Take-off and landing using ground based power –landing simulations using multibody dynamics

P. Wu*, M. Voskuijl*, M.J.L. van Tooren* §

**Faculty of Aerospace Engineering, Delft University of Technology, Delft, Netherlands*

§ Ronald E. McNAIR Center for Aerospace Innovation and Research, University of South Carolina, USA

A novel take-off and landing system using ground based power is proposed in the EU-FP7 project GABRIEL. The proposed system has the potential benefit to reduce aircraft weight, emissions and noise. A preliminary investigation of the feasibility of the structural design of the connection mechanism between aircraft and ground system has been performed by simulating the landing procedure on a moving ground system. One of the key challenges is the landing on a moving ground system under high crosswind conditions. The main focus in the current research is the calculation of the impact loads on both aircraft and ground system for a wide range of landing conditions (sink rate, velocity differences between aircraft and ground system, etc.). For comparison, conventional landing procedures with a traditional landing gear have also been simulated. Two different aerodynamic models (empirical and vortex lattice method) have been used and compared in the simulations for verification and validation purposes. The results of this research study are a set of load cases and operational constraints that can be used for the structural design of the ground system and modifications to the aircraft. Detailed values are presented in the paper.

Key word

Multibody Dynamics, Aircraft Landing, Field performance, Assisted takeoff and landing

Nomenclature

H = altitude with respect to world axes system [m]
p = roll rate with respect to aircraft body axes system [deg/s]
q = pitch rate with respect to aircraft body axes system[deg/s]
r = yaw rate with respect to aircraft body axes system[deg/s]
X_b = pilot longitudinal stick position [-]

Greek notation

α = angle of attack [deg]
β = angle of side slip [deg]
ϕ, θ, ψ = Euler angles defining the orientation of the aircraft with respect to the world axes system [deg]

Subscript

app = approach
measured = measured from aircraft simulation model
trim = trimmed aircraft

Abbreviation

ABS = Anti-lock Brake System
EASA = European Aviation Safety Agency

FAA = Federal Aviation Administration
FMT = Flight Mechanics Toolbox
GABRIEL = Integrated Ground and on-Board system for Support of the Aircraft Safe Take-off and Landing
MTOW = Maximum take-off weight
TD = Touch Down
TL = Traditional Landing

I. Introduction

A novel take-off and landing system using ground based power is proposed in the EU-FP7 project GABRIEL. Two concepts investigated in the GABRIEL project are presented in Figure 1. A detailed introduction about these two concepts is given by Voskuijl et al.[1] and Vos et al. [2, 3]. On the left, a concept is shown which uses a 'shuttle' to launch an aircraft. This concept can only be used for take-off. The concept on the right consists of a sledge which is propelled by a magnetic levitation system (MAGLEV). On top of the sledge, a cart is present to which the aircraft is connected. Shock absorbers are located on the cart. The cart is also used to transport the aircraft to and from the gate. In this concept, the landing gear can be removed from the aircraft. Removing the landing gear results in a significant weight reduction of the aircraft and thus a more efficient cruise flight. The second concept is the main focus of the GABRIEL project.

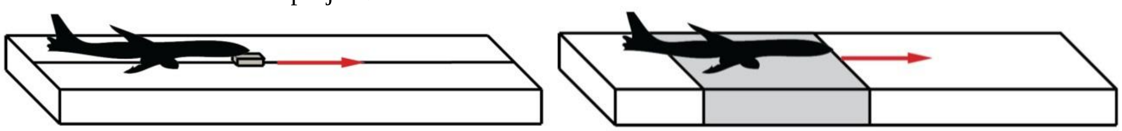

Figure 1 Two concepts for take-off (and landing) using ground based power for civil aircraft [4]

This technology has the potential to remove the landing gear system from the aircraft and thereby results in a significant weight reduction. An extensive multidisciplinary design optimization study performed by Schmollgruber [5] indicates that the MTOW can be reduced by 9% if the aircraft is redesigned for operations with the second concept. The main benefits that can be expected from the GABRIEL system (concept 2) are the following;

- Reduced emissions in cruise flight (due to lower weight)
- Noise reduction on and near airport (due to modified take-off procedure)
- Less chemical emissions near airports

In addition, it may be possible to use smaller engines on the aircraft and to modify the high lift systems. However, many technical challenges have to be solved before this system can be introduced. Every new technology and concept has to be analyzed and tested in detail before it can be certified and introduced in the civil aviation industry. Furthermore, the economic feasibility of the system has to be proven from the perspectives of airports, airlines and aircraft manufacturers. It is therefore an objective to design the system such that only minimal modifications have to be made to the aircraft and airport. In the ideal scenario, existing runways can be used for both conventional take-offs and landings and for take-offs and landings using the GABRIEL system

This paper describes an investigation into one specific aspect of this technology which intends to assist the take-off and landing procedure for commercial aircraft. The focus of the current research is on the connection mechanism between the ground system and the aircraft and the static and dynamic loads that can occur during operation. Since the traditional undercarriage system is removed from the aircraft, the absence of shock absorber in the aircraft system and the presence of shock absorbers on the ground system will result in a different possible load cases during landing compared to a traditional landing procedure. In addition, the landing procedure is modified, resulting in different load cases. For example, in crosswind conditions, the aircraft can land with a crab angle on the ground system because the ground system has a yawing degree of freedom. [6, 7] In order to investigate both the static and dynamic loads during landing, a comprehensive simulation model based on multibody dynamics, which includes both aircraft and ground system, has been developed.

As shown in Figure 2, the normal landing procedure for an aircraft starts when it crosses the altitude of flare start point (around 15m) and ends when the aircraft has come to a stop at the end of runway. During this procedure, the pilot has to control the aircraft position under environmental disturbances. Shortly before touch down, the pilot starts the flare in order to reduce the vertical speed at touch down. After the flare, the aircraft rotates and brakes on the ground. In terms of passenger comfort it is desirable to have a small vertical speed at the moment of touch down. According to the certification specifications of EASA [8] and the FAA [9], this maximum sink rate should not exceed 10 ft/s for airframe structural strength design and 12ft/s for undercarriage structure design. The landing procedure will be significantly different for the GABRIEL system. A general overview of the GABRIEL landing procedure is presented in Figure 2. The landing simulation begins from a trimmed flight condition on the glide slope, after the aircraft passes the flare start point, the pilot model controls the aircraft following a prescribed flight path trajectory. The flare procedure ends when the aircraft touches down on the sledge. The sledge waits for aircraft at the starting side of runway and will be activated to synchronize with the aircraft when the distance between them passes a threshold. In principle, the sledge should locate itself directly underneath the aircraft (identical longitudinal position) with the same horizontal velocity as the aircraft. Once the aircraft touches down on the ground system, the connection mechanism between the fuselage and cart/sledge combination is used to lock the aircraft. The cart/sledge system has two degrees of freedom; pitch and yaw. This allows the aircraft to land with a crab angle. Pool et al. [10]have demonstrated that a landing with a crab angle will allow more accurate position control during the final landing phase. After a successful connection of the aircraft with the ground system, the sledge/cart system can decelerate the aircraft until standstill.

An aircraft simulation model is developed to simulate the landing procedure. In the current study, only longitudinal motion is investigated. The lateral-directional dynamics and control system are present in the model but there is no crosswind, turbulence or asymmetric condition, such as an engine failure, present [11-14]. Clearly, these factors related to the lateral directional dynamics are very important with respect to safety because they directly affect the lateral position accuracy and aircraft attitude at touch down. Investigations into the lateral-directional characteristics are carried out in other research studies within the GABRIEL project. The simulation model is presented in more detail in the next section.

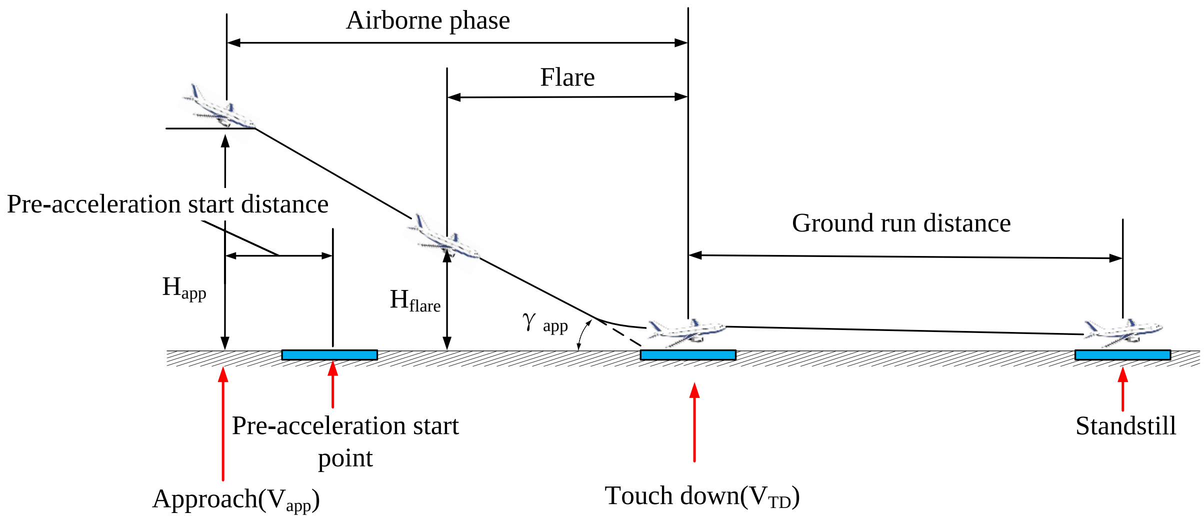

Figure 2 Landing procedure with ground based system

II. Aircraft – Ground system simulation model

A multibody dynamics simulation model of the aircraft and ground system has been developed in Matlab Simmechanics [15]. In order to compare the aircraft performance between the GABRIEL system and conventional aircraft, this multibody dynamics simulation model consists of two aircraft versions: one without undercarriage and one with an undercarriage. As shown in Figure 3, the aircraft model consists of multiple rigid bodies respectively called aircraft main body, nose/main gear outer/inner strut, nose/main tire. The outer struts have a rigid connection to the aircraft main body and springs and dampers are present between outer and inner landing gear strut. Realistic nonlinear spring and damper characteristics are based on data acquired from reference [16]. The tires have a rotational degree of freedom. In this paper, the TNO-Delft tire model is used in combination with typical data representing the aircraft tire and runway characteristics [17, 18]. The TNO-Delft tire model is a semi-empirical tire model which is based on the famous PACEJKA's Magic Formula for describing the dynamics of tires. [17, 18]

The GABRIEL system simulation model is presented in Figure 4. The ground system is modeled as a rigid body with three pairs of shock absorbers, each consisting of three pairs of nonlinear springs and nonlinear dampers generating the loads generated in XYZ direction during landing as shown in Figure 5.

