Magnetic Levitation Technologies and Its Potentials in the Advancement of Aircraft's Take Off System

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***Abstract* - The accelerated growth in aircraft industries desires effectual scheme, programs and innovative designs of advanced systems for accomplishing the augmenting need for home-free air transportation. For safe, efficient landing and take-off of aircraft in future, magnetic levitation technology could turn out to be the best alternative to conventional landing gear system. Thus, this review will focus on the currently available technologies in aircraft landing gear system and also the magnetic levitation concept. The magnetic levitation system will be electrically powered and thus can be better served by the renewable sources, increasing safety and reducing harmful influence on the environment caused by taking-off and landing aircraft. The track of the magnetic levitation will reduce the amount of collisions and accidents. Take–off and landing in Maglev airplanes are much faster due to the elimination of the rolling resistance and will potentially improve the power efficiency.**

***Keywords* - Magnetic levitation, take-off, landing, aircraft, controller**

I. INTRODUCTION

About 50% of the total aircraft accidents are due to the failure of the landing gear [1]. Today and in the future, noise levels are regulated by local and aviation authorities. As the predefined noise levels cannot be exceeded, noise–constrained airports have difficulties to expand and are limited in the amount of daily operation at the airport. This is mainly because of the landing and take-off track system which optimized by another airplane. Every airplane need to reach the optimized speed in order to take-off or landing. The average speed an airplane to take-off is from 120 kts to 155 kts (i.e. kts is knots unit used for aircraft velocity), which is around 240 km/h to 280 km/h [2]. Moreover, when the flight takes off the fuel which is fully used is up to 25 to 40% [1].

Redesign the magnetic levitation (Maglev) assisted take-off system can be a manner for the airport to be able to expand without violating the noise regulation due to the lower thrust setting required by the aircraft to take-off [3]. The primary source of noise pollution during take-off it's from the engine of an airplane. Magnetic levitation for the landing system directly translates to a reduction in the equivalent perceived noise level (EPNL) [3].

The new concept of magnetic levitation could reduce engine power requirement in the take-off phase, and may also reduce the adverse effect of the air traffic on the natural environment by reducing not only the emissivity during take-off and landing but also noise level in airport [4].

This paper will review on the conventional aircraft landing gear system and next discussing in details about the potential of using magnetic levitation theory for aircraft landing track in which the technology was successfully used in the high speed train system. This technology is mainly focused to decrease the fuel consumption and to decrease the surface area occupied by the airports, which can be achieved by Maglev approach.

II. CONVENTIONAL TAKE-OFF OF AIRCRAFT

The take-off is the movement skill by which an aircraft is accelerated from rest on the runway to the climb-out speed V_C over feet [5]. The take-off distance consists of two main parts, the ground run distance and the airborne distance. The ground run part comprises the pre-rotation speed V_R. The airborne distance is the phase when the aircraft's velocity goes from V_R to the lift-off speed V_{LOF}.

The different speeds occurring during take-off are shown in Fig. 1. The rotation velocity is the speed at which the pilot initiates upward rotation of the airplane [5]. The angle of attack is gradually increased from the ground attitude toward the lift-off condition such that at VLOF the airplane becomes airborne.

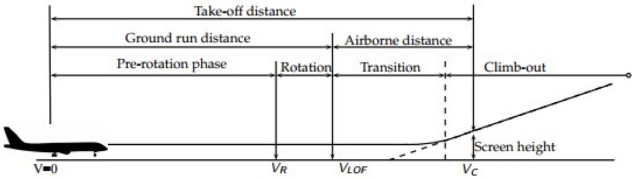


Fig. 1: The conventional take-off, adapted [5]

The balanced field lengths based on the take-off distance is illustrated in Fig. 2. One of the important take-off distance parameters is the decision speed V_1. This point of speed selected in case an engine failure is detected. The pilot can make decision to abort the take-off and make a full stop on runway or continue the take-off to the screen height with one engine out at the same distance [6].

Aircraft are able to accelerate on the ground and perform the take-off due to the presence of landing gear [7]. This is the interesting part to review on, which is different landing gear configurations exist in order to properly design magnetic assisted of take-off system.

