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A Modelling and Simulation Framework for the Integrated Design of Aircraft Systems

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Abstract

New technologies and complex systems are being developed in commercial aviation to meet strict requirements regarding fuel consumption, emissions and noise constraints. This motivates the development of multidisciplinary environments to efficiently manage the increasing complexity of the design process. Under the Clean Sky 2 initiative, the ModellIng and Simulation tools for Systems IntegratiON on Aircraft (MISSION) project aims to develop an integrated framework to holistically support the aircraft design, development and validation processes. Within the MISSION framework, this paper proposes a methodology to handle the integration between the aircraft level and the system level in the early phase aircraft design. We demonstrate it for the case of the Landing Gear System in the rejected take-off scenario.

1. Introduction

In 2016, the International Air Transport Association (IATA) forecasted 7.2 billion passengers travelling in 2035, reaching 16 billion by 2050.[1,2] In addition, the civil aviation industry's CO_2 emissions have grown consistently year-on-year since its emergence[3]and civil airplanes continue having a significant impact on noise pollution. To address this increasing environmental impact of civil aviation, the International Civil Aviation Organization's resolution (ICAO) aims to reduce CO_2 emissions by 50% by 2050, as shown in Figure 1. Therefore, new generation commercial aircraft designs need to meet strict requirements regarding fuel consumption, emissions and noise constraints. Advances in engine design, optimized wing and body shapes, new materials and new electric technologies seem to have good potential to reduce fuel consumption.[3,4] However, this entails the implementation of more complex systems and a likewise complex integration of such systems across the whole design process. The traditional "document-based systems engineering" requirements-driven design approach appears unable to capture efficiently the complexity of the systems and their integration. This is mainly due to the "one-way" requirements flow (usually top-down), that leads to suboptimal solution at system level and is unable to capture the impact that a change at system level has on the aircraft level, thus limiting the adoption of novel system architectures.[5] Literature comprises a wide range of alternative approaches to support system integration for aircraft design. A first approach focuses on the formalization of methodologies for systems integration. For example, Kroo et al.[6] propose methods for multidisciplinary design and optimization of large-scale aeronautical systems, including new approaches to system decomposition, interdisciplinary communication, and methods of exploiting coarse-gained parallelism for analysis and optimization. Some studies[7–10] have proposed approaches for using Hardware-In-the-Loop (HIL) simulations and Model Based Systems Engineering (MBSE) principles for aerospace applications. Arbuckle et al.[11] develop a framework to build simulation models for aircraft dynamic systems integration, increasing model fidelity and reducing the time required to develop and modify these models. Priestley et al.[12]provide an overview of architectural approaches for systems integration in the early stages of aircraft design and,[13] a review of system decomposition and integration approaches. Other works focus on the integration of specific systems in aircraft design process. For instance, Chai and Mason[14]describe the development of a MDO-capable design methodology for landing gear integration in aircraft conceptual design. Heerens,[15] Van Ginneken[16] and Tfaily[17] developed a framework for automated landing gear design and optimization within an integrated aircraft framework using multidisciplinary

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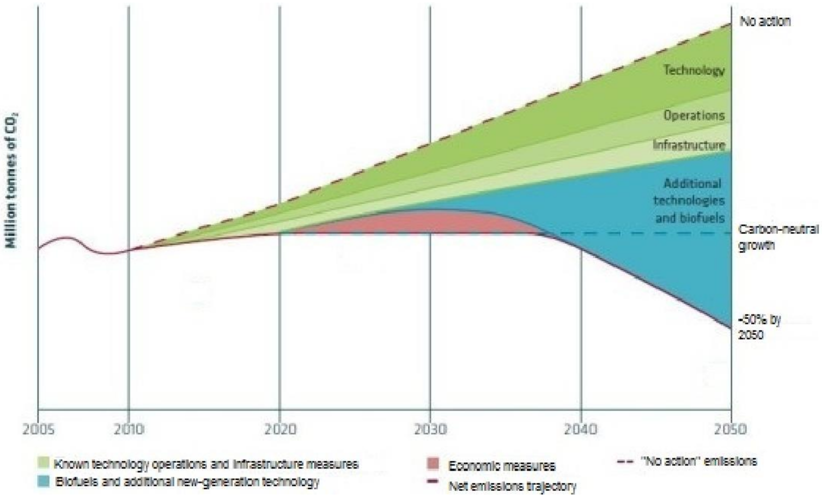