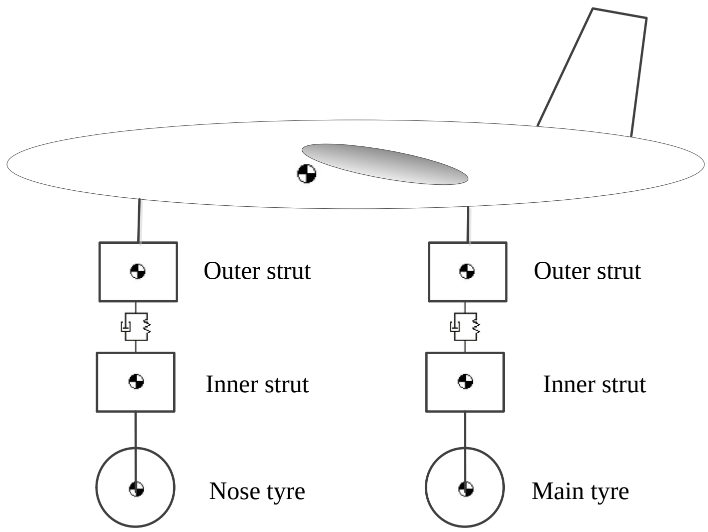

Figure 3 Aircraft multibody dynamics model

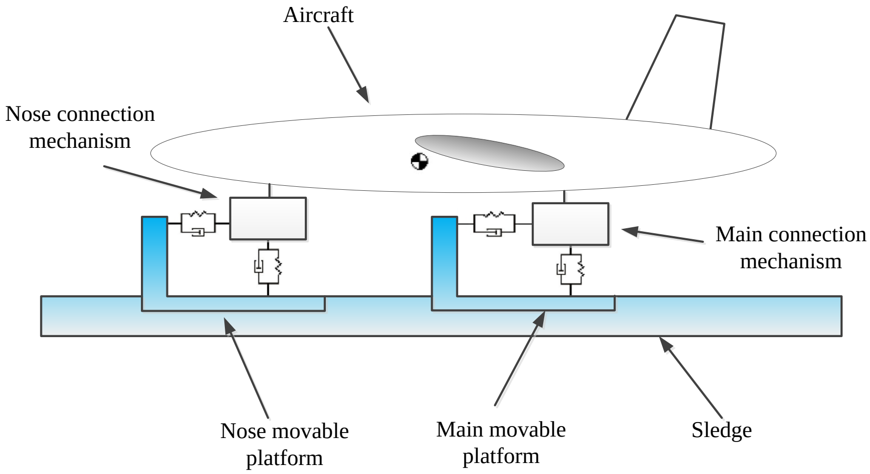

Figure 4 Aircraft-Sledge multibody dynamics model

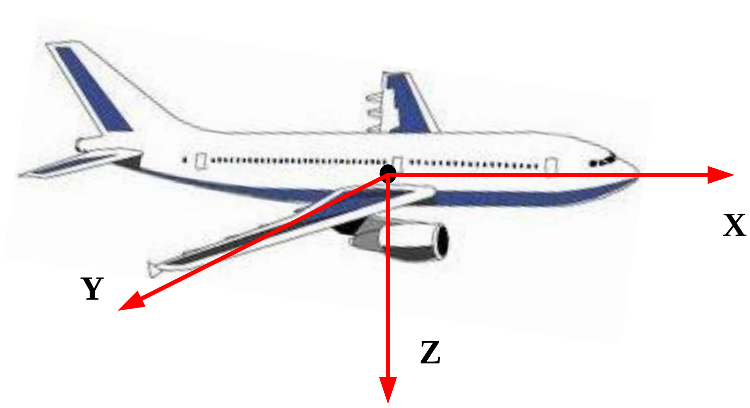

Figure 5 Aircraft coordinate system

The baseline aircraft simulation model is based on a generic Flight Mechanics Toolbox [15] [19, 20] developed at Delft University of Technology and some further development work has been done to enable the aircraft-sledge dynamics simulation. Approximately 80% of all flights at Schiphol airport (Amsterdam) are carried out by aircraft weighing less than 90 tons [3]. A medium size aircraft similar to an Airbus A320 is therefore chosen as research aircraft in this paper. It is difficult to acquire detailed characteristics of this aircraft in open literature. Therefore, a simulation model similar to an Airbus A320 has been developed. The key geometric parameters used in this paper are presented in Table 1[21].

Table 1 Landing gear geometry

Parameters	Nose Gear	Main Gear (Left or Right)
Outer strut	1200mm	2000mm
Inner strut	757.03mm	868.7mm
Horizontal strut	500mm	928mm
Tire model	TNO-Delft tire model for typical aircraft tire [22-24]	TNO-Delft tire model for typical aircraft tire[22-24]
number of tires	2	2
The distance from aircraft CG forward to nose gear in X axis	10m	N/A
The distance from aircraft CG backward to main gear in X axis	N/A	2.56m
The distance between right and left landing gear	N/A	7.6m

III. Overall simulation structure

The FMT is the basic tool to enable the simulation. [15, 19, 20] Accurate aerodynamic data of the Airbus A320 is not available in the open literature. The aircraft stability and control characteristics are therefore obtained using two different methods; (1) Tornado, a vortex lattice method, and (2) DATCOM, an empirical method. [25] [26, 27] The geometric data required as input for these aerodynamic analysis tools is obtained from the open literature.[21, 28] DATCOM has a limitation and does not allow the calculation of the rudder control derivative. This derivative was therefore estimated based on Roskam's method.[29] Tornado is a useful tool in preliminary design because of its low computational effort.[15, 26] DATCOM is a computationally efficient software tool for the prediction of stability and control parameters in the preliminary design phase. It is based on empirical data.[25, 30] The main components of the simulation framework and their interactions are shown in Figure 6. The pilot model provides a desired flight trajectory to the flight control system. An autopilot, which aims to follow this trajectory was developed using classical control theory. It is described in more detail in the following sections. The moment of contact between ground system and aircraft is a key element of the simulation. A reaction force model is developed which calculates the loads on aircraft and ground system when they are in contact. Because the ground system needs to be synchronized with the aircraft in terms of horizontal velocity and position, both of their states should be provided to a synchronization system which controls the position and velocity of the ground system. At this moment, no envriomental disturbance (like gut, crosswind, etc) has been implenmented in this model.

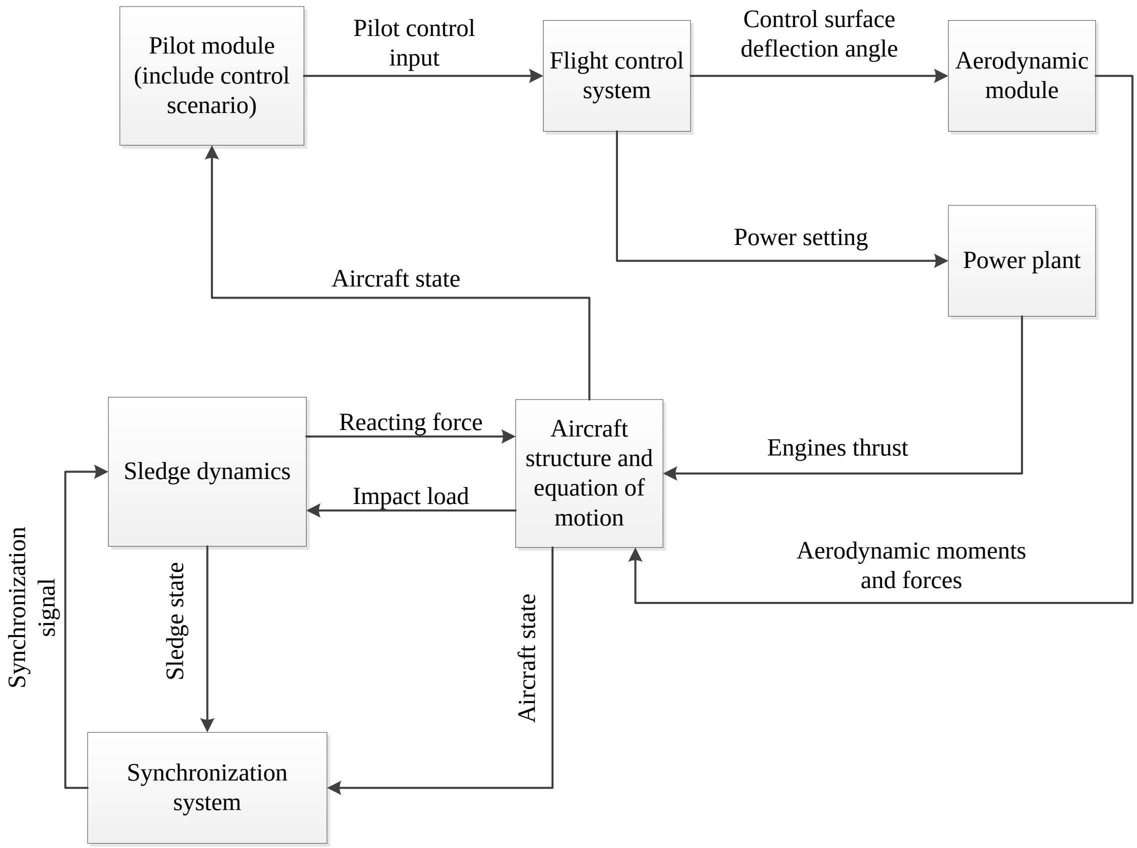

Figure 6 Top level flow chart of aircraft-ground system model

IV. Aircraft system

A landing gear model has been developed for the reference aircraft simulation in the current research study. Each landing gear strut is modeled with three parts: outer strut, inner strut and horizontal strut. The undercarriage characteristics are based on the physical dimension of a real undercarriage acquired from reference [21]. An overview of the model of the aircraft structure is shown in Figure 7 and this model is built in Matlab Simmechanics.[31] The TNO implementation of the Delft-tire model is used for simulation of the tires. [17, 18, 23, 24]