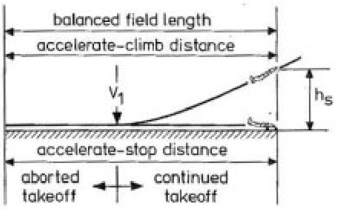


Fig. 2: The balanced field length [5]

III. A REVIEW ON MAGNETIC LEVITATION

A. *Overview*

Nowadays a range of different transportation system exists for air, sea or land transportation. Magnetic levitation system are designed and used in the rail transportation [8]. This system is called as “Maglev” which comes from magnetic and levitation system. The application of this system is in general known through conventional high-speed train systems. Maglev implies a system which vehicle are levitated from guide way by using electromagnetic force between superconducting electro magnets. Countries such as Japan, Germany, United States and China have already implemented the Maglev to their train system [8]. The Maglev using the magnetic forces to perform the functions of vehicle propulsion, levitation, guidance and motion control [9].

There are two types of magnetic suspensions system which are involved in designing the Maglev; electromagnetic suspension systems (EMS) and electrodynamics suspension system (EDS) [10]. EMS establishes levitation by magnetic attraction forces and EDS facilitate levitation by magnetic repulsion force. EMS and EDS are the most common levitation system used and implemented in the train system.

B. *Quick History of Magnetic Levitation*

In order to understand the working principle of magnetic levitation, one has to go back to the basics of electricity and magnetism. In the 18th century, Benjamin Franklin suggested the law of conservation of charge. Besides, Andre-Marie ampere discovered the magnetic effect and turned wires carrying a current into a magnet [9].

In 1831, Michael Faraday made one of the most important discovery in electromagnetism, being the first to discover include current recognized as such [9] namely Faraday’s Law of electromagnetic induction, which revealed a fundamental relationship between the voltage and flux in a circuit [10].

C. *Maglev Applications*

There are a lot of ongoing researches in the electromagnetic field, for example, there will be contactless voltage measurement via Fluke new technology. The first Maglev system was developed in the 20th century [11]. Since the early 1900s, research has been conducted on the electromagnetic method for supporting rotating and moving masses [12].

The development of electromagnetic system was only started in the late 1960s when disadvantages of the test projects based on the aircushion principle became apparent. The two main countries those focus on this implementation are Germany and Japan. The first track developed in Germany which is 100 meters long on 1976 and this entire track becomes the first Maglev licensed transportation on 1979. Fig. 3 shows the first train which using Maglev in Hamburg.

Fig. 3 Transrapid-05 developed in 1979 [9]

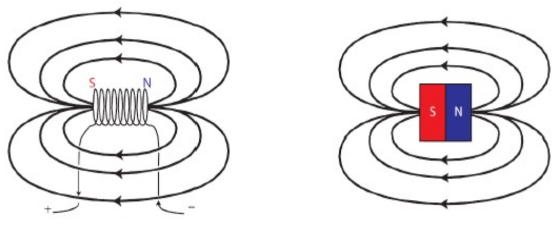
Basically, the result of the testing project was promising and the system needed to be tested under realistic conditions. Therefore, the test facilities build in 1983 and the operation is still running [12].

Seems the project gets a lot attraction and Japan started the research in the field of magnetic levitation. In 1970, there are two projects initiated by Japan Airline and high speed surface Transportation (HSST) and this project called as ‘Linear Motor Car”. The next project starts with superconductive magnetic levitation of which first test vehicle was demonstrated in 1972 [13]. Miyazaki, the first Maglev test centre was opened in 1977 [14].

Electromagnetic Suspension (EMS)

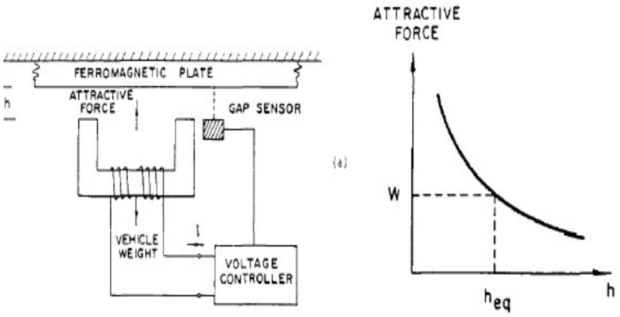
EMS creates the vehicle levitation by a magnetic attractive force between the guideway and electromagnetic [15]. Based on the Fig. 4, the electromagnet is attracted into the ferromagnetic rail and typical force characteristic is generated.

