation Week Network (2015) listed the US national average price of Jet A was $5.20, at this price with 20.32 gallons used, the initial takeoff at a shorter distance resulted in an increased cost of $105.67. As fossil fuels continue to rise in price, contributed to inflation and scarcity, airline companies will have to search for ways to save.



At San Diego International from fiscal years 2009 to 2015, the average daily capacity was 802 (FAA, 2016). Splitting operations between arrival and departures, this leaves an estimated 401 departures per day. Using the Boeing 747-400 as the base aircraft and the requirement of increased flaps for shorter takeoff at San Diego International, the estimated cost of fuel and gallons burnt during daily departures is $42,343.48 and 8,143. Over the course of one year, an estimated 2,972,018 gallons of fuel and $15,455,370 in expenses will have incurred San Diego International.

In addition to lessening fuel consumption, environmental factors such as noise abatement and CO2 emissions will also benefit. The usage of ground-based equipment could reduce CO2 by burning less fuel and noise generated by aircraft during takeoff would be less. Supporting the

FAA's Continuous Lower Energy, Emissions, and Noise (CLEEN) Initiative (2015), $125 million has being invested in driving down noise and CO2 emissions. The FAA's goal is to reduce noise level by 32 decibels, improve engine technology that reduces takeoff and landing emissions 60 percent below current ICAO standards, reduce aircraft fuel consumption by 33 percent, and discover new technology for engines and retrofitting aircraft (FAA, 2015).

Assisted takeoffs contribute to the FAA's initiative. Locations that are highly populated and can't afford runway expansion require aircraft to set flaps to the highest degree to generate lift (Boeing, 2008). This requires more thrust from the aircraft, therefore, increase fuel consumption. When operating at full capacity, the noise generated is estimated between 100 to 130 decibels (FAA, 2015). Utilizing catapult technology will directly impact the CLEEN initiative and enable the FAA to reach its objectives.

Implementing Maintenance Requirements

The US Navy has implemented a maintenance plan specifically for launch and recovery equipment. With $742.6 million being invested into EMALS, the Navy requires that plan to properly implemented with its new technology (Defense Industry Daily, 2016). The program plan is known as the Aircraft Launch and Recovery (ALRE) Program. The primary objective of the program is to achieve and sustain maximum operational readiness of all associated equipment and maintain a zero maintenance error rate with the incorporation of standardized operating procedures, quality assurance practices and review of inspection records and documentation (CNATT, 2013).

The program splits maintenance across three different levels. The levels are organizational, intermediate and depot. Maintenance tasking is split in this way to maintain readiness and material conditions at the lowest practical level;

- Organizational maintenance ensures equipment is properly serviced and within specified limits. In addition, unscheduled maintenance such as troubleshooting and corrective procedures are used to return equipment to a ready condition.
- Intermediate level maintenance is performed at designated facilities to perform tests and modify equipment. Calibration also is performed to ensure equipment is in specified limits.
- Depot level supports both organizational and intermediate maintenance by performing major overhauls of equipment by modernization through modification or full conversion of equipment.

The Naval Aviation Maintenance Program (NAMP) (2013) breaks maintenance into two classifications; upkeep and rework. Upkeep is preventive maintenance, which consists of performing routine maintenance such as daily evaluations of equipment using checklists and experience of personnel, servicing, and non-destructive inspections. Rework maintenance includes major overhauls of equipment and external calibration. The purpose of performing both types of maintenance is to ensure safe operation and life expectancy of the equipment (NAMP, 2013).

Complying with maintenance requirements also requires documentation. Properly documenting the maintenance performed through inspection records ensuring equipment is inspected at required intervals. Ensuring limited life components do not pass usage is critical to safe operation. Life limited components are specified to last if operated beyond its limit can result in catastrophe. The US Navy uses logbooks for steam catapults and will most likely use the same concept to ensure EMALS meets the same standards (CNATT, 2013).

As systems are used over time, issues may arise such as failures. If these failures are consistently happening between upkeep intervals, it must be reported to incorporate additional inspections to prevent failures from happening. Reporting these failures can ensure other locations look at these problems and learn from them. It is a must in aviation in to report reoccurring and even single system failures to get information out and solve the problem (NAMP, 2013).