Figure 1: Emissions reduction roadmap[2]

techniques. Similarly, other research efforts have focused on developing MDO techniques for wing design application.[18–20] More recently, Martins and Lambe[21]surveyed and provided a classification of the various Multidisciplinary Design Optimisation (MDO) architectures available in literature.
Several efforts to improve aircraft design, development, validation and verification processes have been also undertaken within different European Union (EU) projects: CRESCENDO[22] provided realistic demonstrations of simulation-based collaborative product development across all design phases; VIVACE[23] has developed an extended enterprise, with several virtual products to support the aeronautic product engineering life cycle; TOICA[24]creates an integrated platform for the aircraft thermal system, capable of studying the thermal behaviour of the whole aircraft, and also to perform trade-off studies; MOET[25,26] has developed a framework for integrated design of validated electrical technologies; ACROSS[27] has created an integrated framework for cockpit design. These efforts have brought significant advances in real-time simulation, virtual testing and integrated design of specific systems. However, the path to a holistic integrated framework for a whole aircraft, involving multi-physics modelling and simulation, multi-objective optimization, model-based design of algorithms and virtual testing is still long.[5] Continuing the same theme as in previous EU projects, MISSION (Modelling and Simulation Tools for Systems Integration),[5] a project developed under the European Union Clean Sky 2,[28] aims to develop and demonstrate an integrated modelling, simulation, design and optimization framework based on Model-Based Systems Engineering principles oriented to the aerospace industry.
In this paper, we propose a method to manage the integration between different aircraft systems and the aircraft-level flight dynamics in the conceptual aircraft design phase. We develop libraries of parametric models, implement standard interfaces between system models, and ensure that models consistently fulfil aircraft functional requirements. The method entails a double data flow: requirements cascade down from aircraft to system level; here the requirements are treated as simulation parameters or input variables; system dynamic outputs are then transferred from system to aircraft level and treated as input variables. In this paper, we demonstrate the methodology for the landing gear system, in the particular case of rejected take-off (RTO). Section II describes the challenges that arise when an integrated design framework for complex systems is addressed: we provide an overview of different methodologies used to face these challenges and we highlight the integration problem for the case of landing gear system. Section III describes the methodology used to model and integrate an aircraft system with the aircraft level. Section IV shows the simulation results of some aircraft performance, namely "braking distance" and "cross distance", for the cases of asymmetric braking and asymmetric engine cut-off time. Finally, we compare the performance for different technologies for brake actuators. Section V summarizes concluding remarks and proposes further improvements and possible future work.

2. Problem statement and use case definition

New generation aircraft and modern aerospace systems have reached a high level of complexity. There are several reasons that lead to this complexity. Firstly, each of the systems to be integrated consists of several subsystems and components, each of them defined by a high number of variables. Therefore, an integrated modelling framework for the whole aircraft will eventually consists of an excessive number of variables and needs an efficient methodology to manage this complexity. Secondly, an aircraft involves systems from several domains (e.g. electric, hydraulic, thermal and structural). Each of these domain systems is modelled using ad-hoc software, is developed under specific require-