As a force increase, the air gap between the magnet and the guideway will be decreased, therefore this motion is unstable and should be controlled and it is explained in the Fig. 5. The air-gap should be controlled precisely to maintain a uniform air-gap. The air gap of the system is about 10 mm and in order to maintain this gap a number of control devices are required [15].



(a) Electromagnet [3] (b) Permanent Magnet [3]

Fig. 4: Electromagnet and permanent magnet



(a) EMS configuration (b) Force vs gap characteristics

Fig. 5: EMS characteristics [14]

Electrodynamic Suspension (EDS)

Electrodynamic suspension uses repulsive force for levitation. A magnetic field created when the magnets attached to the vehicle move forward on the inducing coils or conducting sheets located at the guideway; this creates induced currents that flow through the coils or sheets generating a magnetic field [10].

A repulsive force originates between the magnetic field and the magnets, which levitates the vehicle. EDS is magnetically stable such that is unnecessary to control the air gap. The air gap is larger than in the EMS system and can be about 10 cm or more. EDS it is not very sensitive to variation of the load [16]. High load variation and the lack of necessity to control the air gap makes this system suited for high speed operations. This EDS system generally considered suited for high-speed transport travelling at velocities beyond 300 km/h. Two types of magnets can used for levitations and propulsion is this system, either superconductive electromagnetic (SC) or permanent magnet (PM).

Japanese JR-MagLev, the Japanese Linear Chuo shinkkansen Project MLX makes use of EDS. Repulsive force is produced between stationary short- circuited coils and moving superconductive electromagnets (SC). These SC electromagnets require cryogenic refrigeration and are located on the vehicle itself [22].

The track of the Maglev has concrete U–Shape. Through the interaction of inductors, currents and the induced currents vertical and lateral force created. It is used as linear synchronous ironless (LSM) propulsion.

When the train is propelled by the LSM at high speed, strong repulsive and lateral stabilizing force are produced in the vehicle by inducing currents in the short-circuited coils together with magnetic field excited by superconducting electromagnets. These superconducting EMS is used for levitation, lateral guidance and propulsion. Fig. 6 shows the propulsion coils and levitation-guidance coils attached to the concrete side walls of guideway.

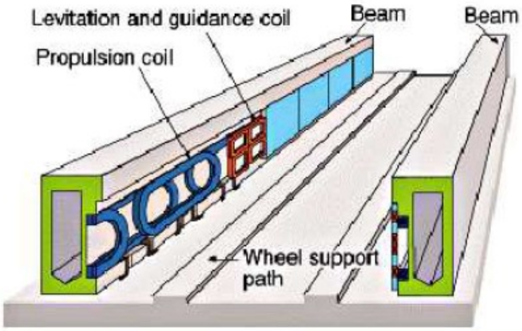


Fig. 6: Electrodynamic MLX infrastructure used in train system [16]

The MLX infrastructure has eight-shaped coils and consists of two sections, providing levitation and lateral stabilization of the vehicle. The guidance section eclectically connected under the track forming a null flux connection. The connection prevents the train from deviating from centre of the guideway [17]. If deviation would occur, the deviation reversed by the attractive force of the superconducting electromagnet on the distant side of the guideway and a repulsive force on the near side.

USA Induct-rack, is a Maglev system developed in the US and is a passive magnetic levitation system for moving objects that employs special array magnets such as Fig. 7.