The NAMP (2013) categorizes several types of maintenance inspections;

- Turnaround Inspections- Ensure integrity of equipment, verify servicing and detect any degradation;
- Daily Inspections- Inspect for defects in greater depth than a turnaround inspection;
- Servicing- replenish fuel and oil;
- Special Inspections- Conduct at specified intervals, such as every 7, 14, and 28 days, and after so many uses;
- Conditional Inspections- Conduct after abnormal operation or specified over limits;
- Phase Inspections- Takes the total maintenance schedule and divides it up evenly at specified intervals such as 200 hours of operation;
- And Zonal Inspections- Inspect specific locations to evaluate for obvious defects.

Not all inspections may apply to electronic catapults; but since aircraft will be launched daily from the system, consideration must be taken to ensure at all times that aircraft are being launched safely (CNATT, 2013). Conducting system checks after major maintenance being performed, such as dry-loads, ensures the system is fully capable of performing its duties. After a specified amount of launches, the guide track and launch block would require an inspection to ensure no cracks, damage or corrosion are present (CNATT, 2013).

Flight Line Personnel

Training flight line personnel in the upkeep of equipment and hiring technical experts to monitor and troubleshoot systems can keep system downtime to a minimum. With the implementation of new equipment, management must be proactive and listen to personnel performing the job. Communication is key to getting the job done right, the first time. Assigning the right people with knowledge and experience is the first part of the equation, ensuring they have all the publications and instructions along with the tools and parts to perform the job is the other.

Top level management must take a serious approach to procedural compliance. Not complying with procedures can cause premature failure of aircraft structure or components, forcing aircraft to perform an emergency landing, or even worse crash. Foreign Object Damage (FOD) is a program that every person that works on the flight line, performing maintenance or flying, accounts for every tool and item taken with them (NAMP, 2013). Not complying with this program can result in loss of life, not only to the people flying in the plane but the people down below. Each person flying in the plane has a family, so this loss of life creates a domino effect on every person involved.

Quality in Maintenance should not be in question, especially when assigning jobs to personnel. When supervisors face pressure from their management, they have to filter it so they do not place unneeded pressure on their personnel. Supervisors must also ensure their personnel have a clear mental state and are not affected by drugs or alcohol. Other external factors such as relationships and finances can also have negative effects on personnel. Mitigating those factors by communicating with personnel and identifying issues can help prevent precursors to unsafe acts. A healthy organization is only as good as the people that work there.

When working on the flight line, supervisors and crews need to communicate to the air traffic control tower to ensure traffic is clear or redirected during the time of maintenance. With proper coordination, runway incursions should be the least of everyone's worries.

The Easy Way

When it comes to new concepts, it is easy to say it won't work. Life experiences will dictate the actions taken. When working with others, fall back to the Golden Rule of "Treating others the way we want to be treated," is the first step respecting others ideas and experiences. For the Wright Brothers, they were committed to the dream of sustainable flight. Although others dismissed their accomplishments at first, eventually people saw for themselves and bought into the wave of the future. Without staying committed to dreams, the human race will become stagnant. Not every idea will takeoff, but dreaming and trying to achieve those possibilities may allow for something even greater to be stumbled upon.

The linear motor was originally developed in the 1840s and it took nearly a hundred years for it to see use. The steam catapult has provided the capability of launching four aircraft per minute over the past 65 years. Today, EMALS is being incorporated into the US Navy's newest carrier and is set to be the forefront of its future warfighting capability. As EMALS solidifies itself as the premier capability of launching various sizes of aircraft, manned or unmanned, it will mature and expand beyond the decks of ships.

The Gabriel Project and EMALS are forward-thinking concepts that can significantly contribute to improving civilian aviation. The only downfall is that current technology is limited and it has to be proven first. Additionally, the infrastructure requires a large initial investment that the government and multiple organizations will have to buy into. The certification process in the United States would have to come from the FAA. IATA has taken the recommendations of GABRIEL Project and added it to the Flightpath 2050 Technology Roadmap (GABRIEL Project, 2014).

