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Reducing Weight and Fuel Consumption of Civil Aircraft by EML

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***Abstract*—**Electromagnetic Launch (EML) systems have been proposed for military applications to accelerate jet planes on aircraft carriers. This paper proposes the implementation of similar technology to aid civil aircraft take-off, which can provide significant economic, environmental and technical benefits. Assisted launch has the potential of reducing on ground noise and emissions near airports and improving overall aircraft efficiency through reducing engine thrust requirements. This paper presents a take-off performance analysis for an Airbus A320-200 taking off with and without the assistance of the electromagnetic catapult. Assisted take-off allows for a significant reduction in take-off field length, giving more capacity with existing airport footprints and reducing the necessary footprint of new airports, which will both reduce costs and increase the number of suitable sites. The electromagnetic catapult may allow the installation of smaller engines with lower rated thrust. The consequent fuel consumption and operational cost reduction is estimated. The potential of reducing the aircraft operational costs and the runway length required make EML system an attractive solution to the air traffic growth in busy airports.

***Keywords*—**EML system, fuel consumption, take-off analysis, weight reduction.

I. Introduction

EML systems have been used to replace the existing steam catapults on current and future aircraft carriers [1]. The steam catapults are large, heavy, and operate without feedback control. An EML system offers lower weight, volume, and maintenance and higher controllability, availability, reliability, and efficiency [2].

This paper proposes the implementation of similar technology to aid civil aircraft take-off in order to reduce the take-off field length and avoid expensive runway extension in modern city airports. The machine topology mainly considered for EML systems for civil aircraft take-off are linear induction motor and linear permanent magnet synchronous motor [3]. The electrical machines design has been proven feasible for the actual technology readiness level (TRL 2) [4].

The launch capability of an electromagnetic catapult can be exploited during take-off to propel civil passenger transport aircraft which are heavier than jet aircraft, but accelerate at lower rate. A reduction in take-off distance and aircraft energy use can be achieved by exploiting the high level of thrust that EML systems are able to deliver. The related acceleration level is selected to guarantee the passengers comfort and safety during take-off. The electromagnetic catapult is used until the nose-rotation speed is reached and the aircraft detaches from the front undercarriage.

EML systems can significantly reduce fuel consumption and exhaust emissions at ground level. In particular, assisted take-off decreases the peak power required from the engines, so that smaller engines can be installed to accomplish the aircraft's mission. The reduced engine cross section and nacelle wet area yield a lower drag coefficient which has positive impact on the fuel consumption across all the stages of the flight.

The take-off performance analysis for an Airbus A320-200 is performed to evaluate the impact of the electromagnetic catapult. The main outcomes are compared assuming constant take-off weight and showing the different flight distances and fuel consumptions across all the flight phases. Then, the engine's rated thrust is progressively reduced to accomplish the minimum climb out gradient requirement established by Federal Aviation Regulation (FAR) [5]. The correct value of the aerodynamic drag and engine thrust at take-off are estimated considering flap deflection and International Standard Atmosphere (ISA) deviation. In this case, the take-off performance analysis is carried out to evaluate the impact of the engine thrust and size reduction on the weight of the aircraft at take-off and to determine the variation of the amount of fuel required to complete the aircraft's mission.

The paper quantifies the possible benefits of the electromagnetic catapult in an example of modern hub airport and estimates the annual fuel saving and operational costs reduction for airline operators.

II. Take-Off Performance Analysis

The first step in estimating the take-off performance is to establish the climb out gradient γ available at the end of runway at an altitude of 10.4 m (35 ft) and the flap deflection during the initial acceleration. To ensure a sufficient level of safety for the passenger, the take-off procedure is investigated considering a possible engine failure at any stage. The aircraft has to be capable of completing the take-off procedure safely with one engine inoperative.

