ICAS 2021 SHANGHAI
International Council of the Aeronautical Sciences
32nd Congress of the International Council of the Aeronautical Sciences
September 6-10, 2021
Pudong Shangri-La, Shanghai, China

Rockets Hybrid Launch System Using Linear Synchronous Electric Motors

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Abstract

The launch of space heavy rockets has always been a challenging mission and witnessed various failures in the past many decades. The current traditional launch systems are employing vertical launch and are powered by main and auxiliary rocket engines. This paper discusses the hybrid launch system for large rockets powered by linear synchronous electric motors and a special track. The novel idea is to have a combination of horizontal and vertical launch and has the potential to be developed to a new technique for launching large rockets. The control of launch process is conducted utilizing a Proportional-Integral-Derivative (PID) controller. A couple of features for this method are real advantage, most important ones are low cost, reliability, stability, and safety. The verification and validation of the technique are documented using MATLAB simulation.

Keywords: Rocket launch, Linear synchronous motors, Launch power system

1. Introduction

The launch operation of space rockets has been a challenge and witnessed many failures in the past decades. The shuttle propulsion system was the most critical system during launch; therefore, a high level of testing was needed prior to launch to demonstrate engine reliability.

The primary challenges in commercial launch systems are cost, safety, maintainability over long periods of time, re-usability of the vehicle, g-forces on the vehicle and astronauts, launch setup time and duration between launches, fuel consumption, compatibility with many variations of vehicle and payload, and risk of damaging the vehicle with initial stationary ignition. Between the first space launch in 1957 and the end of 1998, approximately 4102 space launch attempts have taken place in the world and all but about 129 were successful [1].

One of the routine launch operations is the NASA commercial resupply mission to the International Space Station (ISS) by Space Shuttle and SpaceX using Dragon cargo spacecraft to deliver supplies and science investigations. Space Exploration Technologies Corp. (SpaceX) founded in 2012 with the goal of reducing space transportation costs. It manufactures heavy launch vehicles and has the ability to conduct annual Falcon launches. All launches have been conducted vertically as a conventional technique.

Despite considerable advances in the launch technique and many successful launches, there still have been a number of failures in the launch of SpaceX rockets in the past decade. For instance, a SpaceX Falcon 9 rocket exploded on Sept 1, 2016 during a static fire test [2] on a launch pad at Cape Canaveral Air Force Station in Florida, resulting in the loss of both the rocket and its $200 million payload.

Space rockets need means to accelerate up to a certain speed (usually slightly higher than a specific value) to be able to become airborne. All unmanned aircraft must initially take-off or be launched to become airborne. Moreover, at the end of the flight mission, they must land on an airfield, or be recovered. Launch involves transitioning the UAV from a nonflying state (e.g., stationary on the ground) to a flying state. In the case of a horizontal runway launch, this can be considered as a conventional takeoff. Various conventional and unconventional launch and recovery techniques have been applied to manned aircraft for over a century. The range of options is greater for unmanned aviation. These techniques are largely enabled by the exclusion of pilot physical constraints and the inclusion of much lower UAV weights.

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Vertical launch methods try to address is the inefficiency of launching a rocket at low-g's, as the time spent in the atmosphere combined with the low velocity and air resistance that absolutely tears through fuel, and therefore storage tanks and rocket boosters which must be jettisoned.

Possible major hurdles for a vertical launch are the possibility of failure, low reliability, high cost, and high g load. Assuming the average person can withstand around 2.5 sustained g's, the amount of fuel required for each vertical launch is immense, and extremely expensive.

A linear synchronous motor (LSM) is a motor by which the mechanical motion is in synchronism with the magnetic field. The force can be generated as an action of traveling magnetic field produced by a poly-phase winding and an array of magnetic poles or a variable reluctance ferromagnetic rail. This drive system has long been employed by many urban transportation [10] around the world.

In this paper, LSM is recommended as a source of generating launch thrust. Fundamental construction, feasibility, and development of DC linear motor is presented by [11]. Ref. [12] compares the relative advantages and disadvantages of that linear induction motor and mature linear synchronous motor options for urban and suburban maglev transit systems. Ref. [8] presents a novel method to design a DC-Excited linear synchronous motor. Ref [6] investigated the electric propulsion and its application to space missions including launch system.

In this paper, a novel hybrid launch system for space rockets and UAVs are presented. The governing launch equations, performance analysis, and design technique are provided. In section 2, fundamentals of hybrid launch technique and governing equations will be briefly described. The launch power system using Linear Synchronous Motors are discussed in section 3. The launch control system employing a Proportional-Integral-Derivative (PID) controller is presented in Section 4. The verification and validation of the technique are documented using MATLAB simulation in Section 5.