A Brighter Future

The UNICEF and the World Health Organization (WHO) (2016) estimate 783 million people don't have the proper access to clean and safe water in the world with even more that are not located in places that have adequate food and supplies for survival. Most airports are located in populated and developed locations. Some locations of the world are inaccessible by fixed wing aircraft because proper runways are unable to be built or have limited economic interest. The only way to reach these locations is by boat, helicopter or foot. These rural areas are usually limited to specific groups of people, detached from the rest of the world.

EMALS opens the possibility of serving these people by allowing aircraft to land with short-distance runways. A runway utilizing a catapult to launch and for recovery a catch wire to slow down and stop. To power the catapult and retracting catch wire requires an energy source. The most abundant, sustainable source is solar energy (SEIA, 2016). Implementation of an integrated solar panel system when able these locations operate without large investments of infrastructure. The energy gathered by the panels would be converted to power generators, charging the catapult system to launch aircraft. Additionally, the energy would also be used to power associated lights for the runway and taxiway. The system would be completely self-sustaining and would enable people to thrive across the globe.

Conclusion

Japan has demonstrated its electromagnetic train system is the most efficient transportation system in the world. Resurrecting Powers' "Electropult" to implement into the next carrier, the US Navy and General Atomics have several hurdles to overcome. The project is pushing aviation into a brighter future and with time, civil aviation will see electromagnetic systems as a viable solution increasing efficiency and safety.

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Figure 4. Electric towing-car catapult for aircraft (Sheet 2). Patent filed with US Government, January 28, 1943, Powers, B. From: https://www.google.com/patents/US2404984

Figure 5. EMALS and associated equipment installed on an aircraft carrier. From "Electromagnetic Aircraft Launch System," June 1, 2016, General Atomics, From: http://www.ga.com/websites/ga/images/products/defense/emals/EMALS_Data-060116.pdf

Figure 6. N700-I "Bullet Train" in operation in Japan. From: http://www.japantransport.com/seminar/JRCENTRAL.pdf

Figure 7. Fatal accidents and onboard fatalities by phase of flight (2006-2015). From Statistical Summary of Commercial Jet Airplane Accidents, July 2016, Boeing, retrieved from: http://www.boeing.com/resources/boeingdotcom/company/about_bca/pdf/statsum.pdf

Figure 8. Effects of combining takeoff and climb strategies. Retrieved from:

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Figure 9. San Diego International airport map. From FAA. Retrieved from:

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APPENDIX A

The Next Step in Modern Aviation: Civil Application of Electromagnetic Aircraft Launch System

by

Sheldon T. Frye

A Research Project Proposal

Submitted to the Worldwide Campus

In Partial Fulfillment of the Requirements

of Course ASCI 490, The Aeronautical Science Capstone Course,

for the Bachelor of Science in Aeronautics Degree

Embry-Riddle Aeronautical University

August 2016

Abstract

The most critical times during the flight, which can also be contributed to the majority of fatal accidents, is takeoffs and landings. Creating a means to simplify at least one phase of flight can justify the purpose of investment in an idea that has been in development since the 1950s. Electromagnetic aircraft launch system (EMALS) is the answer in providing safer, greener, more efficient means of taking off to the sky. EMALS is currently deployed on the United States Navy's newest aircraft carrier, CVN-78, and is currently expanding future iterations. The benefit of launching multiple sizes and forms of aircraft on-the-fly is undeniable for the military; providing launch after launch with minimal maintenance required on the gear. The application of EMALS will be further matured and will expand to larger military aircraft. Once proven over time, the electromagnetic catapult will be adapted to civil aviation. A wide array of aircraft can easily be adapted to the system, accounting for aircraft weight, weather and other conditions that are computed through advanced electronic and computer technology. EMALS is poised to launch civil aviation into safe, clean and green future.

Keywords: aircraft, aviation, efficient, electromagnetic, maintenance, safety.

The Next Step in Modern Aviation: Civil Application of Electromagnetic Aircraft Launch System

Statement of the Project

Current development in US naval aviation has been focused on the replacing aging steam catapult systems on aircraft carriers. EMALS is the cornerstone to replacing this system. It has been demonstrated through rigorous other uses that electromagnetic propulsion requires less maintenance time and is more efficient than traditional means of oil, coal and even steam. EMALS has enabled the Navy with a capability to adjust its catapult system on the fly thanks to the development of advanced electronics through a contract with General Atomics, who is bringing EMALS to life.