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ments and constraints, and is described by appropriate interfaces. Moreover, the systems are dynamically coupled, that is, changing a variable or parameter in one of the systems, has an impact on another system and vice versa. In general, the stronger the coupling, the harder the problem that needs to be solved. However, trying to decouple the problem (e.g. linearizing the systems), would lead to a loss of information and accuracy in the model. Another recurring property of aerospace systems, is that they involve different scales in space (from very big to very small components), in time (from very fast to very slow phenomena), and in function (consisting of complex hierarchies of heterogeneous functionalities). All these factors lead to very high computational costs, difficulties in managing the information flow between the different subsystems and components, and in adapting dynamically their interfaces to guarantee an efficient transfer of information. In literature, a number of different approaches to address these problems are proposed,[29,30] spanning from layered design,[31,32] to component-based approaches,[33,34] and from model-based development[26,34,35] to the V-model:[36–39] Layered design copes with complexity by focusing on those aspects of the system pertinent to supporting the design activities at the corresponding level of abstraction. This approach is particularly powerful if the details of a lower layer of abstraction are encapsulated within the design that is carried out at the higher layer. The challenge consists of providing the proper abstractions of lower-level design entities, which must meet the double criteria of, on one hand, being sufficiently detailed to support virtual integration testing, while at the same time not overly restricting the space of possible lower-level implementations. Whereas layered designs decompose complexity of systems "vertically", component-based and model-based approaches reduce complexity "horizontally" whereby designs are obtained by assembling strongly encapsulated design entities called "components" or "models" equipped with concise and rigorous interface specifications. These interfaces have to be "small" and minimally constraining: "small" both in terms of number of interface variables or ports, as well as "logically small", that is, simple to handle. On the other hand, interfaces have to be rich enough to cover all phases of the design/simulation cycle. Another model being widely used in product development is the V-model of the design process: Its characteristic V-shape splits the product development process into a decomposition and integration phase. The decomposition phase is further divided in different steps: analysis of product level requirements, system design, subsystem modelling and implementation (see Figure 2). These decomposition phases are paralleled by similar integration phases from subsystem level to the final product integration. The main challenge of the V-model is the parallelization of design activities that unavoidably leads to many concurrent design processes. However, the use of strategies such as component-based design can separate these activities and thus significantly reduce the effort in both decomposition and integration steps.
MISSION adopts the V-model to support the whole aircraft design and optimization process, employs component and model based approaches for systems modelling and simulation, and uses layered design approach for requirements definition. Across the V-cycle, it is fundamental to define and handle efficiently the interfaces between the different phases, to assure that specifications from previous phases are captured in the following phases, to demonstrate that changes at subsystem levels are reflected in expected changes at system level and vice versa. Moreover, each of the V-cycle phases is characterised by testing activities used to verify the compliance of the system, also called System Under Test (SUT), to the specifications coming from the previous phase. These activities entail the integration between the SUT and the aircraft. In this paper, we describe the methodology we used to handle this integration and we demonstrate it for the Landing Gear System (LGS) in the rejected take-off scenario, considering the cases of asymmetric braking and asymmetric engines cut-off. We consider a common Landing Gear System configuration for a single-aisle

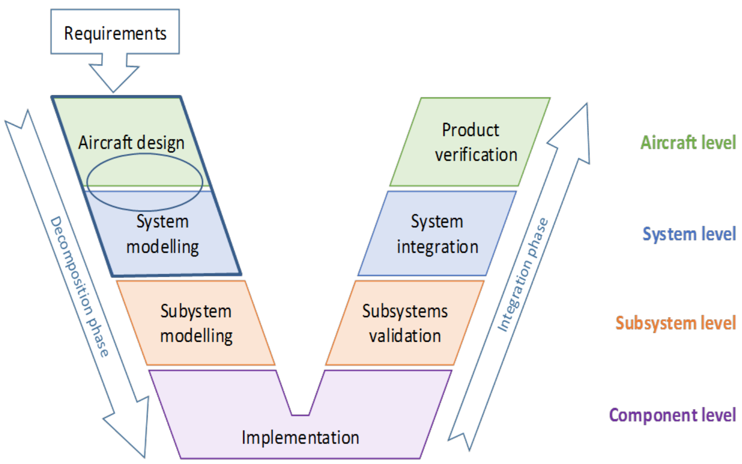

Figure 2: V-model

aircraft with two engines such as the Airbus A320 or the Boeing 737,[40–42] including two main landing gears and one

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nose landing gear. Each main landing gear retracts inboard, has twin wheels and an oleo-pneumatic shock absorber. Each main wheel has an antiskid brake. The nose landing gear retracts forward. The two-wheeled nose gear has an oleo-pneumatic strut and a nose wheel steering system.
The rejected take-off is a sizing scenario for landing gear brakes. According to FAR 25.109,[43] brakes should also be able to withstand the maximum kinetic energy generated during the accelerate-stop scenario, i.e. a rejected take-off for the most critical combination of airplane take-off weight and speed. The mean deceleration must not be less than 6fps2. In the context of a rejected take-off, we can identify one main landing gear function and the respective entailed coupling between the aircraft and the system level: the braking. This has to guarantee that the airplane stops in a determined distance. In absence of brakes, the landing gear wheels would be simply dragged by the airplane thrust, they would translate with a linear velocity equal to the airplane's (v) and rotate with an angular velocity equal to the ratio $\omega_v = \frac{v}{R}$ (with R being the tire effective radius). However, when the brakes are applied, they exert a torque on the brake disks and reduce the angular velocity of the wheel (ω_w). The normalized difference between the actual angular velocity of the wheel and the vehicle angular velocity induces a longitudinal slip (λ). Depending on the slip amplitude (therefore on both the linear velocity of the aircraft and the angular velocity of the wheel), the ground exerts a higher or lower friction force on the wheel tires, thus reducing ω_v and changing the value of λ. In the following paragraphs we describe the methodology we adopted to tackle the coupling between aircraft dynamics and landing system dynamics and we demonstrate it for the braking function.