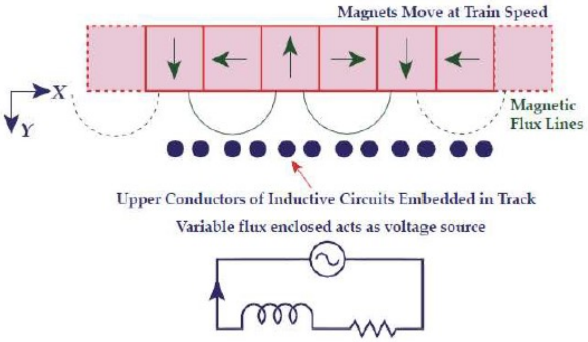


Fig. 7: Halbach array method [22]

This array used to increase the magnetic field in the active air gap and to decrease the field on the outside surface [22]. Induced currents in the "track" created by the magnetic field from these arrays and create strong lifting forces by interacting with the magnetic field.

IV. MAGNETIC PROPULSION

The Maglev train receives its propulsion force from linear motor. This linear motor is different from a conventional rotary motor since its does not use the mechanical coupling for the rectilinear movement. Conventional rotary motor creates a moment (torque) which transformed in a rectilinear movement. The linear motor is actually a cut-open rotary motor [14].

The main different between both type of motor (rotary and linear) is that the linear motor has a finite length but both operating principles are similar. Both motors have efficiency dependent on the size of the air gap; the bigger the gap, the lower the efficiency [14]. Advantages linear motor as compared to the rotary motor is the superior rectilinear motion and the amount of vibration and noise generated from the mechanical contact of component is substantially lower.

A. Linear Induction Motor

Fig. 8 shows the linear induction motor (LIM) which has the same operation principle of an (ordinary) induction motor [24]. The only different is that the stator is laid out flat. The shape and the speed of the magnetic field of linear induction motor are identical to that of rotational induction motor. The flat stator produces a field that moves a plate at constant velocity in a straight line. The magnetic fields are generated by the primary part across the air gap and induce an electromotive force (EMF) in the secondary part This EMF generate the eddy currents which interact with the air-gap flux and also produces the Lorenz's force [14].

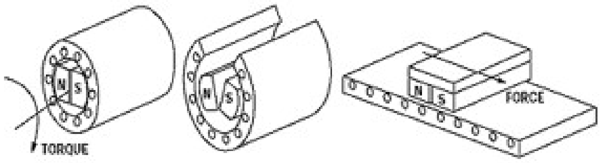


Fig. 8: Concept of linear motor from rotary motor [14]

There are two types of system exits, which is short primary (SP) and long primary (LP). SP focuses on the on-board stator coils and conducting sheets on the guideway. However, the LP focuses on the reversed configuration, on board conduction sheets and stator coils in the guideway. The high-speed train uses LP type because the SP cannot be used when the speed is higher than 300 km. LP use when there is a low energy efficient system. Fig. 9 shows the illustration the LIM LP-type.

The difference between a linear induction motor and regular motor is that linear synchronous speed does not depend on the number of poles but on the pole-pitch [21].

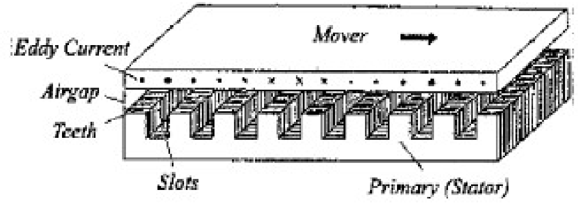


Fig. 9: Linear induction motor (L-P type) [15]

Linear synchronous speed (m/s) formula is given as:

$$Vs = 2wf \quad (1)$$

where;

Vs = Linear synchronous speed [m/s]

w = width of one pole-pitch [m]
f = Frequency [Hz]

B. Linear Synchronous Motor (LSM)

A Linear Synchronous motor (LSM) is another linear motor, which can be used for Maglev application and has a similar lay-out as the LIM. Fig. 10 shows the illustration of the linear synchronous motor picture.

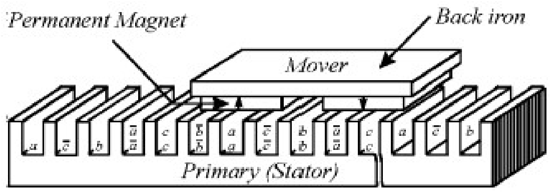


Fig. 10: Linear synchronous motor (LP) [14]

Characteristic to a linear synchronous motor is that the mechanical speed is equal to the speed of travelling magnetic field. This implies that the mechanical motion synchronized with the magnetic field. The speed of the moving part V is equal to the Vs , and control by the frequency.