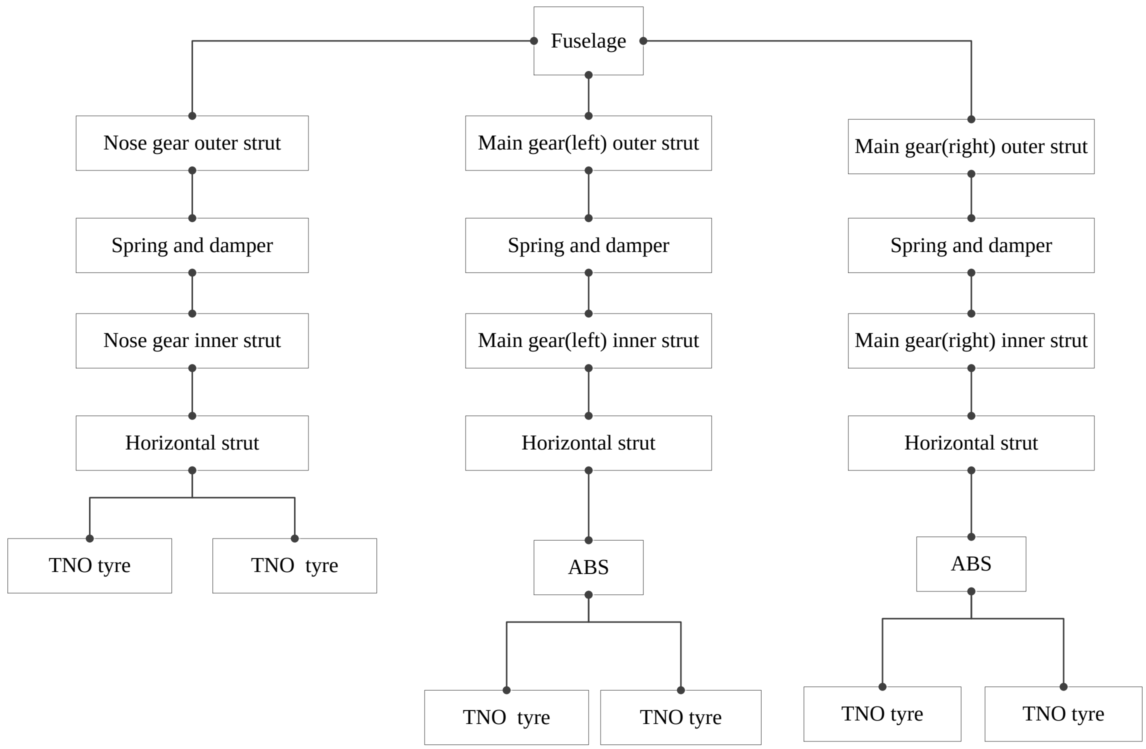

Figure 7 Aircraft model structure

A. Anti-lock brake system (ABS)

Although the brake system is not used when the aircraft lands on a ground based system, a simple ABS can still be used in this model in order to make a comparison between conventional landings and landings on the GABRIEL system. The braking system is a very important element of the undercarriage. After touch down, the brake system is activated to decrease the ground run distance. Aircraft have a large mass, high velocity and have to be decelerated to standstill over a limited distance. The brake control system enables the aircraft to smoothly slow down at the maximum friction coefficient. It is well known that there is a nonlinear relationship between the slip ratio and the ground friction coefficient [32]. The Anti-lock Brake System (ABS) has been used in the aviation and car industry for many years. There are many different ABS systems, using different control methods and physical implementation methods. For this research study, a simple but representative ABS is used [33-35]. The slip ratio is calculated in the tire model and provided as input to the ABS model. The logic of the ABS is presented in Figure 8. It can be observed that the brake torque is divided into two parts: the basic brake torque and the adjustive brake torque. If the slip ratios measured from the aircraft tyres are higher or lower than the desired value, the corrective brake torque will be activated to adjust the brake load applied on the landing gear system. For example, if the slip ratio is less than the desired value, the corrective brake torque will be increased in order to increase the total brake torque. If the slip ratio is too high, the corrective brake torque will reduce the total brake torque. The desired slip ratio is set at 0.18 based on reference [32]. A reference brake torque of 15000 $N \bullet m$ is set, based on reference [32] which uses a comparable type of tyre. The corrective brake torque is proportional to the difference between measured and desired slip ratio. The gains in the system have been estimated based on a range of simulations in the current research project.

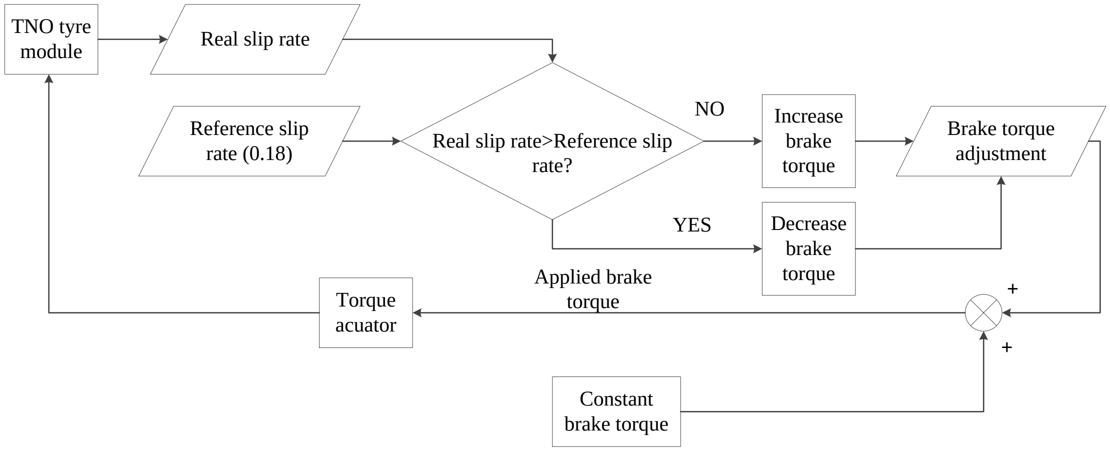

Figure 8 Anti-lock brake system

B. Aircraft control system

In order to simulate a typical landing procedure, a simple flight path control system is developed. The system measures flight path angle, pitch angle and pitch rate as the feedback signals to control the aircraft position and attitude. The desired flight path is a -3 degree glide slope until the flare is started. The following equation describes the flare [36].

$$h = h_0 e^{-t/\tau} \tag{1}$$

Where, h is the altitude of aircraft; h_0 is the altitude at which the flare starts; t is the time, measured from the start of the flare and τ is a parameter to describe the geometry of the flare

Based on the equation given above, the time derivative of h can be derived[36]:

$$\dot{h} = -\frac{h_0}{\tau} e^{-t/\tau} \tag{2}$$

The parameter τ is set to 4s in order to represent a typical landing profile for the aircraft under investigation.

The flare control system, which consists of 3 nested feedback loops, is shown in Figure 9. The feedback variables are the flight path angle, pitch angle and pitch rate. In the inner loop, the pitch rate is controlled using a proportional gain on the difference between the measured and desired pitch rate. The desired pitch rate is determined based on the difference between the desired pitch attitude and the measured pitch attitude. The outer loop compares the measured flight path angle with the desired flight path angle in order to determine the desired pitch attitude.

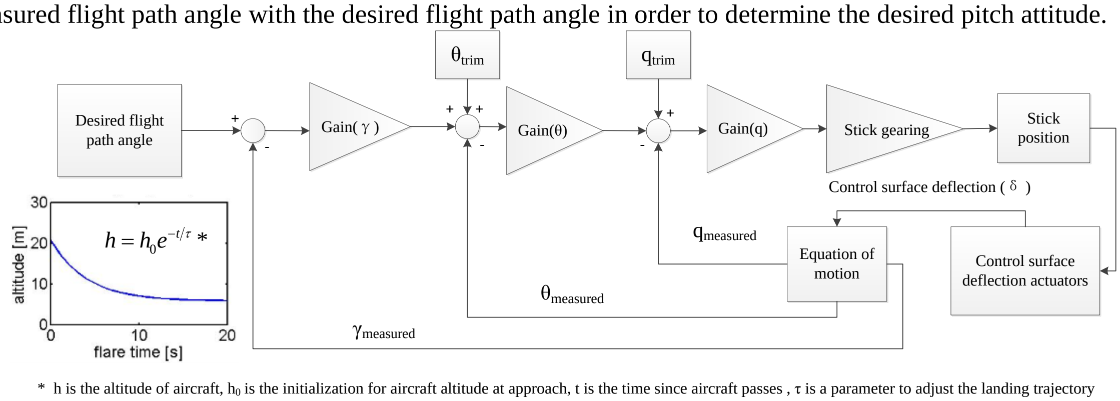

Figure 9 Flight path control system flow chart

After the aircrafts touches down on the runway with the main gears, the aircraft has to de-rotate to enable the touchdown of the nose gear. Figure 10 shows the control strategy for this rotation phase.