2. Fundamentals of Hybrid Launch Technique

One solution to solve the complexity of vertical launch is a combination of a few methods, mixed with some technology not currently being used in rockets. The launch track (Figure 1) comprises three segments: 1. Horizontal segment, 2. Circular segment, 3, Vertical/inclined segment. In the Horizontal segment, the rocket/UAV will accelerate along the track using its rocket engine along with the help launch power until reaches V_1. In the circular segment, the air vehicle begins to rotate along a circular path until reaches velocity of V_2. The third segment is the climbing operation of the vehicle until it gains the desired safe launch velocity. This part has a constant angle, either 90 degrees (i.e., vertical) or a value below that angle (i.e., inclined).

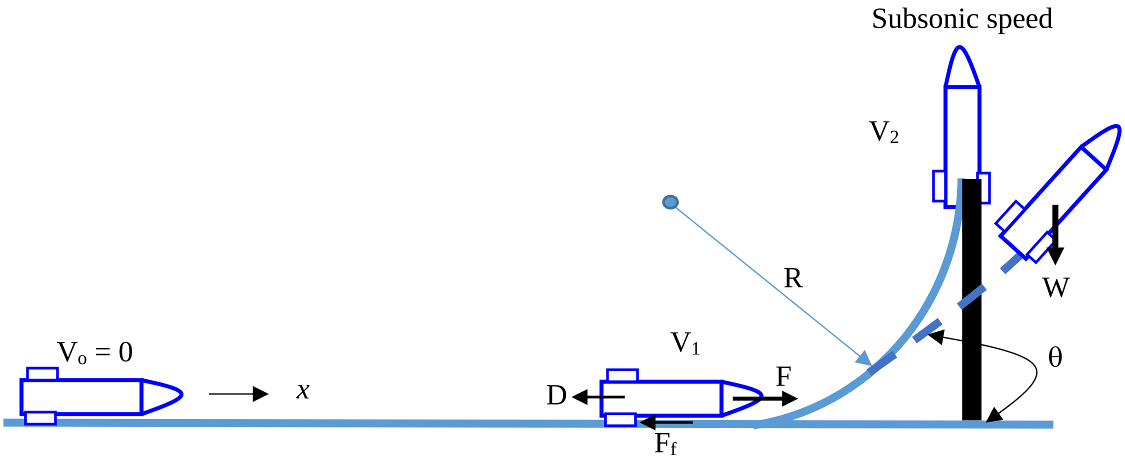

Figure 1 - Hybrid launch forces and track segments

After the rocket/UAV is placed at the beginning of the track (with a zero angle of attack and zero speed, V_o), it will wait for a ground control station (GCS) permission. At this stage, the engine is off and the brakes hold the aircraft from moving forward. Soon after the GCS receives permission to launch, the operator pushes the engine throttle to the end position and then releases the brakes. This generates the maximum permissible engine thrust and aircraft begins to accelerate, based on Newton's second law. The prime job of the track at this point is to hold the aircraft inside rails and to avoid any deviation (maintain the straight path).

At this time, remote pilot must quickly decide to continue the flight and control unwanted yaw; or abort the launch. One of factors influencing pilot's decision is the time of mishap, whether it is at the beginning of launch or at the end of horizontal motion (When speed is V_1). This operation continues until the aircraft speed reaches a specific speed, called the launch speed (V_2). Launch is considered complete when the aircraft has reached a safe altitude, or a steady climb has been established.

In the horizontal (x) direction, the summation of four horizontal forces is equal rate of change of linear momentum. If the launch force (F) is provided by the launch power system (not by the rocket itself), the rocket mass would be contact. In this case, sum of the forces is equal to vehicle mass times acceleration, a (i.e., rate of change of vehicle speed, V):

$$F - D - \mu N - Wsin(\theta) = ma = m\frac{dV}{dt} \tag{1}$$

where D denotes the vehicle (plus cart) drag, μN is the friction force (F_f), W is the vehicle (can include cart) weight, N is the normal force, a is the linear acceleration, m is the mass of vehicle plus cart, θ is the launch angle, and μ is the friction coefficient between cart and the track. If Linear Synchronous Electric Motors – for generation of thrust - are employed, the friction can be assumed to be zero. The normal force is the algebraic sum of the vehicle weight and aerodynamic lift:

$$N = W - L \tag{2}$$

The vehicle lift (L) and drag (D) forces [3] during launch operation are expressed as functions of the airspeed (V), air density (ρ), the vehicle reference area (e.g., wing, S):

$$\mathrm{L} = \frac{1}{2}\rho \mathrm{V}^2 \mathrm{S}\mathrm{C}_\mathrm{L} \tag{3}$$

$$\mathrm{D} = \frac{1}{2}\rho \mathrm{V}^2 \mathrm{S}\mathrm{C}_\mathrm{D} \tag{4}$$

where and C_L and C_D are the lift and drag coefficients, respectively. The lift and drag coefficients are primarily functions of the vehicle configuration, flight Mach number, and angle of attack, which is the angle between the vehicle axis (or the wing plane) and the launch direction. For wingless rockets or space launch vehicles, reference area is the maximum cross-sectional area normal to the vehicle x-axis.