3. Methodology

To address the integration problem between aircraft and system level, we distinguish three key elements: the scenario, the environment, and the aircraft platform. The scenario defines the operational conditions in which the system is tested; in our case, a RTO. A take-off may be rejected for a variety of reasons, including engine failure, activation of the take-off warning horn, directions from air traffic control (ATC), blown tires, or system warnings. The "go/no-go" decision must be made prior to reaching the decisional speed V1. The environment defines the atmosphere and ground conditions in which the system is tested. We assume standard atmospheric conditions at sea level and dry runway. Finally, the aircraft platform describes the aircraft dynamics, the aerodynamic loads and the propulsive forces involved in a fixed scenario and environment. This section describes more in detail the methodology used to model LGS and the aircraft dynamics, as well as how the integration model approach has been executed for a fixed scenario and environment.

3.1 System Level: the Landing Gear

In this paragraph we describe a methodology to model the Landing Gear System, using a function-based approach. Typically, there are two different and complementary ways to model a system: function-based and discipline-based decomposition. The former consists of modelling a system according to the functions it has to fulfil. This decomposition reduces the initial complex system into more simple subsystems (usually identifiable with physical components). At this level, the different subsystem models are refined considering the disciplines involved in that system: aerodynamic effect, structural loads, thermodynamic phenomena and so on. These approaches have led to the modelling methodology used for the case of the Landing Gear as described in the following paragraphs.

Landing Gear functions and dynamics identification The first step is to identify the landing gear functions and dynamics. During the different aircraft operations, each landing gear will be involved in several dynamics including extension, retraction, braking and steering.[44] All these functions and dynamics, that are coupled in real conditions (e.g. steering and braking), can be decoupled with some simplifying hypotheses (e.g. symmetric landing, absence of gusts, absence of failures in any of the LG components, etc.) and thus modelled and simulated separately.

Main component identification The second step consists of identifying the main components involved in each dynamic. Table1 shows the different components necessary to perform each function. For example, the braking function, requires the wheel (including the tyre model) and the brakes. The brakes architecture (namely Disc Brake), has been further decomposed into two sub components: the calliper and the actuators. For the steering function, we have considered the wheel (including the tyre model) and the steering system. The steering has been further decomposed into two sub models: the steering architecture (namely Dual Actuator Nose Wheel Steering architecture) and the actuators.

Different component option exploration The third step consists of modelling different types (if any) for each component. For the braking function, civil aircraft widely use disc brakes. The disc brake is a wheel brake that slows the rotation of the wheel by the friction caused by pushing brake pads against a brake disc with a set of callipers.[45] For the

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Table 1: Functional Decomposition Matrix

	Vertical Landing	**Acceleration**	**Braking**	**Steering**	**Extension/Retraction**
Shock Absober	x				
Wheel and Tyre	x	x	x	x	
Bogie	x				
Brakes			x		
Ext/Ret Actuators					x
Up/Downlock					x
Steering				x	
Shimmy Damper		x	x	x	

steering function, gear-rack and dual actuator nose wheel steering mechanisms are widely used in large civil aircraft. For instance, the Airbus A320 and A340 aircraft use the gear-rack steer mechanism. In contrast, the Airbus A330 and A380, and almost all Boeing civil aircrafts (B737, B747, B767, B777 and B787) use dual nose wheel mechanism, because theoretically it can provide much larger steer torque when compared to the gear-rack steering mechanism for the same amount of supplied power. For both braking and steering, several actuator options are possible: from conventional solutions such as hydraulic actuators, to the novel technologies of Electromechanical actuators (EMA) and Electrohydraulic actuators (EHA). Even though mechanical-hydraulic actuators are still widely used, EMA and EHA are expected to be largely employed in the new concept of More Electric Aircraft (MEA). Aircraft such as the Airbus A320, A330, A340 and A380 and the Boeing B787 have indeed already begun using EHAs for the steering system.[46] Different models are possible for the wheel tire, many of them adopted from the automotive industry. However, even the Pacejka "magic formula" model, widely used in automotive industry, is not suitable to represent the fast-dynamics in aircraft landings; moreover, the lack of dependence on time-derivatives results in less accurate predictions as transient behaviour is not captured.[47] On the other hand, a simple elastic string model or more complex models such as the LuGre tire model seem to capture fast dynamic conditions.[47,48]