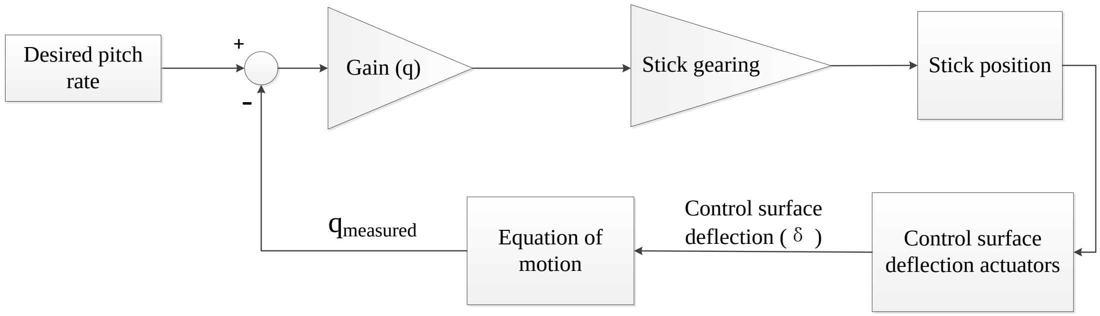

Figure 10 De-rotation control system flow chart

V. Ground based system

A. Sledge system

The baseline GABRIEL concept utilizes a platform with a pitch and yaw degree of freedom. The yaw degree of freedom is present to enable the aircraft to land with a crab angle. This increases the lateral landing accuracy since the aircraft does not have to complete a de-crab maneuver just before touchdown. In the current study, a modified configuration is analyzed which does not have a pitch degree of freedom. Without a pitch degree of freedom, the platform will be more lightweight and less expensive. However, a pitch degree of freedom simplifies the landing procedure with a high accuracy. In the modified configuration, a more traditional landing scenario including “de-rotation” operation is proposed as illustrated in Figure 11. The connection mechanism system is designed to provide a restraining clamp force and moment in all 6 degree of freedom. Since this is a preliminary research study and the detailed characteristics of ground based system are still not clear, so weight estimation is choose as 45000kg for A320 series research in this paper. [4]

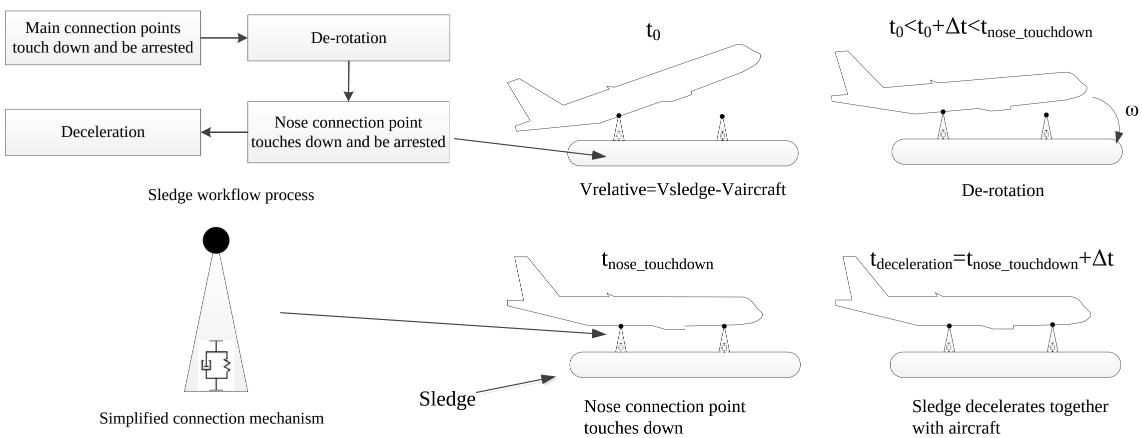

Figure 11 Sledge workflow process

B. Synchronization control system

The GABRIEL control system can be divided into two parts:

- onboard control system
- ground based control system.

It is desirable to make use of the existing aircraft control system to the largest extent possible. A separate control law is present in the ground based control system that synchronizes the yaw degree of freedom with the aircraft yaw angle. In the current research, only landings with no crosswind and thus no crab angle are investigated. As has been described in Ref. [7], the ground based control system will consists of two essential parts: Pre-acceleration phase and Synchronization phase. In the first phase, the sledge is accelerated with a prescribe acceleration scheme from standstill instantly when aircraft passes predefined position threshold. In ideal flight condition, the sledge will has to rendezvous velocity and position at the end of Pre-acceleration phase. However, due to disturbance caused by pilot control and environmental condition in real lift, there will be various possibility of speed and position difference existed between them. Then the synchronization phase is indispensable. Figure 12 shows the control system architecture chart for the aircraft-ground system synchronization system. This control system uses the position and velocity of the aircraft and ground system (in an earth fixed reference frame) as feedback variables. The positional error is multiplied with a proportional gain to create a reference velocity signal since the sledge control system not only need to synchronize the position but also requires ensuring the synchronization of horizontal speed. The output of the control system is the propulsive force of the ground system. The maximum thrust that can be provided by the ground system is one of the factors that determine ground based system performance. [37]

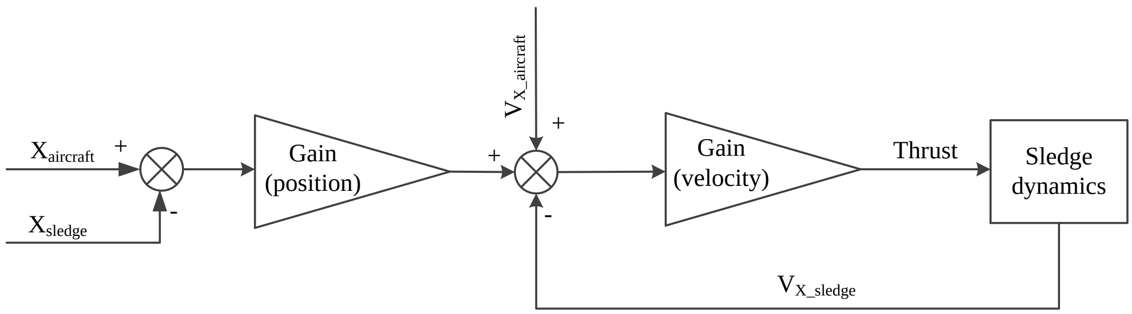

Figure 12 Aircraft-Sledge synchronization system

VI. Multibody dynamic simulation

A. Simulation procedure

The main research goal of this paper is to investigate the critical landing load case(s) which can be provided as a reference for the structural design of the ground system. Since the aircraft is landing on a moving sledge, a dynamic simulation to calculate the impact and loads during landing procedure is considered essential. The system makes uses of a full automatic landing procedure with a high accuracy. Consequently, the sink rate at the moment of touchdown is expected to be small. However, due to the absence of regulations for this innovative concept, the existing EASA certification specification [8] for is used as the baseline for design. The regulations will therefore most likely result in conservative load cases. A traditional landing simulation with a normal landing gear is also done in the simulations in order to compare the GABRIEL landing procedure with a conventional landing and to illustrate the performance of this new concept. Both the traditional and GABRIEL landing make use of the same initial flight condition as shown in Table 2.

Table 2 Initial flight condition for simulation

Altitude	Airspeed	Flight path angle	Heading angle	Turn rate
70m	70m/s	-3 deg	0	0

B. Simulation results

Simulations are conducted using two different aerodynamic models; Tornado and DATCOM. The effects of the aerodynamic model on the load-cases are investigated.

The first simulation results investigated is the synchronization system performance. Figure 13 to Figure 16 show the synchronization performance of the ground based system, which indicates that the ground based control system can accurately control the sledge motion together with aircraft. The sledge is pre-accelerated when its horizontal distance from aircraft is shorter than the specified threshold. It has to be noted that no atmospheric disturbances are present in the simulation. Before the aircraft and sledge make contact with each other, they have the same horizontal position and velocity. In this specific simulation, the maximum allowed thrust level for the ground based system is 400kN. [4, 37]