The LSM operations on the principle of travelling field may have the following excitation system [21];

1. Permanent magnet in the reaction rail
2. Permanent magnet in the armature
3. Electromagnetic excitation system
4. Passive reaction rail with saliency and neither permanent magnet nor winding.

For high-speed system, which is faster than 300 km/h the most suitable system is using a linear synchronous motor with long or short stator due to higher efficiency and power compared to LIM [24]. Electrical power consumption is of economic importance for high-speed operation. The main difference between an induction motor and asynchronous motor is the starting torque (of load) which greater than for synchronous motor [25]. The reason, resistance of the squirrel-cage winding can be high without affecting the speed or efficiency at synchronous speed.

V. CONTROL APPROACHES OF MAGLEV

Precise motion control can be understood at its best by, a kind of contact free and wear-free suspension device known as, magnetic levitation (or maglev) systems, playing an important role among engineers worldwide and applicable to wide applications.

This section will discuss on the available control approaches of magnetic suspension systems. The approaches aim to precisely control the magnetic height above the ground by levitating it against the force of gravity using electromagnets. This will develop a complex and nonlinear dynamics with open-loop unstable system, demanding an appropriate control strategy to stabilize them.

The mathematical model of Maglev system depends on various factors. Due to its nonlinearity, it is difficult to design a conventional controller and the results often do not yield satisfactory. Non-linear and complex systems could be handled by the Proportional-Integral-Derivate (PID) controller, but their results often unable to attain the satisfaction. As most of the dynamic processes have nonlinearities behaviour, exact mathematical model is not derived and nonlinear model is typically assumed [26].

Alternatively, intelligent control came into existence to analyze complex systems whose information cannot be interpreted qualitatively, quantitatively or exactly. The proposed logic was characterized by human knowledge and experience, leading to the design of control algorithm. In recent years, fuzzy logic controllers presented several improvements in numerous applications in comparison to conventional control schemes. This was mainly due to their capacity to handle our inexact knowledge about real world systems [26,27]. On the theoretical basis, the lack of rigorous stability and robustness is the greatest drawback of fuzzy control. However, most stable analysis methods for fuzzy controllers are based on approximations, and there is no rigorous way to obtain a measure of robustness.

A. Classical Controller

PID controller also called as three-term controllers were introduced by Taylor Instrument Company in 1936. Although 1-DOF PID controller has simple structure and less parameters to be adjusted, it cannot well control the magnetic levitation system, and even may cause larger overshoots and reduce the stability of the system due to the system`s nonlinearity. However, a feed-forward gain presented in the 2-DOF (i.e. two degree of freedom) structure can be used to obtain superior plant output and control the responses effectively. As an example, a feed-forward type 2-DOF PID controller has been introduced to control a magnetic levitation ball system [28].

The structure of the system in [28] is shown in Fig. 11. In the figure, the feed-forward part G_q is defined as:

$$G_q(s) = \frac{q_1}{s} + q_2 \qquad (2)$$

where the additional gain parameters q_1 and q_2 help to add a zero at desired location to achieve superior responses. The feedback part is defined as:

$$\mathrm{PID}(s) = k_\mathrm{p} + \frac{k_i}{s} + k_d s \qquad (3)$$

where k_p, k_i, k_d are the gains for the proportional, integral, and derivative terms, respectively:

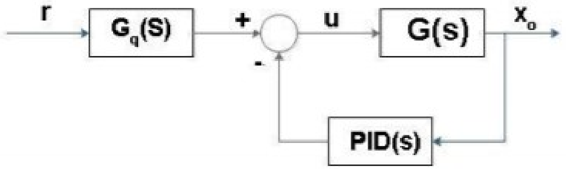


Fig. 11: A 2-DOF feed-forward PID controller for a magnetic levitation ball system [28]

The closed-loop system transfer function is:

$$G(s) = \frac{x_0}{r} = \frac{G_q(s)G(s)}{1+PID(s)G(s)} \qquad (4)$$

In the model simulation, q_1 and q_2 have been set to zero to make it a 1-DOF PID controller. The best parameters of PID have been set to 10, 4 and 0.125 for k_p, k_i and k_d , respectively. The result in Fig. 12 shows that the solution generates a large overshoot at the beginning which means that the normal 1-DOF PID controller cannot achieve a satisfactory result.