Typical value for the C_D for a rocket with a considerable wing is about 0.01 - 0.03. However, for a wingless rocket, the C_D is about 0.15 - 0.25. The typical value for C_L during launch is from 0 to 0.2. For the calculation of C_D for an air vehicle, the technique provided by Ref. [7] is recommended. By substitution of the velocity (V = dS_T/dt) into equation 3, and solving for track length (S_T), we obtain:

$$S_\mathrm{T} = \int_o^{V_2} \frac{mV}{F - \mu N - D - Wsin(\theta)} dV \tag{5}$$

By plugging drag, lift and weight forces (Equ. 3 and 4) into equation 5, and assuming the engine thrust is constant over the course of launch, we can solve for S_G. This integration is performed from zero to launch speed (V_2).

$$S_T = \int_0^{V_2} \frac{mV}{F - mg(\mu + sin(\theta)) - \frac{1}{2}\rho V^2 S(C_D - \mu C_L)} dV \tag{6}$$

This integration can be directly solved – to find the track length - using a mathematical or engineering software package. Equ (8) can also be utilized to solve for required thrust (F), if the length of track (S_T) is given.

In the second segment, the vehicle is climbing while rotating about a circular path. This rotational motion will generate a centripetal acceleration (a_c) and a centrifugal force (F_C):

$$a_c = \frac{V^2}{R} \tag{7}$$

$$F_c = m\frac{V^2}{R} \tag{8}$$

where R is the radius of the circular path (See Figure 1). As the names imply, the centripetal force is applied outward, while the centripetal acceleration will be inward. The centripetal force must be handled by the launch structure as well as the rocket body.

There are two motion accelerations: 1. Linear along x-axis, 2. Centripetal along the radius. These two accelerations must be added as two vectors to determine the total acceleration (a_t):

$$a_t = \sqrt{a_c^2 + a^2} \tag{9}$$

This acceleration can be non-dimensionalized by diving by gravitational constant (i.e., g).

$$n = \frac{a_t}{g} \tag{10}$$

The launch acceleration will significantly influence the rocket structure as well as the installation of payloads, due to imposing inertia force (i.e., g-load). All of the on-board equipment, including sensitive camera, and navigation sensors must withstand this acceleration. Below 2g (i.e., n = 2), the amount of hardening and support needed for the equipment may be ignored. To withstand acceleration beyond 5g, installations require more substantial hardening, and will add to the cost and overall weight.

If the space rocket employs its own rocket engine during launch for generating part of the launch force, the thrust [1] contributed/provided by rocket engine(s) is:

$$F = \dot{m}V_2 + (P_2 - P_3)A_2 \tag{11}$$

where $\dot{m}$ denotes the rocket engine propellant mass flow rate, A_2 is the cross-sectional area at the nozzle exit, V_2 is the exit velocity, and P_2 is the pressure at the exit, and P_3 is the atmospheric pressure. The internal launch efficiency (η) is:

$$\eta = \frac{\frac{1}{2}\dot{m}V^2}{\eta_P P_L} \tag{12}$$

where V denotes the instant vehicle velocity, η_P is the efficiency of the rocket engines, and P_L is the launch power of vehicle rocket engines (e.g., chemical power). Due to a longer runway for a hybrid launch, instead of rocket engine, a turbofan engine can also be employed which provides much higher propulsion efficiency with a much lower overall cost. It can be shown that, the hybrid launch technique will provide a much higher efficiency as compared with a vertical launch.

3. Launch Power System

Design of hybrid launch systems is a challenging task; and requires a large amount of analysis and calculations. The design of launch system begins with development of the problem statement, and to formulate the design problem. This activity is based on the given objectives (by customer) and technical requirements (through engineering evaluations). Then, a functional analysis is performed to describe tasks or "functions" to be performed by the launch system and its major components. The functional analysis provides the baseline from which reliability requirements, maintainability requirements, human factor requirements, supportability requirements, and manufacturability requirements are identified. One of the important design requirements for a launcher is the space needed for the operation of the launch unit.

Linear synchronous electric motors have been widely employed in industry applications such as in roller coasters. They can drive a linear motion load without gears and mechanical intermediates. For instance, the Incredible Hulk roller coaster was designed in 1999 by Ing.-Büro Stengel as part of a 1-billion dollar park construction. In this roller coaster, 230 electric motors power a series of drive tires which provides 0-40 mph in 2 seconds at a 30° incline, 1 g of acceleration. Moreover, flywheels are used to draw and store energy from the grid evenly. Some characteristics of this roller coaster is provided in Table 1.