Component modelling Each component is modelled using Modelica language[49] in SimulationX environment.[50] Each component's model is identified by four main characteristics: connectors: they define the model interfaces (inputs and outputs); components: this is the list of parameters, variables, discrete data, used to model the physical component (e.g. the actuator); behaviour: this is the set of equations used to describe the model; Modelica code: this is the automatically generated Modelica code associated with the model. Moreover, all the different types of the same component (e.g. EMA, EHA) have standard interfaces (e.g. EMA and EHA have current as input and force as output). This assures that the components are interchangeable, allowing for the assessment of different technologies for the same system and to compare their performances. The Main Landing Gear model considered in this paper consists of: an oleo-pneumatic shock-absorber, a wheel, a disc brake architecture, and two actuators (Figure 3). Similarly, the Nose Landing Gear model consists of: an oleo-pneumatic shock-absorber, a wheel, a steering mechanism, and two actuators (Figure4).

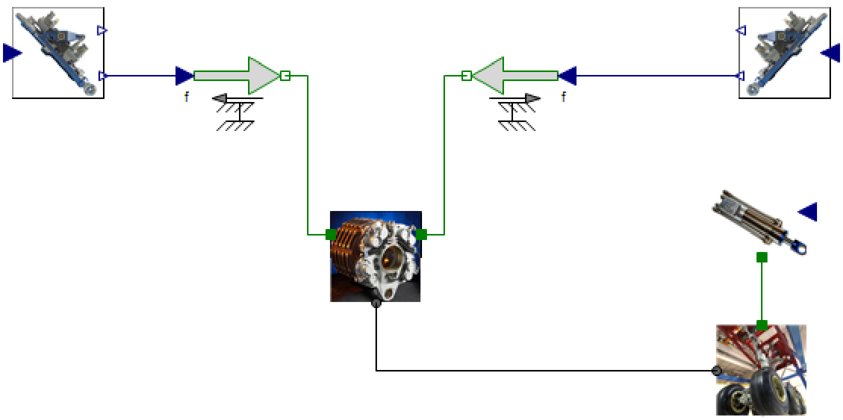

Figure 3: Schematic of Main Landing Gear Model comprising of wheel and tire, shock absorber, and brake actuators components.

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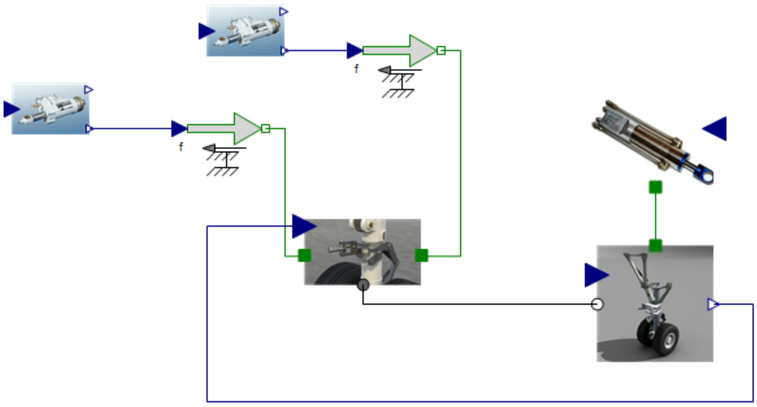

Figure 4: Schematic of Nose Landing Gear Model comprising of wheel and tire, shock absorber, and steering actuators components.