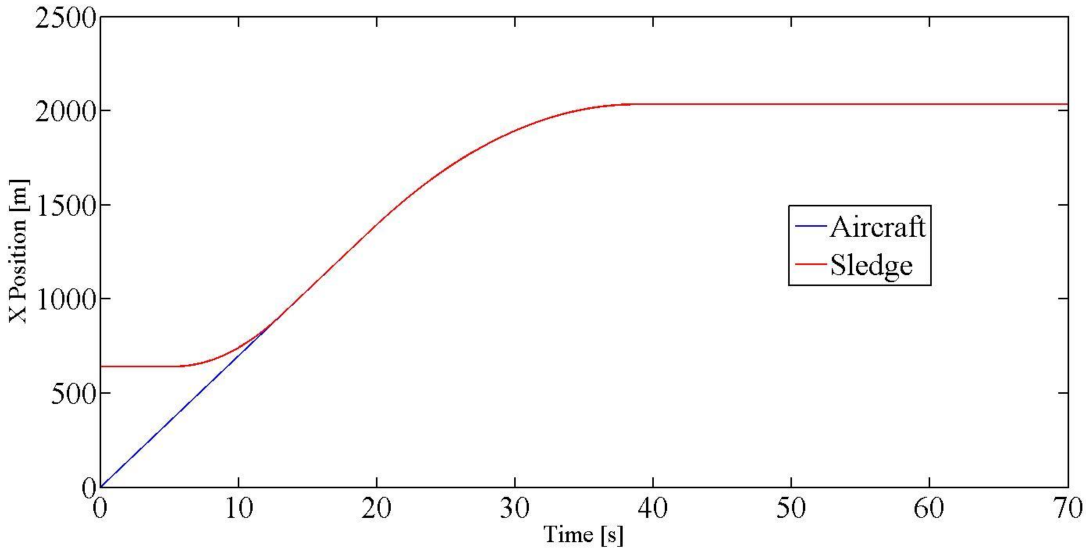

Figure 13 Synchronization for position based on DATCOM

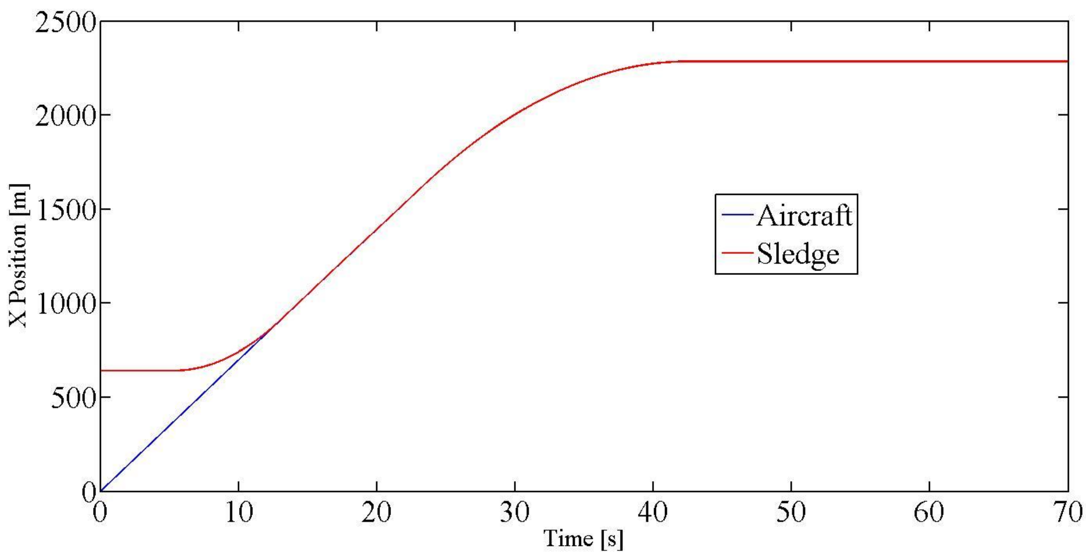

Figure 14 Synchronization for position based on Tornado

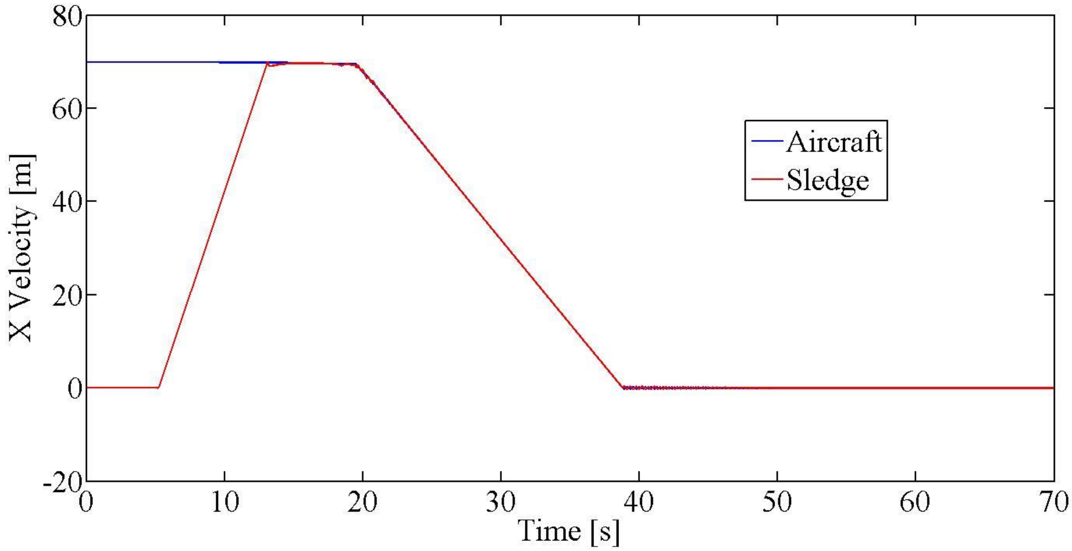

Figure 15 Synchronization for velocity based on DATCOM

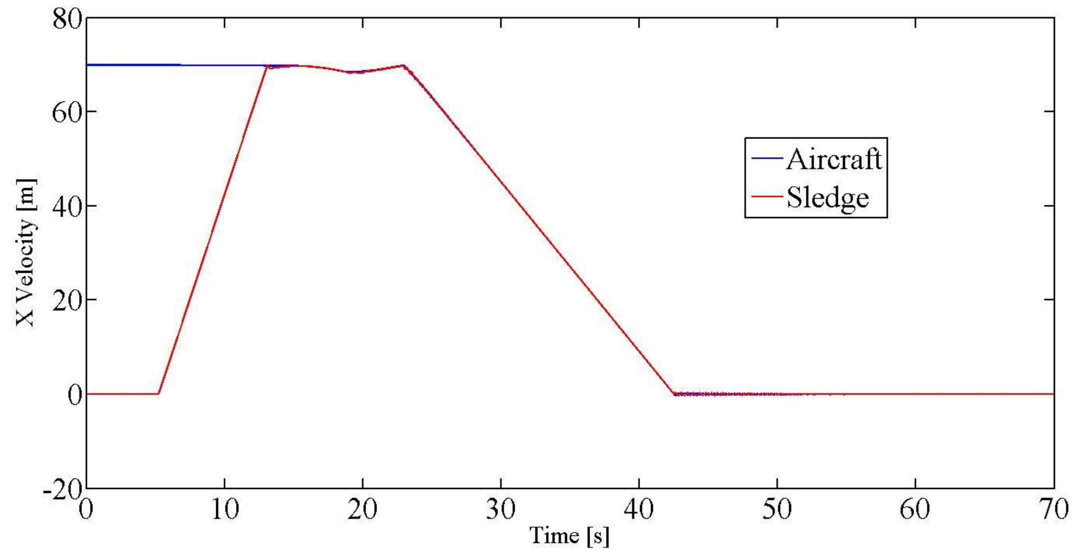

Figure 16 Synchronization for velocity based on Tornado

Figure 17 illustrates the aircraft trajectory during the landing procedure. The final altitude difference at the end of the simulation represents that the sledge is above ground level. Figure 18 shows how airspeed changes as a function of time for both simulations and for the two different aerodynamic models. The MAGLEV system can achieve a higher deceleration rate compared to a conventional landing gear. In the current study, the deceleration rate is set to 0.4g. This can be used to improve field performance. Fewer runways are needed and the runway occupancy time can be reduced. Clearly, the deceleration rate should not affect passenger comfort.