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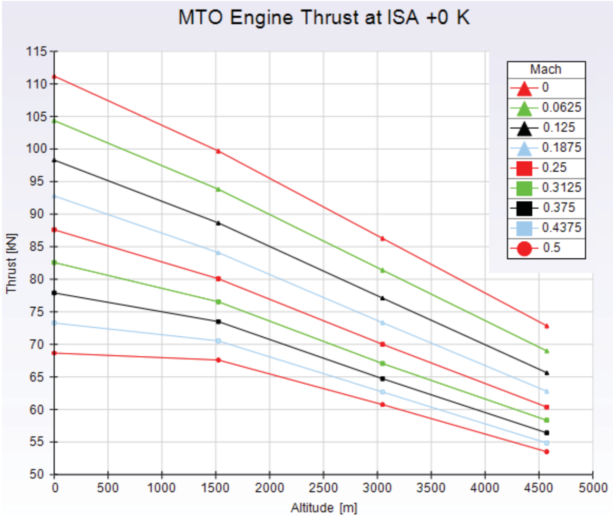

Fig. 1 Thrust decrease with airport altitude and aircraft Mach number

The climb out gradient may be expressed as a function of the aircraft net thrust T and of the aerodynamic drag D as

$$\gamma = \frac{T - D}{W} \tag{1}$$

where W is the weight of the aircraft and V the aircraft speed. The minimum climb out gradient requirement in (2) considered during the take-off design procedure ensures that the aircraft can avoid a 35 ft obstacle at the end of the runway with enough clearance and with a sufficient thrust excess to allow safe operations [5].

$$\gamma_{min} = 0.018 + 0.003 \cdot N_{eng} \tag{2}$$

where N_{eng} is the number of engines. In order to verify whether $\gamma > \gamma_{min}$, it is necessary to determine the thrust and drag force in one-engine-inoperative conditions.

A. Thrust

When the aircraft speed and altitude change, the engines deliver different levels of thrust according to the rating the pilot can select for each particular flight condition. The thrust decrease during take-off with the airport altitude and the aircraft speed is shown in Fig. 1. The Mach number in Fig. 1 is the ratio between the aircraft speed and the speed of sound. The thrust profiles also depend on the local atmospheric conditions and in particular on the air temperature. This analysis is carried out in standard air at 20 °C often referred as ISA [6].

Assuming an aircraft taking off at sea level, the thrust can be computed from the take-off speed using the engine data in Fig. 1. The aircraft take-off speed is calculated as

$$V_{TO} = \sqrt{\frac{2W}{\rho_{air} S_w C_L}} \tag{3}$$

where ρ_{air} is the air density, S_w is the wing surface, and C_L is the lift coefficient. The lift coefficient is assumed to be approximately the 70% of the maximum lift coefficient achievable with a flap deflection of 15°.

B. Aerodynamic Drag

The aerodynamic drag can be computed using the expression:

$$D = \frac{1}{2} \rho_{air} S_w C_D {V_{TO}}^2 \tag{4}$$

where the drag coefficient C_D corresponds the lift coefficient C_L in (3). In one-engine inoperative condition, the total aerodynamic drag needs to consider some additional contribution due to the engine failure.

When an engine fails the pressure losses in the air flow across the engine due to the movements of the fan, compressor and turbine blades are associated with a drag increment called windmilling drag. The windimilling drag D_{WML} can be computed as [7]:

$$D_{WML} = \frac{1}{2} \rho_{air} S_{eng} {V_{TO}}^2 \cdot 0.3 \tag{5}$$

where S_{eng} is the engine cross section and is often assumed to be 80% of the nacelle cross-section.

When an engine fails, the asymmetric thrust generates a momentum around the vertical axis of the aircraft that tends to destabilize the trajectory. This momentum is compensated by a rudder deflection that generates a counteracting force that allows the aircraft to continue the take-off maintaining the desired direction. Any rudder deflection causes an additional drag force called trim drag that can be estimated as

$$D_{Trim} = \frac{1}{2} \rho_{air} S_{ESDU} {V_{TO}}^2 \cdot C_{D\,Trim} \tag{6}$$

where S_{ESDU} and $C_{D\,Trim}$ are the reference wing area and the trim drag coefficient established experimentally in [8]. The total drag can be now determined summing up the results of (4)-(6).

Once the total drag and thrust are known, the available climb out gradient can be determined using (1). If the requirement $\gamma > \gamma_{min}$ is not respected, the entire procedure has to be repeated with a lower flap angle.