No	**Parameter**	**Value (unit)**
1	Maximum speed	67 mile/hour
2	Height	110 ft
3	Length	3,700 ft
4	Inversions	7
5	Maximum acceleration	4g
6	Capacity	1,920 riders per hour
7	Electric power per launch	8 MW

Table 1 - Some characteristics of the Incredible Hulk roller coaster

Basically, the idea is that by launching the rocket horizontally, using Linear Synchronous Motors (LSM) and a rail system separate from the rocket itself. The system is using detachable (and recoverable) wings instead of booster engines in order to get the rocket near-vertical, it eliminates the need for the entire first stage of rockets. LSMs are currently in use in amusement parks around the world as a method to launch roller coasters, and they have been proven to be reliable at quickly and smoothly accelerating large payloads hundreds of times a day.

A linear electric motor is a motor that has its stator and rotor unrolled. So, instead of producing a torque, it generates a linear force along its length. In a linear synchronous motor (LSM), the mechanical motion is in synchronism with the magnetic field. LSM drives a load (here, rocket) linearly without a need to gears and mechanical intermediates.

Linear synchronous motors [9] are the low-acceleration, high speed and high-power motors with an active winding on one side of the air-gap and an array of alternate-pole magnets on the other side. Figure 2 illustrates the free-body diagram of a U-channel synchronous linear motor (Top-view).

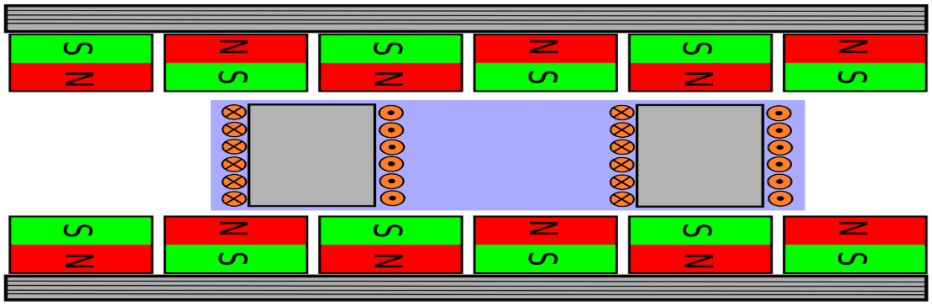

Figure 2 - Free-body diagram of a U-channel linear synchronous motor

The hybrid launch would be similar to the launch system on an aircraft carrier, except without the need for cables or many moving parts. The rocket would lay attached to a cart (Figure 3) on the rails, and would accelerate to very high subsonic Mach number, which would only take a few second. The track (rail) contains on-board exciting magnets for LSM. Flux from the exciting magnet interacts with the traveling magnetic wave from the stator to generate launch force.

The launch force is generated as an action of traveling magnetic field produced by a poly-phase winding and an array of magnetic poles or a variable reluctance ferromagnetic rail. The part that generate the magnetic flux or variable reluctance is referred to as salient pole rail [9]. The part that generates the traveling magnetic field is referred to as the armature.

The length of required track is mainly a function of rocket weight, its engine thrust, and launch power. It could be as short as a few hundreds of feet to about 2 miles. LSMs benefit from high efficiency due to low magnetizing current and zero slip. This leads to a significant reduction of inverter rating, resulting in a substantial cost saving.

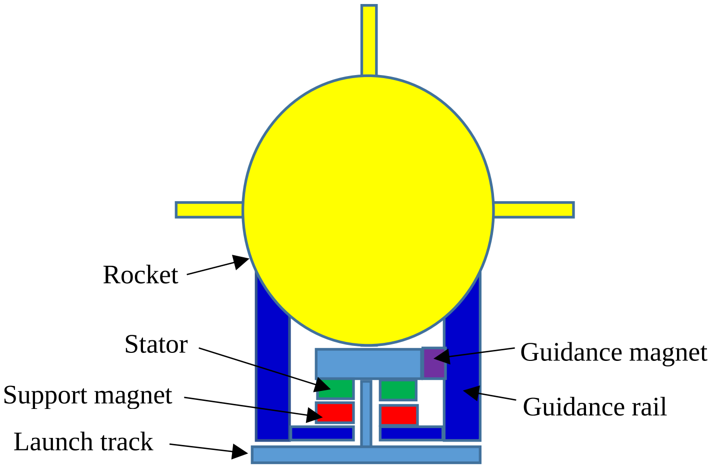

Figure 3 - Structure of the launch track and elements (back view)

By launching horizontally, not only is g-Force reduced by not accelerating against gravity, but there is plenty of time to abort should something go wrong. Even a power outage of some sort would result in an intense deceleration due to the nature of LSMs. So long as the engine is ignited to a low burn before launch, the aircraft should have no problem getting to a decent angle of ascent and having the engines kick in with a massive head start. Should something go wrong after the point of no return in the launch, the rocket can just burn off its velocity and glide back to earth.