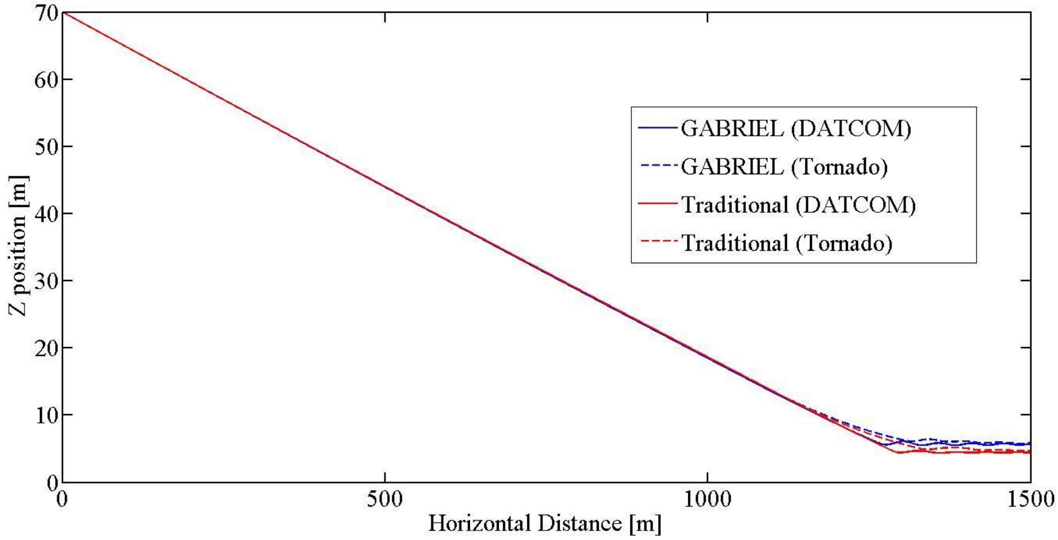

Figure 17 Flight path trajectory of aircraft

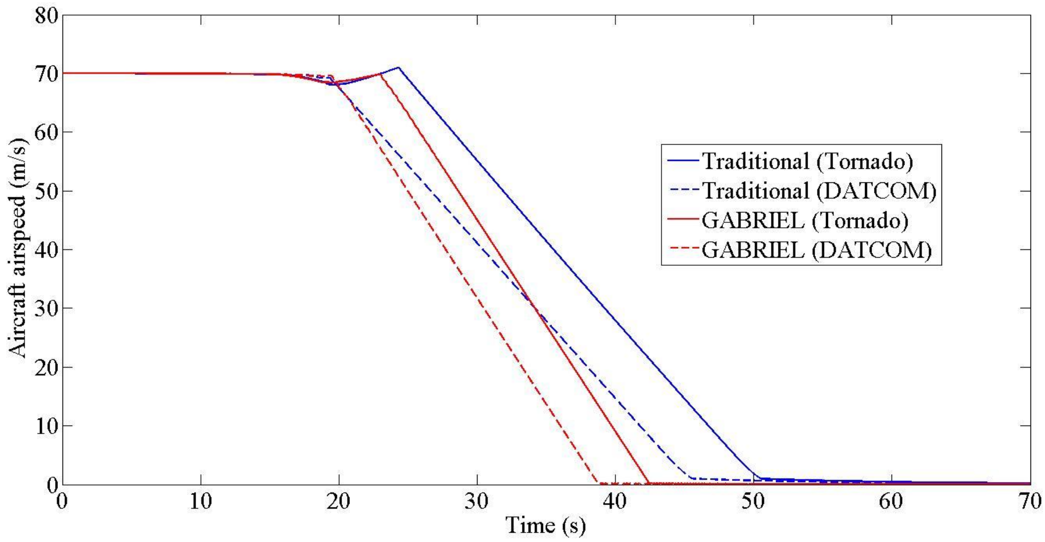

Figure 18 Aircraft airspeed

The landing impact loads are the main focus of the current paper and they are essential for the successful design of the structure of the ground system. A landing impact loads time history comparison for both the traditional landing and the GABRIEL system is shown in Figure 19 and Figure 20. The vertical direction at here refers to the direction of the length axis of the undercarriage, and for GABRIEL the direction of the ground based connection mechanism (for example: harpoon). One clear difference can be observed directly from the figures. The ground based system provides a clamp force which restricts the aircraft from moving upwards or performing a bounce motion. [38, 39] The oscillations appeared around 45s in Figure 20 is raised by the pitching moment caused by extending of nose connection shock absorber. Because at this moment, the deceleration period finished and aircraft standstill on the runway. For the other aspects, it can be observed that these two types of landing procedure impact tendencies are very similar. Due to Tornado is a aerodynamics software based on vortex lattice theory while the DATCOM generates aerodynamics paramenters and coefficients by empirical and experimental data, based on the results of simulations conducted in this paper which utilize Tornado and DATCOM, the landing load simulations is validated and the difference between two aerodynamics tool has limited effection on landing load.

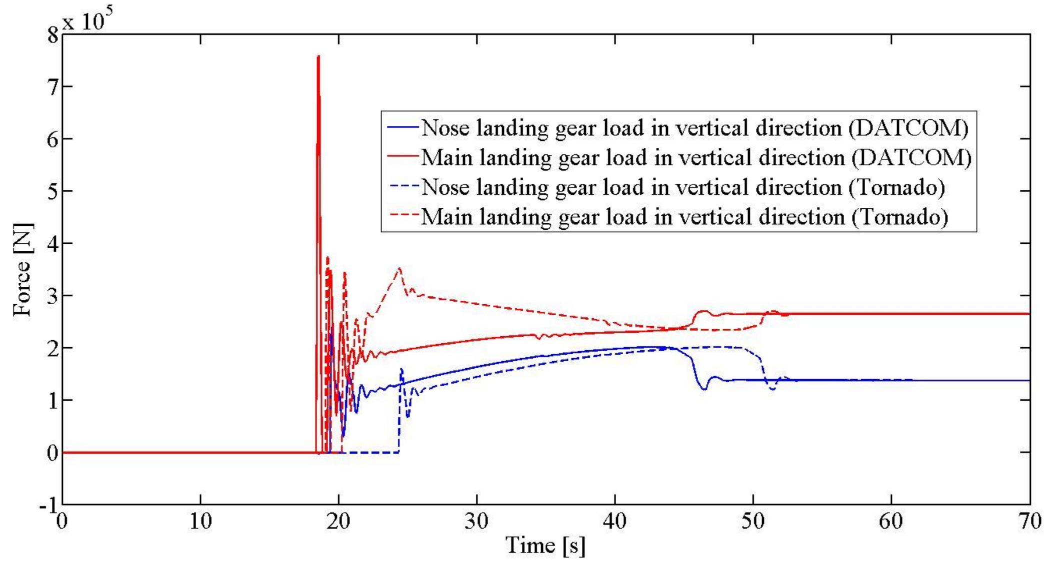

Figure 19 Traditional landing gear structure loads

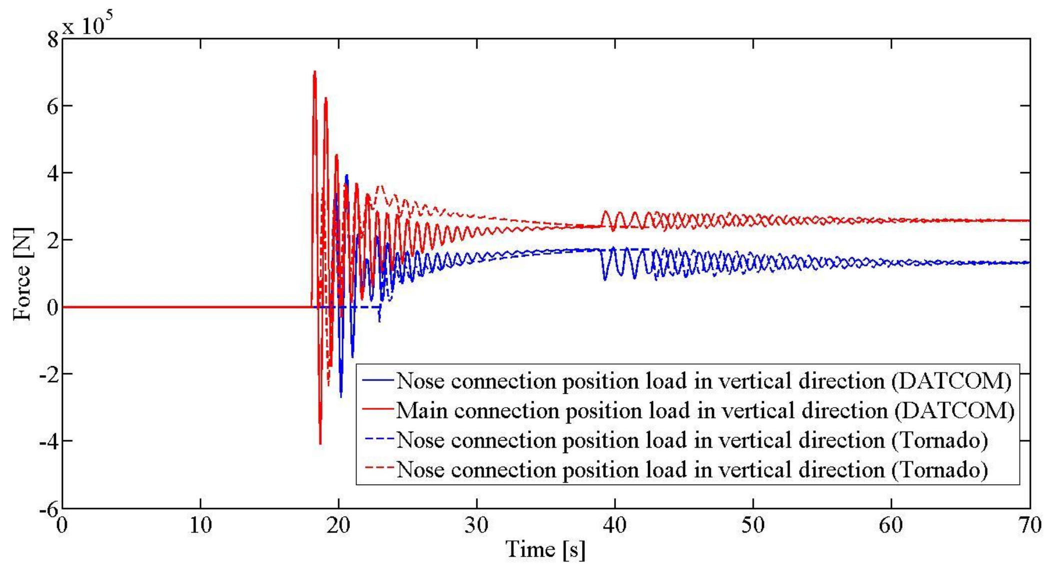

Figure 20 GABRIEL undercarriage loads

VII. GABRIEL landing impact

A. Flight attitude in longitudinal direction

In order to investigate the critical landing load cases for GABRIEL concept, it should be determined under which conditions the aircraft can land. As indicated in EASA CS-25.473 and FAA 25.473, the lift should not exceed aircraft weight.[8, 9] Experience has shown that aircrafts are floating and then touchdown the runways at the end of flare period and the EASA and FAA certifications are already strict enough to lead to reasonable design. So at the conceptual design stage, there is a widely accepted simplification assumption for civil aircraft touchdown simulation and test: lift equals to weight which could also been treated as trimmed status. [40-47]

References [40, 41] indicated the following initial conditions should be specified if aircrafts touchdown attitude needed to be fully defined:

- Vertical velocity
- Lateral velocity
- Horizontal forward velocity
- Roll angle

- Pitch angle
- Yaw angle
- Rolling angular velocity
- Yawing angular velocity
- Pitching angular velocity

Due to the variation in aircraft characteristics, landing control scenarios and environmental conditions, it is a challenging task to determine the individual contribution of these parameters and their interaction effects in the landing load cases References[40, 48] have proposed an effective approach to estimate values for these parameters based on statistical data collected from experimental records. It is shown by [40, 48] that the landing impact load is to a large extent determined by the vertical velocity, horizontal velocity, bank angle and roll rate. Taylor[40] and Westfall et al. [48] also proposed that based on the information derived from this statistical research, there was no dependent relationship has been found between them. In the current research study, only longitudinal motion is investigated. Therefore, the investigation can be limited to the influence of vertical velocity and horizontal velocity on the impact loads. For conventional aircraft with a traditional landing gear, the horizontal velocity has a significant effect on the landing load due to the spin-up phenomenon which occurs when the landing gear touches down on the runway. Significant forces and moments forces can occur as a result. Clearly, there is no spin up phenomenon present in the GABRIEL concept because there are no tires. However, in this new concept, there can be a relative longitudinal velocity and position difference between the ground based system and the aircraft. This will most likely affect the impact loads to a large extent. At this step, only velocity difference has been investigated. For nose connection position landing impact, it is a crucial landing load which is sensitive to many parameters in traditional landing. [49] However, in GABRIEL it is more complex due to the implementation of innovative connection mechanism. So this part of research could be further investigated combined with the design of ground based system detailed structure. Finally, the brake force provided by the ground system has an impact on the landing performance and is a design parameter at the same time. Therefore, the influence of the following parameters on the impact loads and landing performance will be investigated:

- Sink rate
- Relative velocity
- Ground based system brake force (or deceleration rate)

B. Sinking rate

The EASA regulations state that the maximum sink rate should not exceed 12 ft/s for civil aircraft landing gear[8]. In the current research study, the aircraft simulation starts in a trimmed steady and symmetric flight condition with a constant flight path angle. The sink rate at the moment of touchdown is varied by selecting the appropriate flight path angle in the range 0 to -3deg for a constant airspeed of 70 m/s, as shown in Table 3. As discussed previously, the load at the nose connection point is not included in this paper. Therefore, only the differences in the loads acting on the main connection point as a result of different sink rates are investigated. When designing the connection mechanism, it should able to sustain the worst case load generated in for the different sink rate simulations. The flare operation is not included in this part of simulation which means simulations begin from the almost last second before aircrafts touchdown. The resulting loads obtained with a full aircraft simulation are summarized in Figure 21.