III. Take-Off Time and Aircraft Fuel Consumption

In order to estimate the amount of fuel consumed by the aircraft during the take-off phase and determine the fuel saving due to the electromagnetic catapult implementation, an estimation of the time required to complete the take-off procedure is required. The take-off elapsed time is needed because the fuel consumption is often expressed as a mass flow in kilograms per second.

The engine fuel flow for an A320-200 with CFM56-5A1 engines has been obtained from the evaluation of the performance of the engines using the data provided in [9].

The take-off procedure can be subdivided in three different phases, each one with a specific elapsed time:

1. *Take-off Run*: acceleration from standstill position to the instant at which the aircraft leaves the ground;
2. *Airborne Phase*: phase that starts when the aircraft becomes airborne until it reaches the altitude of 35 ft;
3. *Climb Out*: the aircraft gains altitude and speed until it reaches 1500 ft.

The catapult affects time and fuel consumption during the first take-off phase whereas the other remain unchanged.

The time t_{Run} required by the engine boosted A320 to get the take-off speed can be estimated as:

$$t_{Run} = \frac{\sqrt{2}}{2gV_{TO}} \int_0^{V_{TO}} \frac{dV^2}{\frac{T}{W} - \mu - (C_D - \mu C_L)\frac{1}{2}\frac{\rho_{air}S_W V^2}{W}} \quad (7)$$

where g is the gravitational acceleration and μ is the ground friction coefficient [10]. When the catapult operates, a constant acceleration can be achieved independently from ground friction and aerodynamic drag. In this situation, the time required to reach the take-off speed is

$$t_{Run} = \frac{V_{TO}}{0.6g} \quad (8)$$

where 0.6 g is the catapult rated acceleration.

The time $t_{Airborne}$ required to complete the airborne phase can be estimated on the basis of the energy conservation principle; i.e., the kinetic and potential energy variations are equal to the energy in input.

$$t_{Airborne} = \left(\frac{{V_{Obs}}^2 - {V_{TO}}^2}{2g} + h_{Obs}\right)\frac{1}{\gamma V_{TO}} \quad (9)$$

where $V_{Obs}$is the speed above the virtual obstacle and $h_{Obs}$is the obstacle height (35 ft). In a similar way, the time required to climb up to the altitude h_{Climb} of 1500 ft and terminate the take-off phase is

$$t_{Climb} = \left(\frac{V_{Climb} - V_{Obs}}{g} + \frac{2(h_{Climb} - h_{Obs})}{V_{Climb} + V_{Obs}}\right)\frac{\bar{W}}{\bar{T} - \bar{D}} \quad (10)$$

where V_{Climb} is the speed at the end of the take-off phase, and $\bar{W}$, $\bar{T}$, and $\bar{D}$ are the average aircraft weight, thrust, and aerodynamic drag during the climb out phase, respectively.

The times t_{Run}, $t_{Airborne}$, and t_{Climb} can be multiplied by the respective fuel flow to determine the fuel consumption.

IV. Impact of EML on the Aircraft Mission

The take-off analysis presented in the previous section is applied to compare the take-off performance of an aircraft A320-200 with CFM56-5A1 engines accelerating with and without the aid of the electromagnetic catapult.

When the aircraft takes off with the maximum weight, the fuel saved using the electromagnetic catapult can be used to extend the aircraft operating range. On the other hand, the aircraft that takes off with the catapult can travel the same distance consuming the less fuel and having a reduced take-off weight. Therefore, the take-off analysis has been carried out simulating two possible mission scenarios:

TABLE I
A320-200 Mission Data Comparison

Parameter	Conventional take-off	EML with constant take-off weight	EML with constant mission range
Take-off weight	73500 kg	73500 kg	73447 kg
Fuel	18273 kg	18273 kg	18221 kg
Range	2450 NM	2459.3 NM	2450 NM

TABLE II
Take-Off History Comparison

Aircraft A320-200 conventional take-off				
	Start	Run	Airborne	Climb Out
Altitude [ft]	0.0	0.0	35	1500
Time [s]	0.0	23.41	29.62	96.0
Weight [kg]	73500	73439	73422	73252
Fuel Burnt [kg]	0.0	61.4	77.72	248.37
Speed [m/s]	0.0	72.99	79.66	131.4
Fuel Flow [kg/s]	2.584	2.622	2.630	2.619
Thrust [kN]	222.4	181.1	177.74	163.04