Ref. [8] designed a single-sided WSLSM with a long primary. Three-phase iron-core windings build the primary which extended along the motion path. The rail consists of two parts, energized and not-energized sections. The moving part of the motor has an iron core and excitation electromagnetic poles. The mover is located above the primary with an air-gap to experience a contactless motion along the track. Copper windings have made the mover's electromagnetic poles. The energized section length along the primary is chosen about five times longer than the mover length. The windings are made of copper and laid in the open slots of the primary iron core.

The LSM is selected as a source of generating launch thrust along the track. The model modeling of LSMs nonlinear, long, and complicated. The electromagnetic launch force [8] developed by a LSM is obtained by:

$$F = \frac{P_{elm}}{u_s} \tag{13}$$

where P_{elm} is the electromagnetic power and u_s is the synchronous speed. The P_{elm} and u_s are functions of frequency of primary supply, the number of armature phase, rms value of the input voltage, and the rms value of armature current.

The electromagnetic power and the synchronous speed [8] are obtained by:

$$P_{elm} = mV_1 I_a cos(\phi) - mR_1 I_a^2 \tag{14}$$

$$u_s = 2f\tau \tag{15}$$

In Equ. 14 and 15, m represents the number of armature phase number, cos(ϕ) is the input power factor, I_a is the rms value of armature current, R_1 is armature winding resistance, and V_1 is the rms value of the input voltage, f is the frequency of primary supply, and τ is the mover (pole) pitch. The armature current is a function of desired launch force (F_{des}):

$$I_a = \frac{F_{des} u_s \left(\frac{1}{\eta} - 1\right)}{\rho_w l_w j_c} \tag{16}$$

where j_c is the amplitude of linear current density, ρ_w is the electrical resistivity of the primary windings, and l_w is the primary windings length. The parameter η is estimated in 0 - 1 range and will be finalized during the design.

A major requirement in launch power system design is the ability to operate at various power levels. The original launch power system life requirement could be 100 nominal missions and x number of hours of engine life at nominal thrust or rated power level.

A lower thrust requirement for hybrid launch results in smaller throat for main combustion chamber. This consequently is a significant safety improvement for the main engine by effectively reducing operating pressures and temperatures. This design also incorporates improved cooling capability for longer life which uses high-strength castings.

This launch system has a number of significant advantages as compared with conventional vertical launch. Loading rockets horizontally and setting them up would also take much less time and effort than vertically.

4. Launch Control System

Two important motion parameters need to be controlled during a launch operation: 1. Velocity (V), 2. Acceleration (a). This objective requires a closed-loop feedback control system using an appropriate control law. The goal of control law is to have a near-constant acceleration at start of the launch but ease off slightly at the end. Proximity sensors should be installed at increments along the track to measure and report rocket position and speed to calculate the linear acceleration. For safety reasons, some other parameters such as the armature current (I_a) of LSMs may be controlled too.

In literature, various aspects of LSMs including their modeling, analysis, design, and control have been discussed. For instance, Ref. [4] has presented the design and characteristic analysis on the short-stator LSM for high-speed Maglev propulsion. Here, we use a linear model, since the objective of this paper is mainly to provide the effectiveness of hybrid launch system.

The block diagram of closed-loop control system of the launch operation is shown in Figures 4. Two blocks of “s” and “1/s” represent differentiation and integration, respectively to derive acceleration from velocity and vice versa. There are motion sensors for three outputs: 1. Position is measured, 2. Velocity is calculated by differentiation of position, and incorporating time of measurement, 3. Acceleration is calculated by differentiation of velocity, and incorporating time of measurement.

The controller sends full-power signal to all motors when triggered. It may be audible for miles, launch extremely fast, and sustain unusually high forces. Various control laws (e.g., optimal, robust, and nonlinear) may be utilized to effectively control the launch operation. Due to the linear motion of the rocket along the track, a PID control law will suffice in effectively controlling the launch operation.

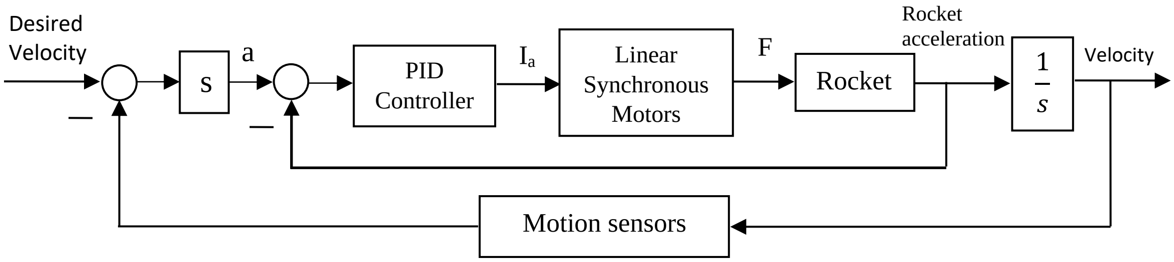

Figure 4 - Block diagram of control system of the launch operation

Launch section is controlled via a Proportional-Integral-Derivative (PID) controller. Two objectives of control are: 1. Keep the acceleration below 3g, 2. Keep the launch speed to follow the desired velocity profile and keep it below Mach 1. Rocket weight plays a major role in PID parameters due to incline angle. The controller is generating a signal to the actuators (i.e., LSM) based on a PID control law. The PID gains are functions of LSM features and rocket weight. Tabular values for PID gains may be determined for various rockets weights. The main output of the PID controller is the rms value of armature current (I_a) of LMSs, which will be the input to the LMSs. The main output of the LMSs and the track is the launch force (F), which will be the input to the rocket.