Table 3 Initial flight conditions with different sink rate

Sink rate (ft/s)	Flight path angle (deg)
0	0
2	-0.4990
4	-0.9978
6	-1.4971
8	-1.9963
10	-2.4956
12	-2.9952

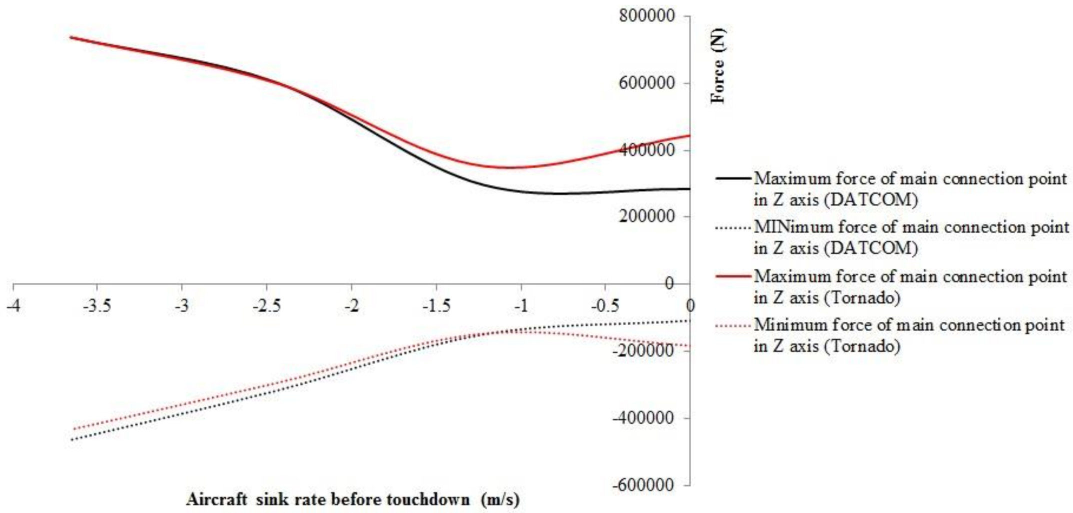

Figure 21 Effect of sinking rate on the landing load in Z axis

C. Relative velocity

Figure 22 to Figure 23 indicate the landing impact force caused by related velocity difference between sledge and aircraft for two different sink rates; 0ft/s and 12 ft/s. From these figures, it can be concluded that the relative velocity mainly affects the load in horizontal direction. As these simulations are based on rigid multi body dynamics, there are no elastic deformations modeled. These figures can be used to determine the maximum allowable relative velocity difference for a given structural design or vice versa to design the structure for a pre-specified maximum allowable relative velocity difference.

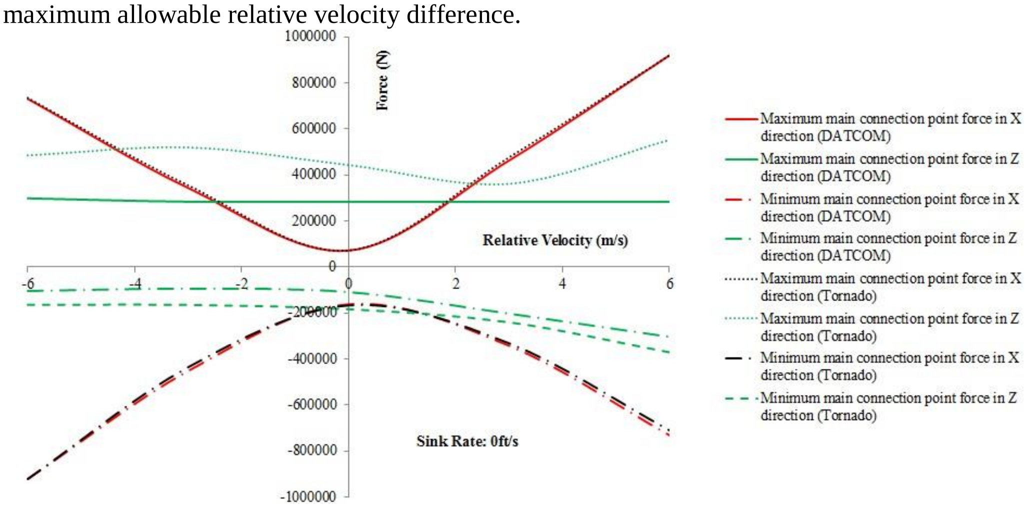

Figure 22 Effect of relative velocity on peak landing load in X and Z direction (0 ft/s)

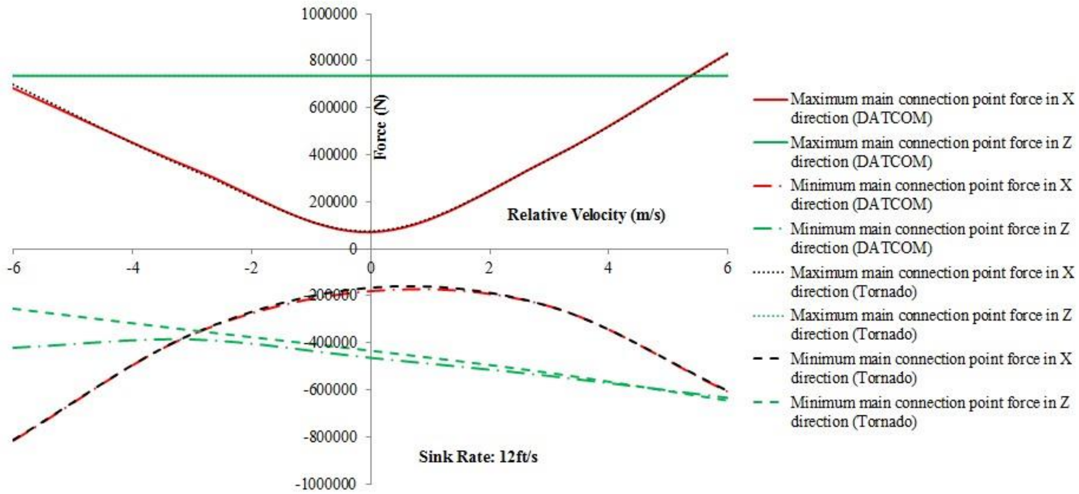

Figure 23 Effect of relative velocity on landing load in X and Z direction (12 ft/s)

D. Ground based system brake force (deceleration rate)

According to EASA CS 25.735[8] and FAA 25.735[9], the mean deceleration must not be less than 3.1m/s^2 (10ft/s^2). Although an increase of ground system reverse thrust can shorten the deceleration distance, a large a deceleration can be uncomfortable for passengers and lead to damage on the airframe. As reported in reference[1], an appropriate value for sledge reverse thrust is around -400 KN. So the maximum deceleration rate is around 4 m/s^2 and the reverse thrust provided by sledge can be adjusted according to different requirements of deceleration rate. As illustrated in Figure 24, the maglev rail for deceleration period should not be shorter than 800m for safety for the aircraft under consideration.

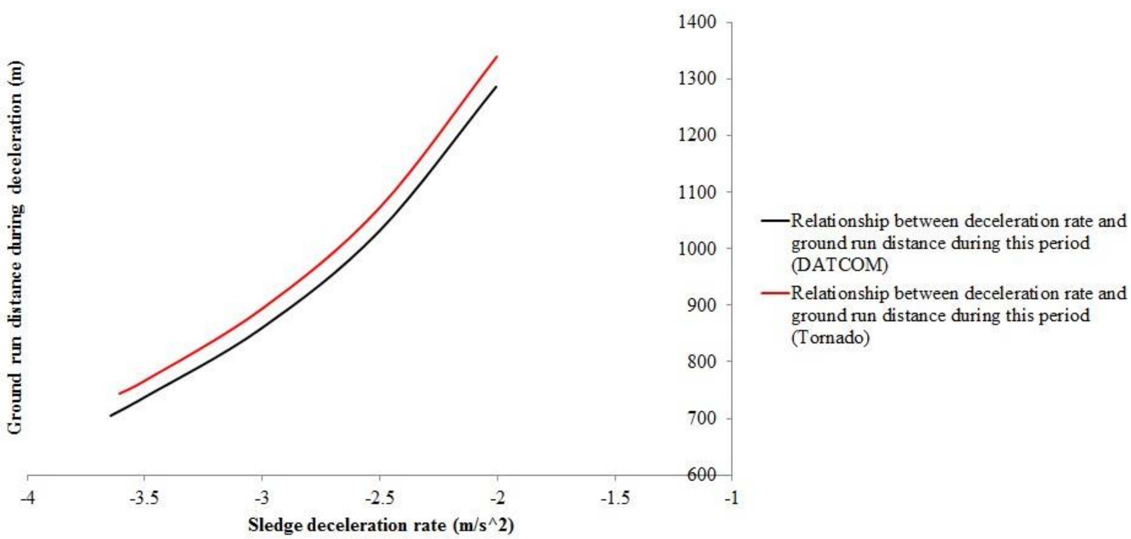

Figure 24 Relationship between sledge deceleration rate and its deceleration distance

VIII. Conclusions and recommendations

A take-off and landing system using ground based power has been proposed in the EU FP7 project called GABRIEL. A dedicated simulation model based on multibody dynamics has been developed to investigate critical the load cases that can occur during landing on such a system. The critical static and dynamic loads can be used for the design of the ground system and the redesign of the aircraft. In the current study, only longitudinal motions are investigated. The effects of: (1) sink rate on the dynamic loads during landing, (2) relative velocity difference between aircraft and ground system are calculated with the model. Compared with traditional landing, the GABRIEL concept can also perform landing based on typical landing simulation. Different extreme landing cases show that:

- the relative velocity should be limited with in ±3 m/s
- the sledge reverse thrust should not exceed -400 KN
- the maglev rail for deceleration part should not shorter than 800m
- the peak main connection positions landing loads generated by GABRIEL concept are 450 KN / -400 KN and 750 KN / -600 KN in X and Z axis respectively
- the sink rate of the last moment before aircraft touchdown is a main parameter affect main connection position landing load

In order to further investigate critical static and dynamic loads during landing, the nose connection position loads investigation and lateral directional dynamics under crosswind conditions and turbulence should be included.

IX. Acknowledgments

The authors would like to express their gratitude and thanks to Prof. Egbert Torenbeek for his valuable input related in the field of aircraft design. The authors are also grateful to Roy Bouma and Thomas Dumoulin who worked on the design of connection mechanisms and helped with the development of the aerodynamic models.

X. Reference

[1]Voskuijl, M., Rohacs, D., Rohacs, J., and Schoustra, R.-J. "Preliminary Evaluation of the Environmental Impact Related to Aircraft Take-Off and Landings Supported with Ground-Based (MAGLEV) Power," *Air Transport and Operations Symposium*. Toulouse, France, 2012.