Aircraft A320-200 assisted take-off					
	Start	Idle	Max Throttle	Airborne	Climb Out
Altitude [ft]	0.0	0.0	0.0	35	1500
Time [s]	0.0	7.62	11.62	17.83	84.0
Weight [kg]	73500	73498	73487	73471	73300
Fuel Burnt [kg]	0	2.14	12.63	28.95	199.8
Speed [m/s]	0.0	44.81	72.99	79.66	131.4
Fuel Flow [kg/s]	0.281	0.281	2.622	2.630	2.619
Thrust [kN]	0.0	0.0	181.1	177.74	163.04

1. Take-off with constant weight;
2. Mission with constant range.

The main outcomes of the take-off performance analysis are reported in Table I. The calculation of the flight characteristics across the full aircraft mission was performed in order to compare the effects of EML all over the flight. The computation techniques can be found in [10].

Table II compares the characteristics of an aircraft A320-200 with conventional take-off and assisted take-off. When the aircraft accelerates with the aid of the electromagnetic catapult, the engines do not need to provide any thrust and they initially work in idle condition. This particular operating mode can be noticed in the second part of Table II where the initial fuel flow corresponds to the one required to keep the turbine blade in motion without any thrust production. Since the engines usually take approximately 4 seconds to pass from idle to full throttle condition, the changing of engine rating is considered only few seconds before the take-off.

V. Engine Size Reduction

It has been shown how the electromagnetic launcher brings significant benefits for city airports in terms of take-off field length, fuel consumption, and fuel emission. However, it does not seem to imply drastic cost relief for airline operators which do not experience consistent annual saving on aircraft operational costs. The fuel saving corresponds to a cost saving $S_€$ that can be computed as

$$S_€ = \frac{M_{Fuel}}{\rho_{Fuel}} F_€ \tag{11}$$

TABLE III
FLIGHT PERFORMANCE OF AN AIRCRAFT A320-200 WITH REDUCED ENGINE SIZE AND ASSISTED TAKE-OFF

Thrust [kN]	111.2	105.0	100.0	95.0	90.0	85.0
Climb Gradient	2.471	2.417	2.421	2.434	2.974	2.606
Flap Angle	14°	11°	8°	4°	0°	0°
Drag Coefficient	.03231	.03219	.03209	.03199	.03189	.03179
T.O. length [m]	1347	1411	1471	1547	2247	2243
T.O. weight [kg]	73447	72674	72357	71448	70832	70270
Fuel mass [kg]	18273	17936	17816	17493	17267	17092
Eng. mass [kg]	5921	5583	5447	5042	4773	4506
Struct. mass [kg]	20929	20814	20767	20629	20536	20445

where M_{Fuel} is the mass of the fuel burnt, $\rho_{Fuel}$is the fuel density and $F_€$ is the fuel price per liter. Considering that a civil transport aircraft completes approximately 750 flights every year, (11) estimates an annual saving of 27315 €/year which is negligible compare to the fuel annual expense of 8.227 M€/year. The total investment on fuel in Heathrow airport may be reduced by 23670 €/day and 8.64 M€/year, but this does not directly affect a single airline.

The take-off analysis can be applied to estimate the performance of the aircraft A320-200 with smaller engines and reduced rated thrust. This can be done exploiting EML system during the initial acceleration and satisfying the climb out requirements $\gamma > \gamma_{min}$in (2). Equation (1) shows that a thrust decrease implies a climb gradient reduction. However, the reduction of the nacelle cross section and wet area causes a reduction of the aerodynamic drag across all the flight phases as can be seen in Table III.

The reduction of the engine mass has a positive impact on the mass of the aircraft structure, for the decrement of the mass of the nacelle and of the engine structural supports. Drag and weight reduction significantly decreases the mass of fuel needed to reach the final destination and the maximum take-off weight MTOW.