To reduce "jerk", we need to have an overdamped velocity profile. To have a successful launch, the wind speed and direction should be measured at the launch sight and incorporated in the control process. To avoid any need for vehicle yaw control, a long rail track can be constructed. Otherwise, a rudder is needed to provide directional trim/control during horizontal segment of the launch.

5. Simulation and Results

In order to validate the design outcome, a hybrid launch system including a linear model of LSM for launching a rocket with a mass of 1,000 kg has been simulated by matlab Simulink. It is desired that the rocket reaches the velocity of 100 m/sec along the track before the end of launch operation.

The simulation is presented to demonstrate the efficacy of the proposed launch system with the control algorithm. Figures 5 through 10 illustrate the simulation results for: 1. LSMs current in Amps, 2. Velocity of rocket in m/sec, 3. Vehicle non-dimensionalized acceleration, 4. Rocket displacement in meter, 5. Force generated by LSM in kN, and 6. Electric power provided to LSMs in MW, respectively. It is assumed that voltage for LSMs is 240 Volts.

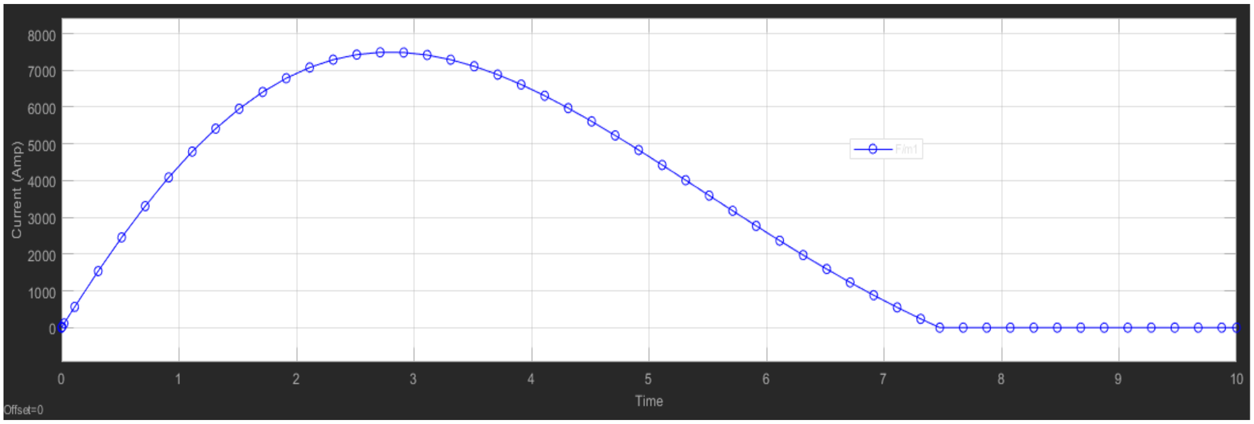

Figure 5 - Variations of LSM current (in Amps) as a function of time (in seconds)

From figure 5, the maximum current is about 7,500 Amps at 2.8 seconds to the launch. When the rocket reaches the desired velocity, the LSMs current is reduced to almost zero.