[2]Vos, R., Eeckels, C., Schoustra, R.-J., and Voskuijl, M. "Analysis of a Ground-Based Magnetic Propulsion System," *JOURNAL OF AIRCRAFT* Vol. submitted for publication, 2013.

[3]Vos, R., Eeckels, C., Schoustra, R.-J., and Voskuijl, M. "Conceptual Design of a Magnetic-Assisted Take-Off System for Mid-Range Transport Aircraft," *51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*. AIAA, Texas, 2013.

[4]Eeckels, C. B. H., "Magnetic Assisted Take-Off for Commercial Aircraft", Master Thesis, Faculty of Aerospace Engineering, Delft University of Technology, Delft, The Netherlands, 2012

[5]Schmollgruber, P., Rohacs, D., Voskuijl, M., Andreutti, G., and Capizzano, F. "Deliverable D3.6: Conceptual design of the aircraft and aircraft systems using the GABRIEL concept," *GABRIEL project deliverables*. 2013.

[6]Rogg, D., Rohacs, J., Rohacs, D., Voskuijl, M., and Sibilski, K. "Deliverable 3.5: Conceptual Design of the Ground Based System Related to the GABRIEL Concept," *GABRIEL project deliverables*. 2012.

[7]Siepenkötter, N., Moormann, D., Schaik, F. v., and Voskuijl, M. "Theoretical Investigations Deliverable D3.7: Conceptual design of the control system for using the GABRIEL concept," *GABRIEL project deliverables*. 2013.

[8]Anonymous. "Certification Specifications for Large Aeroplanes (CS-25)," *CS-25*. 2003.

[9]Anonymous. "Electronic Code of Federal Regulations." Federal Aviation Administration.

[10]Pool, D., Voskuijl, M., Falkena, W., Siepenkötter, N., Majka, A., Falkowski, K., Wróblewski, W., and Sibilski, K. "Deliverable D4.2: Simulation Technology and Simulation of the GABRIEL Concept," *GABRIEL project deliverables*. 2013.

[11]Ebbatson, M., Harris, D., and Jarvis, S. "Crosswind Landings in General Aviation: A Modified Method of Reporting Wing Information to the Pilot," *THE INTERNATIONAL JOURNAL OF AVIATION PSYCHOLOGY* Vol. 17, No. 4, 2007, pp. 353-370.

[12]Mori, R., and Suzuki, S. "Neural Network Modeling of Lateral Pilot Landing Control," *JOURNAL OF AIRCRAFT* Vol. 46, No. 5, 2009.

[13]Mori, R., and Suzuki, S. "Analysis of Pilot Landing Control in Crosswind using Neural Networks," *Aerospace conference*. IEEE, 2009, pp. 1-10.

[14]Xu, K. "A Novel Dual Fuzzy Neural Network to Civil Aviation Aircraft Disturbance Landing Control," *Communications in Computer and Information Science* Vol. 289, 2012, pp. 131-139.

[15]Voskuijl, M., Rocca, G. L., and Dircken, F. "Controllability of Blended Wing Body Aircraft," *26th International Congress of the Aronautical Sciences*. ICAS, Anchorage, USA, 2008.

[16]Khapane, P. D. "Simulation of Aircraft Landing Gear Dynamics Using Flexible Multibody Dynamics Methods in Simpack," *24th Congress of International Council of the Aeronautical Sciences*. Yokohama, Japan 2004.

[17]Pacejka, H. B., and M., B. I. J. "Magic Formula Tyre Model with Transient Properties," *Vehicle System Dynamics: International Journal of Vehicle Mechanics and Mobility* Vol. 27:S1, 1997, pp. 234-249.

[18]Pacejka, H. B., and Bakker, E. "The Magic Fromula Tyre Model," *Vehicle System Dynamics: International Journal of Vehicle Mechanics and Mobility* Vol. 21:S1, 1992, pp. 1-18.

[19]Pfeiffer, T., Nagel, B., Bohnke, D., Rizzi, A., and Voskuijl, M. "Implementation of a heterogeneous, variable-fidelity framework for flight mechanics analysis in preliminary aircraft design," *60. Deutscher Luft- und Raumfahrtkongress* Bremen, Germany, 2011.

[20]Voskuijl, M., Klerk, J. d., and Ginneken, D. v. "Flight mechanics modelling of the Prandtl plane for conceptual and preliminary design," *Variational Analysis and Aerospace Engineering: Mathematical Challenges for Aerospace Design*. Vol. 66, Springer-Verlag London Limited, 2012.

[21]Anonymous. "A320 AIRCRAFT CHARACTERISTICS AIRPORT AND MAINTENANCE PLANNING." AIRBUS, 2012.

[22]Schmeitz, A. J. C., Besselink, I. J. M., and Jansen, S. T. H. "TNO MF-SWIFT," *Vehicle System Dynamics: International Journal of Vehicle Mechanics and Mobility* Vol. 45:S1, 2007, pp. 121-137.

[23]Anonymous. "MF-Tyre/MF-Swift 6.1.2.1 Help Manual." TNO, 2010.

[24]Anonymous. "TNO DELFT TYRE." TNO, 2010.

[25]Anonymous. "THE USAF STABILITY AND CONTROL DATCOM Volume I, Users Manual." McDonnell Douglas Astronautics Company, 1979.

[26]Melin, T. "User's Guide for Tornado 1.0." The Royal Institute of Technology (KTH), 2001.

[27]Anoymous. "DATCOM Beginner's Tutorial: Modeling a MiG-17," http://wpage.unina.it/agodemar/DSV-DQV/DATCOM_Tutorial_I.pdf [cited 2013].

[28]Anonymous. "A320." Jane's All The World's Aircraft, 2011.

[29]Roskam, J. *Airplane Design PART VI: Preliminary Calculation of Aerodynamic, Thrust and Power Characteristics*. Kansas: Roskam Aviation and Engineering Corporation, 1985.

[30]M. Baarspul, J. A. M. "Then Synthesis of Flight Simulation Models: DATCOM Techniques versus Flight Test Identification." Delft University of Technology, 1993.

[31]Anonymous. "Matlab." The MathWorks, Inc., 1994-2013.

[32]ESDU. "Frictional and Retarding Forces on Aircraft Tyres Part II: Estimation of Braking Force," 1971.

[33]Jiang, F., and Gao, Z. "An Adaptive Nonlinear Filter Approach to the Vehicle Velocity Estimation for ABS," *International Conference on Control Applications*. IEEE, Anchorage, Alaska, USA, 2000.

[34]Wurde, Z. E. d., "Simulation of Landing Gear Dynamics and Brake-Gear Interaction", Ph.D Thesis, Braunschweig University of Technology, 2008

[35]Zhang, M., Nie, H., and Zhu, R. "Design and Dynamics Analysis of Antiskid Braking System for Aircraft with Fourwheel Bogie Landing Gears," *CHINESE JOURNAL OF MECHANICAL ENGINEERING* Vol. 24, 2011.

[36]aylor, Ngoc, L. L., Borst, C., M.Mulder, and Paassen, M. M. v. "The Effect of Synthetic Vision Enhancements on Landing Flare Performance," *AIAA Guidance, Navigation, and Control Conference*. AIAA, Toronto, Ontario Canada, 2010.

[37]Patterson, D., Monti, A., Brice, C., Dougal, R., Pettus, R., Srinivas, D., Dilipchandra, K., and Bertoncelli, T. "Design and simulation of an electromagnetic aircraft launch system," *Conference Record of the 2002 Ieee Industry Applications Conference, Vols 1-4*, 2002, pp. 1950-1957.

[38]Anonymous. "Flight Operations Briefing Notes-Landing Techniques: Bounce Recovery - Rejected Landing." AIRBUS.

[39]Anonymous. "FSF ALAR Briefing Note 6.4-Bounce Recovery - Rejected Landing." Flight Safety Foundation, 2000.

[40]Taylor, J. *Manual on aircraft loads*. Oxford: Pergamon, 1965.

[41]IJFF, J., "Analysis of dynamic aircraft landing loads, and a proposal for rational design landing load requirements", Doctor Thesis, Delft University of Technology, 1972

[42]Chartier, B., Tuohy, B., Retallack, J., and Tennant, S. "Research Project: LANDING GEAR SHOCK ABSORBER." University of Duisburg-Essen.

[43]Berry, P. "Sizing the Landing Gear in the Conceptual Design Phase," *2000 World Aviation Conference*. San Diego, CA, 2000.

[44]Anonymous, "Study on Optimization Design Technology for Landing Gear Shock-Absorbing System of Large Civil Aircraft", Mastor of Engineering Thesis, College of Aeronautics and Astronautics, Nanjing University of Aeronautics and Astronautics, 2009

[45]Qi, P., Shi, W., Qi, Z., and Shi, Q. "Wing Lift Simulation in Landing-gear Drop Test," *MECHANICAL SCIENCE AND TECHNOLOGY* Vol. 21, No. 11, 2002.

[46]Spieck, M. "Simulation of Aircraft Landing Impact Under Consideration of Aerodynamic Forces on the Flexible Structure," *10th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*. Albany, New York, 2004.

[47]Uhemeister, B. "Optimization of the Passive Shock Absorber of a Military Aircraft," *RTO AVT Symposium on "Active Control Technology for Enhanced Performance Operational Capabilities of Military Aircraft, Land Vehicles and Sea Vehicles"*. Braunschweig, Germany, 2000.

[48]John R. Westfall, B. M., Norman S. Silsby, Robert C. Dreher. "A SUMMARY OF GROUND-LOADS STATISTICS." Langley Aeronautical Laboratory, NACA, 1957.

[49]Chester, D. H. "Aircraft Landing Impact Parametric Study with Emphasis on Nose Gear Landing Conditions," *JOURNAL OF AIRCRAFT* Vol. 39, No. 3, 2002.