Even though the engine thrust reduction has such a positive impact on the overall flight performances extra care must be dedicated to the aircraft performance in adverse atmospheric conditions. In fact, the data in Table III were obtained in standard atmospheric condition at sea level. The engine performance decrease with the altitude and the environmental temperature imposes a limit on the thrust reduction. Accounting for airport altitude and atmospheric conditions, a thrust reduction to 105 kN is accepted. With this different installed thrust, the aircraft would save 337 kg of fuel each flight to accomplish the same mission (2450 NM).

Equation (11) can be applied to estimate the annual saving of the airline operator of an A320-200 with reduced installed thrust. Considering 750 flights per year 189800 €/year can be saved, approximately 2.31 % of the total fuel expense.

VI. RUNWAY LENGTH REDUCTION

The take-off analysis allows the estimation of the take-off field length considering the times in (7) and (9) and the average speeds during the respective phase. Considering a possible failure at any time during the aircraft acceleration the take-off field length required by the A320-200 conventional take-off is approximately 2260 m.

TABLE IV
ENGINE EXHAUST EMISSION

Mode	Power setting	Emission Indices [g/kg]		
		HC	CO	NOx
Take-off	100 %	0.23	0.9	24.6
Climb	85 %	0.23	0.9	19.6
Approach	30 %	0.40	2.5	8.0
Idle	7 %	1.40	17.6	4.0
Emission reduction at Heathrow [g/day]		7251	28373	775515
Exhaust emission for passenger car [g/day]		35.4	309	22.78
Equivalent number of cars		205	92	34044

Table III reports the runway length required by assisted take-off. The take-off length of EML can reach 50% of the conventional distance, so that actual runways could be used to serve two aircraft taking off simultaneously from the center of the runway and accelerating in opposite direction, virtually doubling the airport capacity. EML launch system may be a viable alternative either to Heathrow third runway or to the Heathrow runway extension proposals of £17.6 billion and £14.4 billion, respectively [11]. The cost of two launchers would be approximately one tenth of the lump sum reported in the official proposal for the Heathrow runway extension. The suggested technology may not have only a significant economic impact, but it also affects the local communities living around airport by preventing the need of mandatory home purchase, 242 for the runway extension, and 783 for the third runway [11].

VII. NOISE AND EXHAUST EMISSION REDUCTION

The comparison of the take-off performance in Tables I and II shows that the EML meanly impacts the take-off distances and the take-off time leading to lower fuel consumption. The 48.5 kg of fuel that is saved on each flight can be used to cover longer flight distances or can be removed to fly with lighter aircraft.

The propellant that can be saved in single flight is just a small portion of the total amount of fuel on board the aircraft at the departure. However, considering an airport like Heathrow with approximately 650 flights per day and assuming the same fuel saving for each take-off, about 31525 kg of fuel can be saved on a daily basis. Although there are many kinds of airplanes with different fuel consumption, maximum thrusts and take-off times that depart from Heathrow, the A320-200 class of aircraft can be considered as an average in terms of fuel consumption.

Considering the engine emission indices per kilo of fuel burnt reported in [9], it is also possible to estimate the daily exhaust emission reduction. The emissions for each pollutant in Table IV were compared with the respective car daily emission [12]. Comparing the fuel consumption during conventional and assisted take-off, the overall exhaust emission reduction corresponds to 19.5% of the ground emission of actual airports.

Aircraft engines emit less noise during assisted take-off since the take-off procedure has a shorter duration and the engines initially work in idle condition. Assuming zero noise emission during idle operation the electromagnetic catapult has the potential of reducing the noise pollution of 20.4% with respect to conventional take-off.

VIII. Conclusion

This paper has shown the benefits in terms fuel saving, runway length and exhaust emission reduction of EML system in city airports like Heathrow. The operational cost saving for an aircraft A320-200 was estimated in the hypothesis of engine size and rated thrust reduction. Indeed, the electromagnetic catapult implementation alone would not bring any particular cost relief for airline operators, whereas the reduced thrust requirements at take-off may allow significant cost saving through the installation of smaller engines.

Although the installation cost of linear electrical motor and power conditioning system for a machine of such a high rated power is certainly high, the investments to cover the expenses foreseen in [11] are greater of an order of magnitude. Therefore, this paper proposes a valuable alternative solution to airport extensions or additional runway constructions.

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