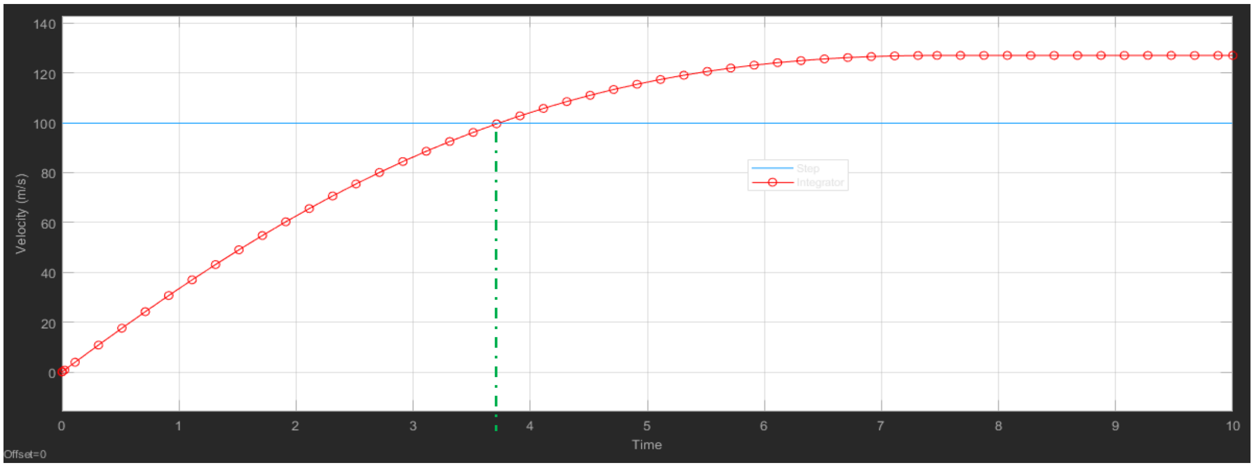

Figure 6 - Variations of rocket velocity (in m/sec) as a function of time (in seconds)

In Figure 6, the desired velocity of 100 m/sec (blue line) is a given value and shown. It can be seen that the rocket reaches this velocity in about 3.7 seconds (intersection of red graph with blue line) and continue to increase to about 125 m/sec due to the rocket linear momentum. Since no brake is considered in the launch system, the velocity is not reduced back to 100 m/sec during launch.

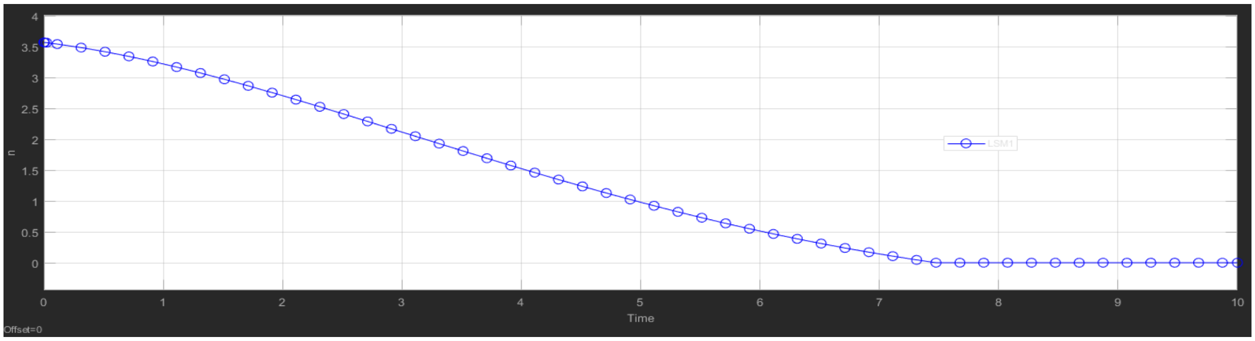

Figure 7 - Variations of vehicle non-dimensionalized acceleration as a function of time (in seconds)

As shown in Figure 7, the maximum non-dimensionalized acceleration i.e., (in g) is about 3.5, it happens in the beginning of launch. When the vehicle reaches the desired velocity, the acceleration will become zero.

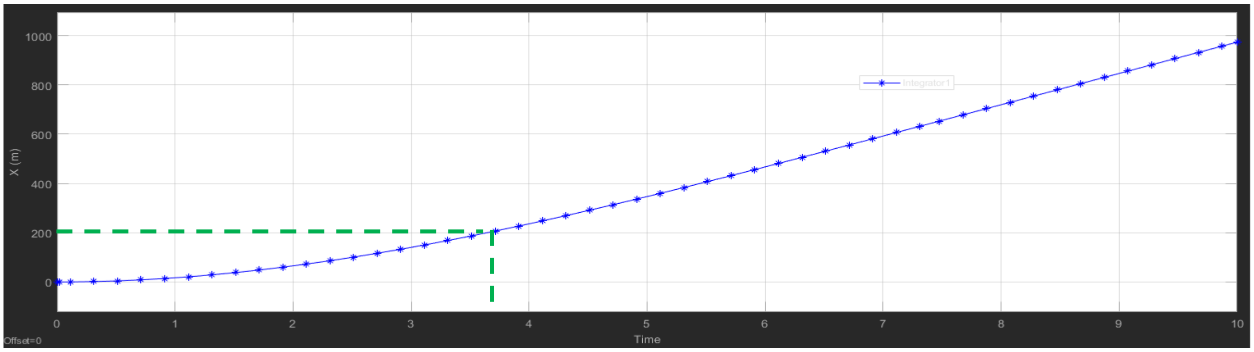

Figure 8 - Variations of vehicle displacement (in m) as a function of time (in seconds)

As shown in Figure 8, the rocket reaches 100 m/sec in about 200 meters. The rocket continues to move (due to conservation of linear momentum). However, after 10 seconds, the vehicle has displaced about 950 m. From this part of the simulation, it is concluded that a launch track with the length of 200 meters is required to launch a ticket with a mass of 1000 kg. To have a launch site for rockets with various masses and weights, a longer lunch track should be constructed.