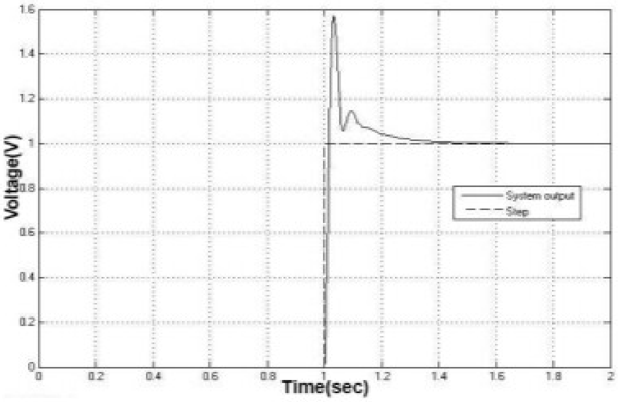


Fig. 12: Normal PID controller at step response.

In 2-DOF approach, q_1 has been set to 4 and q_2 is varied. Fig. 13 shows that, the 2-DOF PID with q_2=0 has minimal overshoot, however the rise time is the longest. By increasing the q_2 value the settling time becomes shorter however the overshoot tends to slightly increases but overall response still considerably good as compared to 1-DOF PID approach.

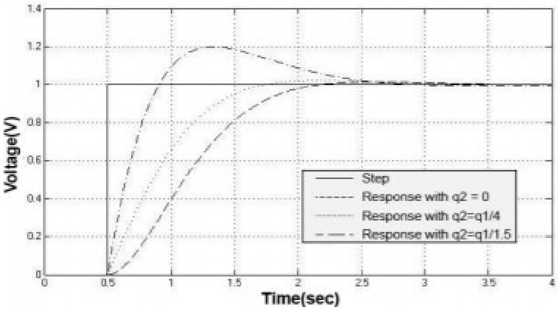


Fig. 13: 2-DOF PID controller at step response

B. Intelligent Controller

Fuzzy logic is a technology based on engineering knowledge, experience and observations that are more important than the underlying mathematical model, because linguistic variables are used to define system behavior rapidly. It is a very recent technology relative to conventional controllers, increasing its application areas. Fuzzy PID, fuzzy PI, fuzzy PD and fuzzy mixed controllers are fuzzy controller design approaches, but unlike conventional controllers that focus on system model [29].

For Maglev system, the control strategy aims to move the object to the desired equilibrium location and levitating it to the position. The methodology can be utilized in stabilizing the sludge of airplane by using fuzzy if-then rules which defined by an expert. A fuzzy control system can be considered as a real time expert system, which performs the control tasks in a human-like way as suggested in [27]. In the Maglev model, the height of the sludge obtained is compared to reference height. Choosing the actual height difference *h*, and the derivative of the difference *dh* as the inputs and the output assumed to the reference voltage *v*, for the fuzzy controller. Each variable of the fuzzy controller is represented by using membership functions at the inputs and output. A fuzzy rule based is then used in the control strategy. Fig. 14 shows the control surface of the FLC. It can be noted that, FLC has a linear control surface. This is due to the equal widths of membership function for input and output. Finally, this voltage is applied to Maglev Model.

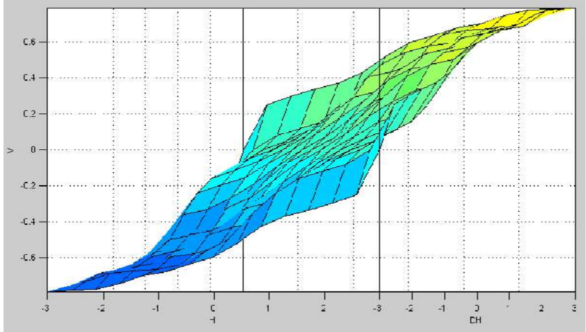


Fig. 14: Fuzzy Control Surface for Maglev System [27]

The method reported in [27] able to stabilize the Maglev system efficiently. The performance during the transient period of the fuzzy system is better in the sense that less overshoot was obtained. However, completing the rule base becomes much harder than in the case of having only two input signals. This work is directly relevant to track design for airplane application as proposed by us and is expected that the fuzzy approach could provide good performance towards this application.