The purpose of this paper is to discover the benefit of using EMALS for civil aviation. This project is an individual project that will draw points from accredited sources and evaluate available data on electromagnetic propulsion transportation systems, patents related to such systems, and the collaboration effort of General Atomics and the US Navy.

This paper is written to satisfy the requirements of Embry-Riddle Aeronautical University's Bachelor of Science in Aeronautics and contribute to improving modern aviation.

Introduction

Electromagnetic Aircraft Launch Systems (EMALS) allows for aircraft to be launched with graded acceleration, reducing stress on the airframe (General Atomics, 2016). The ability to readily control EMALS through computer technology and electronics gives way to faster launch turnarounds increasing warfighting capability for the US Navy. The use of advanced electronics also allows for catapult configurations that weren't possible with steam technology; paving the way for larger aircraft and smaller, unmanned aircraft, to takeoff at a short distance with the system.

Aligning the collaboration effort from General Atomics (GA) and the US Navy with improving civil aviation can provide a solution to preventing thousands of pounds of fuel burnt during take-off. Boeing (2008) reported that the 777-200 Extended Range used an estimated 3,605 to 3,730 pounds of fuel during each takeoff (depending on the setting of flaps). Also, during takeoff and the initial climb phases, Boeing (2016) reported that 12 percent of fatal accidents occurred. If there's a way to save fuel and increase safety, the electromagnetic catapult system appears to be a solid solution.

In Japan, the Shinkansen line, better known as the "Bullet Train" line (Suyama, 2014), uses electromagnetic propulsion to propel the train forward; it also suspends the train through magnetic levitation, preventing the train from making contact with the rails, creating limited friction and increasing acceleration (Gao, Zhou, Fang & Smith, 2016). With limited friction, the amount of maintenance required to upkeep the rails and train is lower compared to standard trains touching the track. It was created with a focus to replace traditional trains by providing faster, cleaner travel connecting Tokyo to Osaka (Suyama, 2014).

In 2014, the Tokaido Shinkansen celebrated its 50^{th}-anniversary commencement of operations. During its many years of operation, it has maintained an unblemished safety record of no train accidents, without loss of life or even injury. The train system has been committed to consistency, with less than a minute of delay reported in the fiscal year of 2013 (Suyama, 2014). The Japanese have created the most efficient train system in the Shinkansen train lines (Gao et al., 2016). Understanding the added value of magnetic levitation and propulsion seen in maglev trains can pave the way to improving not just existing train systems outside of Japan, but taking this concept and applying it other modes of transportation.

Life Cycle Energy Consumption (LCEA) is an approach to calculate all energy inputs, from the initial manufacturing of the product (to include energy used to produce individual components, materials and other services required in the overall process) (Gao et al., 2016). The research performed by Gao et al. (2016) reported that the carbon footprint from air and road transportation, to include operation, flight and driving, and infrastructure, produce roughly 95% more CO2 when compared to high-speed rail transportation.

The amount of fuel spent (burnt and in costs) during takeoff is appeared to be initially negligible but can change depending on airfield elevation, runway slope, air temperature, wind, runway length and the flap configuration (Hurt, 1965). During shorter takeoffs at locations such as San Diego International Airport, San Diego, CA, and Midway International Airport, Chicago, IL, flap angles have to be increased to account for the shorter takeoff distance (FAA, 2016). In a 747-400, Boeing (2008) reported that with a flap setting of 10 degrees burns an estimated 5,633 pounds of fuel and when set at 20, it burns an estimated 5,772 pounds of fuel. This leaves us with fuel differential of 139 pounds of fuel or 20.32 gallons if using Jet A as the base fuel. The weight of Jet A is 6.84 per US gallon (e2Energy, 2011). In August 2015, Aviation Week Network (2015) listed the US national average price of Jet A was $5.20, at this price with 20.32 gallons used, the initial takeoff at a shorter distance resulted in an increased cost of $105.67. As fossil fuels continue to rise in price, contributed to inflation and scarcity, airline companies will have to search for ways to save.