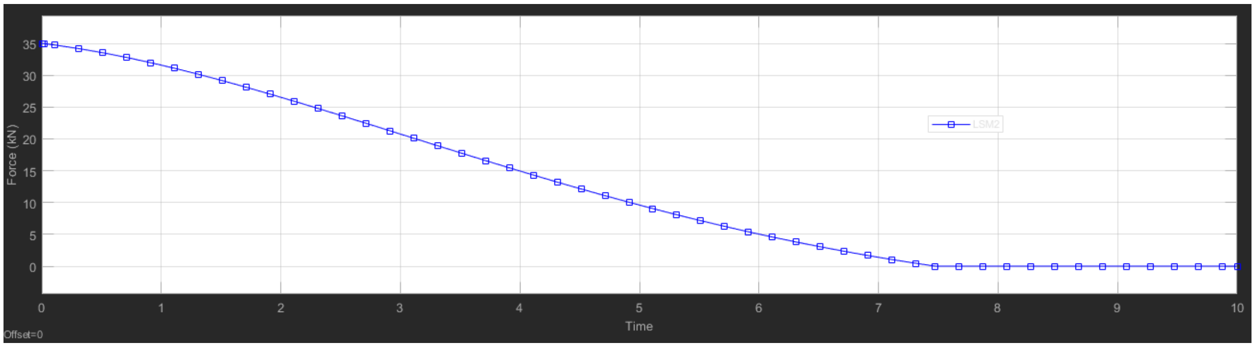

Figure 9 - Variations of the LSMs generated force (in kN) as a function of time (in seconds)

As Figure 9 indicates, the maximum force generated by LSMs is 35 kN at the beginning of launch. When the vehicle reaches the desired velocity, this force will become almost zero. Afterward, a small amount of force is needed to cover the track friction and rocket drag.

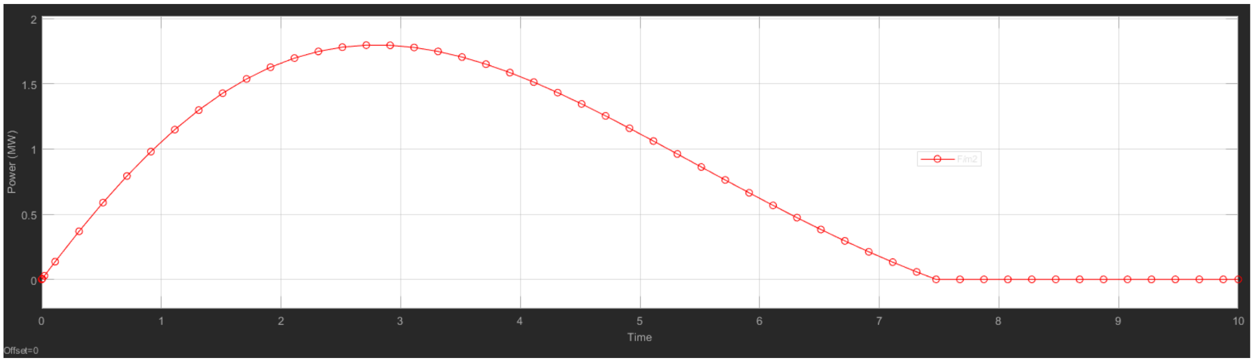

Figure 10 - Variations of the electric power (in MW) as a function of time (in seconds)

As shown in Figure 10, the maximum electric power provided to LSMs is 1.75 MW after about 2.8 seconds. BTW, the rocket engine of the vehicle should be started when the vehicle reaches the desired velocity (i.e., before rocket reaches the end of launch track). However, if the rocket own engine is operating along the track (concurrent with LSMs), the vehicle will have a much faster velocity at the end of the launch operation.

By examining the simulation results, one can conclude that hybrid launch operation is feasible. Via the PID controller, the rocket is tracking and following the desired velocity on the track. For other rockets with different weights, the PID gains should be adjusted/changed. As the simulation results indicate, the hybrid launch operations using LSMs is successful. Since, the vehicle is along a horizontal/vertical track and uses a special rail connection, the rocket is stable and reliable.

Moreover, this system can be employed over and over again for various rockets, so the overall launch cost is much lower than a vertical launch. The investment for the track and LSMs is for a long run application. Furthermore, there is no possibility of explosion by rocket engines, since the launch power system is of electric type. Thus, this hybrid launch system is highly safe.

Conclusion

This paper presented the hybrid launch system for large rockets powered by linear synchronous electric motors and a special track. This is a novel idea and can replace the current conventional vertical launch. It has a combination of horizontal and vertical launch track segments. The control of launch process is conducted utilizing a Proportional-Integral-Derivative (PID) controller. For other rockets with various weights, the PID gains should be adjusted/changed. Important features for this technique are low cost, reliability, stability, and safety. The verification and validation of the technique are documented using MATLAB simulation.

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