C. *Optimal Controller*

Linear quadratic regulator (LQR) is one of the optimal control methods in modern control theory. The method is based on the manipulation of the equations of motion in state space form and makes full use of the appropriate computational tools in the analytical process [12].

Chrif et al. [36] has used Linear Quadratic Controller (LQR) to stabilize the lateral and longitudinal flight dynamics of an aircraft control system. The controller is used to achieve robust stability and good dynamic performance against the variation of aircraft parameters. LQR control system used for the lateral directional control of an aircraft is shown in Fig. 15. Kalman filter has also been added to combine all various systems dynamics to generate an overall best estimate of pitch, roll and side-slip angle.

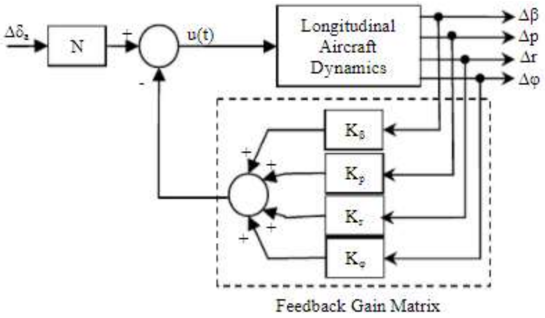


Fig. 15: Full-state feedback controller with reference input for the roll control system.

Valer and Lia construct a nonlinear model for magnetic levitation system and proposes systems linearization principle (the expansion in Fourier series and the preservation of the first order terms) to linearize the acquired nonlinear model [37]. They designed a Non-fragile optimal controller so a linear controller was designed to give safety and ride comfort to passengers inside the cabin of an airplane. LQR has good and acceptable performances according to the results from simulation and analysis. Practically obtained results show that LQR controller relatively gives the best performance in comparison to FLC and using such controller increases speed of the time response

VI. CONCLUSION AND SUGGESTION FOR FUTURE ADVANCEMENT

This paper is pointing out different techniques that could be considered in take-off and landing of aircrafts. The conventional method of landing is using more fuel energy. The current landing gear system needs more maintenance and it releases more carbon dioxide (CO_2) to the environment during take-off of the aircraft.

It is suggested that the Maglev technique which is one of the latest techniques used to levitate the train transportation could be a better approach to be implemented in airplane system to replace the conventional airplane landing gear system. In this concept, the airplane is installed on a moving and levitating platform which is accelerated along the track to achieve the launching velocity, as illustrated in Fig. 16. Meanwhile, the Maglev system runs on the superconducting magnet and do not require the fuel energy in order to take-off. Thus, this will make the lesser of CO_2 released into the environment.

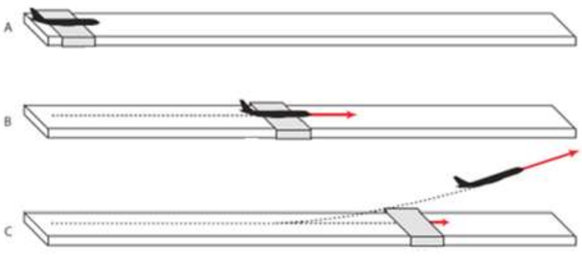


Fig. 16: A proposed take off system using Maglev approach

Maglev based aircraft landing system is less expensive to build as compared to the conventional system. The track of the Maglev will reduce the amount of collisions and accidents. Takeoff and landing in Maglev airplanes are much faster because of the eliminating the rolling resistance and potentially improving the power efficiency. For control system, intelligent and optimal controller could be considered in the proposed application as they have performed well in other similar systems, as compared to the conventional PID method.

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