At San Diego International from fiscal years 2009 to 2015, the average daily capacity was 802 (FAA, 2016). Splitting operations between arrival and departures, this leaves an estimated 401 departures per day. Using the Boeing 747-400 as the base aircraft and the requirement of increased flaps for shorter takeoff at San Diego International, the estimated cost of fuel and gallons burnt during daily departures is $42,343.48 and 8,143. Over the course of one year, an estimated 2,972,018 gallons of fuel and $15,455,370 in expenses will have incurred San Diego International.

Small adjustments can pay huge dividends in the future. Showing the right source the benefits of the system such as the FAA, US government, airport management and airliners can generate interest. A well thought out plan covering each faucet of the implementation process is the biggest hurdle. Laying the foundation for EMALS starts with dedicated research. Commitment to the purpose of the implementation and having the vision to see it through is the key to success. EMALS is the next major improvement for aviation that needs to happen now.

Program Outcomes to be Addressed

Critical Thinking

"The student will show evidence of knowledge at a synthesis level to define and solve problems within professional and personal environments" (ERAU, 2015, pp. 12).

Looking at a problem and understanding each factor that contributes to it will create a path for a solution. Solutions are not clear cut, but assessing the problem will allow for the ability to define it and from there, making a decision on a direction to take will be easier. The US Navy identified that it needed to improve its air superiority capability, so it enlisted the help of General Atomics to develop a new system to replace aging steam catapults.

Civil aviation has used the concept of long runways when compared to the short length of an aircraft carrier. What's the benefit of investing time and effort in a launch system for civil aircraft? The assistance from a guided launch system will allow aircraft to burn less fuel, creating less CO2 emissions and saving the airlines money. The initial investment for any new system is high, but over time it will pay for itself. Drawing from data available on EMALS and related electromagnetic transportations systems will justify the purpose of civil aviation using an electromagnetic catapult.

Information must be gathered from: the FAA for safety statistics, runway lengths and estimated departures per day; the United States Navy and General Atomics regarding EMALS development; transportation sources utilizing electromagnets; and Boeing aircraft fuel consumption based on takeoff distance.

Quantitative Reasoning

"The student will show evidence of the use of digitally-enabled technology & analysis techniques to interpret data for the purpose of drawing valid conclusions and solving associated problems" (ERAU, 2015, pp. 14).

Gathering numerical data such as fuel consumption during takeoff and the number of departures per day will show evidence of how much fuel is burnt. Finding the cost of fuel and factoring consumption of fuel per takeoff and the number of departures per day will give the information that is significant to justifying the purpose of developing a way to decrease costs and burn less fuel. Laying out the cost over time for system implementation will show the benefit outweighs the cost.

Numerical data will be gathered from Boeing's internal study on fuel consumption and the number of departures per day will be derived from NextGen data from the FAA.

Information Literacy

***"**The student will show evidence of meaningful research, including gathering information from primary and secondary sources and incorporating and documenting source material in their writing"* (ERAU, 2015, pp. 15).

Incorporating information from the FAA, Boeing, IATA, ICAO, US Navy, General Atomics, electromagnetic transportation systems will provide evidence to support the purpose of this project. Other academic resources such as the Hunt Library, Google Scholar, Aerodynamics for Naval Aviators, Modern Jet Transport Performance, Practical Aviation Law, and Flight Theory and Aerodynamics will be used to draw conclusions on improving civil aviation by using EMALS.

Communication

"The student will show evidence of communicating concepts in written, digital, and oral forms to present technical and non-technical information" (ERAU, 2015, pp. 16).

This project will present information by using a written report that uses visual aids to demonstrate technical and non-technical information so it can be understood by various audiences. Thoroughly understanding civil aviation and how incorporating EMALS into it will justify the purpose of the project. The collaboration between the US Navy and General Atomics must be the central point of demonstrating the successful deployment of EMALS. Discovering the success of transportation systems that use electromagnetics, like reduced maintenance cost and lower CO_2 emissions, can help sell the idea of using EMALS for civil aviation.

Scientific Literacy

"*The student will show evidence of analyzing scientific evidence as it relates to the* *physical world and its interrelationship with human values and interests"* (ERAU, 2015, pp. 18).

Demonstrating how EMALS will improve civil aviation, such as less energy consumption and lower carbon footprint, will enable others to understand the benefits of EMALS implementation. Because the goal of EMALS to make civil aviation safer, greener and more efficient, many people can buy into the project and align their values with the project's purpose. Evaluating data from sources that extend beyond aviation, such as train operations and maintenance will help solidify the support for EMALS for civil aviation.

Cultural Literacy

"*The student will show evidence of the analysis of historic events, cultural artifacts and philosophical concepts"* (ERAU, 2015, pp. 18).

Looking at historical data and understanding concepts from major contributors to aviation; not just limited to the United States, but global aviation history. Gathering information from these people and events will provide better understanding on the direction of project. Starting from the inception of man taking to the skies like bird, commitment to the vision of to build off these ideas and concepts to improve aviation. Using historical information from the History of Flight, FAA data, and the Smithsonian will provide a solid foundation to build off of.

Lifelong Personal Growth

"The student will show evidence of the skills needed to enrich the quality of life through activities which enhance and promote lifetime learning" (ERAU, 2015, pp. 20).

With a professional career, continuously applying knowledge and learning new concepts will provide great benefit to one's career and any organization that they're associated with. Finding ways to improve aeronautical science by utilizing experience, knowledge and available information to analyze and discover new concepts will ensure contributions to aeronautical professional field. Staying engaged with people by encouraging them to achieve the impossible and establishing obtainable goals can ensure positive direction.

Aeronautical Science

"*The student will show evidence of advanced concepts of aviation, aerospace, and aeronautics to solve problems commonly found in their respective industries"* (ERAU, 2015, pp. 21).

Drawing from aeronautical science concepts and research will justify the benefit of implementing EMALS. Applying aeronautical concepts and demonstrating the benefit of EMALS to civil aviation by providing safer and more efficient means of taking off is the overall aim of this project. Evaluating and interpreting data in areas such as the amount of fuel burnt during takeoff, changing flap angles, FAA takeoff safety-related statistical information, and reported EMALS operational statistics from General Atomics will point towards achievable improvements in modern aviation with implementation of EMALS.

Aviation Legislation and Law

"*The student will show evidence of the basic concepts in national and international legislation and law as they pertain to the aviation, aerospace and aeronautics industries"* (ERAU, 2015, pp. 22).

Understanding current FAA regulations, the ICAO, multinational rules and regulations that affect global aviation can help further modern aviation while still being in compliance. Evaluating current rules and regulations will ensure the research stays in compliance and can be adapted, if required, into civil aviation. Research will provide evidence for a safer, greener approach to modern aviation. Evaluating current rules and regulations while also looking at available military data from the US Navy and General Atomics for EMALS will allow for any adjustments need prior to implementation for civil aviation.

Aviation Safety

"*The student will show evidence of basic concepts in aviation safety as they pertain to the aviation, aerospace, aeronautics industry"* (ERAU, 2015, pp. 24).

Using FAA and Boeing safety data will allow for analysis of improving takeoff and initial climb phases of flight. EMALS can improve takeoff and initial climb by providing gradual acceleration and controllability, guiding aircraft until generating enough lift for takeoff. Data has shown that takeoffs are critical times during flight operations, so creating a safer experience can ease the minds of pilots, passengers and airports. Evaluating current safety information such as circulars and advisories, the FAA and other related studies can provide more justification for the incorporation of EMALS.

Aviation Management and Operations

"*The student will show evidence of sound, ethical management principles within standard aviation, aerospace, and aeronautics operations"* (ERAU, 2015, pp. 25).

Applying the understanding of aviation operations and management principles to identify the benefit of utilizing EMALS by performing research in maintenance for EMALS and required enhancements to aircraft so EMALS can be utilized. Available data to identify maintenance requirements and estimations to outfitting aircraft with gear required to using EMALS. Data from the US Navy and General Atomics to identify requirements of maintenance for EMALS and look at aircraft that utilize catapults for take-off.

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