3.2 Aircraft level Integrated Simulation

The final step integrates the aircraft dynamics and the system dynamics to perform a validation test on the SUT, namely the landing gear brake actuator. In order to validate our brakes at the aircraft level, we consider the aircraft (including engines), other landing gear subsystems, atmosphere and runway as our environmental systems, i.e. the systems needed to validate the SUT. This is illustrated in Figure5 where the brake actuator is integrated with such environmental systems. This representation is usually called the Experimental Frame[51] and helps to segregate and visualize what is being tested i.e. SUT versus what is needed to validate this SUT (environmental systems). This is particularly useful in an industrial context where each system is developed by different stakeholders and fidelity requirements are usually specified at the interfaces.The models of these environmental systems are implemented in Matlab-SIMULINK[52] and finally integrated with a Functional Mock-up Unit (FMU) of landing gear model built in SimulationX[?] based on Modelica. An FMU is an executable implementing a Functional Mock-up Interface (FMI) that defines a C-language interface for exchange of models between tools.[53] This allows interfacing different modelling languages, such as causal (e.g. Simulink) and acausal (e.g. Modelica). It is essential to demonstrate model exchange where different stakeholders use different modelling tools which are then integrated in a simulation platform to perform V&V. Such an approach has already been demonstrated at TRL3 and TRL4 for the MISSION toolchain.[54]

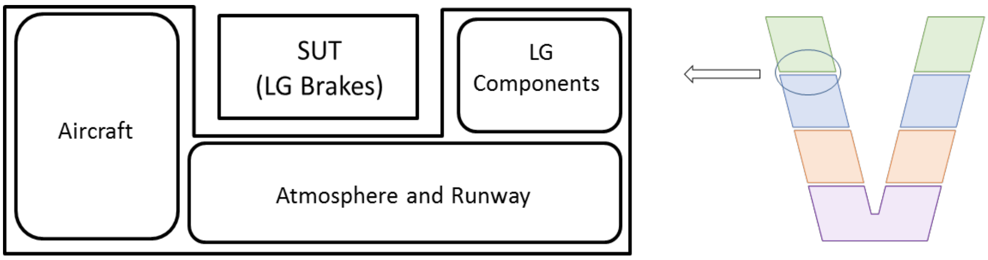

Figure 5: Integration between the SUT and the simulation environment in the V-cycle

In terms of validation, two different types of test scenarios are considered. The first is the evaluation of SUT impact on other systems or on the aircraft, and the second is the aircraft's or other system's impact on the SUT. In general, a V&V scenario encompasses both top-down and bottom-up impact analysis on or by the SUT, each usually having different validation criteria. However, for the sake of simplicity, we consider that these two types of scenarios have the same validation criteria. The effectiveness of brakes is typically validated under worst case vehicle dynamics and, for aircraft, the worst case is the Rejected Take-Off (RTO). RTO refers to the scenario under which, during the course of take-off roll, the pilot decides to abandon take-off due to critical events (e.g. critical system failures, obstacle on the runway, blown tyre), and engages the braking systems including thrust reverser and speed brakes. The RTO can only be initiated when the aircraft is under certain speed V1 (decision speed). The validation criterion for this scenario becomes the stopping distance (Accelerate & Stop Distance, ASD) prescribed in the FAR/EASA Regulations.[43,55] The test procedure consists of few steps: i) failure initiation at a given time, ii) failure detection and verification of aircraft

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speed at that instant, and iii) subsequent engagement of brakes until the aircraft velocity becomes zero. The following sections briefly describe the models of the SUT environment (aircraft) and its integration with the SUT (LGS).

Aircraft Model

The aircraft dynamics model is briefly presented in this section according to Barnes and Yager.[56] The model follows standard axis conventions of local vertical axes, wind axes, body stability axes and the transformations between them. The translational and rotational velocities, denoted by V and ω respectively, are initially calculated in the aircraft body axis from the force and moments acting on the aircraft based on the following standard equation:

$$\dot{V} = \left(\frac{F}{m}\right) - \omega \times V \tag{1}$$
$$\dot{\omega} = I^{-1}(M - \omega \times I\omega) \tag{2}$$

where I is the aircraft moment of inertia, and the force, F and moments, M are given by:

$$F = F_a + F_g + F_T + F_{LG} \tag{3}$$
$$M = M_a + M_T + M_{LG} \tag{4}$$

with the suffixes a, g, T, LG referring to aerodynamics, gravity, thrust and landing gear respectively.
The aerodynamic force and moments are given as follows:

$$F = \frac{1}{2}\rho V^2 S \begin{bmatrix} C_X \\ C_Y \\ C_Z \end{bmatrix} \tag{5}$$

$$M_a = \frac{1}{2}\rho V^2 S\, d \begin{bmatrix} C_l \\ C_m \\ C_n \end{bmatrix} \tag{6}$$

where ρ and V refer to atmospheric air density and airspeed respectively. S and d refer to the reference surface area and the aerodynamic mean chord, respectively.
The aerodynamic derivatives which characterise the coefficients in the above equations are given as follows:

$$C_X = C_{X_0} + C_{X_\alpha}\alpha \tag{7}$$
$$C_Y = C_{Y_\beta}\beta + C_{Y_{\delta_r}}\delta_r \tag{8}$$
$$C_Z = C_{Z_0} + C_{Z_\alpha}\alpha + C_{Z_q} q \frac{d}{V} + C_{Z_{\delta_e}}\delta_e \tag{9}$$
$$C_l = C_{l_\beta}\beta + C_{l_p} p \frac{d}{V} + C_{l_{\delta_\alpha}}\delta_\alpha + C_{l_{\delta_r}}\delta_r \tag{10}$$
$$C_m = C_{m_0} + C_{m_\alpha}\alpha + C_{m_q} q \frac{d}{V} + C_{m_{\delta_e}}\delta_e \tag{11}$$
$$C_n = C_{n_\beta}\beta + C_{n_r} r \frac{d}{V} + C_{n_{\delta_\alpha}}\delta_\alpha + C_{n_{\delta_r}}\delta_r \tag{12}$$

where C_X,C_Y, C_Z are the drag, side force and lift coefficients respectively and C_l, C_m, C_n are the rolling, pitching and yawing moment coefficients respectively. The coefficients are influenced by aerodynamic parameters such as angle of attack, α and sideslip, β, aircraft rotation rates denoted by p, q, r and the control surface deflections $\delta_{a,e,r}$ where the suffix a, e, r denotes aileron, elevator and rudder respectively.The aerodynamic force and moments are calculated on the wind axis which is then transformed to body axis. Similarly, gravity forces are calculated in the body axis with respect to aircraft orientation. The nonlinear aircraft dynamics model includes the effect of aerodynamics whose coefficients are estimated using TORNADO based on the Vortex Lattice Method,[57] whereas the mass and inertia characteristics are estimated from available literature. The engine thrust is modelled as a simple two state hybrid automata[58] in Stateflow. The engine cutoff time refers to the time at which the pilot cuts off thrust to the engine to abandon the take-off. The engine will be shut down only when the aircraft velocity is less than the decision velocity. The landing gear kinematics,

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including the effect of landing gear geometry such as strut attachment and cant angle, are considered. A simple ISO atmosphere model is built based on Ref.59. The ASD distance is calculated in terms of both longitudinal and lateral distance covered by the landing gears, and includes the effect of runway geometry. The environmental system also includes, within the aircraft, a simple auto brake activation system which activates the brake actuator i.e. SUT. This system automatically engages the brakes when it detects the thrust starting to fall due to shut down and holds until the aircraft comes to a stop.

4. Results and Discussion

In this paragraph, we describe the simulation results for different scenarios. It is assumed, for all the scenarios, that the aircraft is at maximum take-off weight, m=73500 kg, with corresponding inertia and the engine is at maximum thrust of 111kN.[60] The runway is assumed to be of length, $L_{rwy} = 6000ft$ and width, $W_{rwy} = 200ft$, at elevation 200 m with no gradient. The environment is assumed to be with a wind of 5 m/s at 20° measured from north and the misalignment between the aircraft fuselage and runway is 16° . The take-off setting is assumed to be 10° deflection of high lift surfaces, and the corresponding aerodynamic derivatives were used in the simulation. Failure and engine shutdown is assumed to occur at time $t = 26s$ and no pilot action on any control surface is assumed. Then, as prescribed by the ASD criteria, the brake actuators are usually validated against two scenarios, namely asymmetric braking and asymmetric engine shutdown at RTO. The former corresponds to the effect of dissimilar actuator output, for example due to wear, on ASD; the latter corresponds to the effect of yawing moment introduced by asymmetric shutdown of engines on the braking performance and ASD. Before simulating the two mentioned scenarios, we assume that neither asymmetric braking nor asymmetric engine shutdown occur and simulate the brake behaviour under normal conditions for two different types of brake actuators in order to see the impact of component choices on the system. We compare the longitudinal braking distance and cross track distance with an EMA and an EHA. The input currents for the EMA and the EHA are identical. The cross track distance is shown for the left main gear, which is located at 5m distance with respect to the aircraft centre of gravity. The negative sign is due to the axis conventions.
Figure 6 shows the aircraft stopping distance and the left gear cross distance for the cases of EMA and EHA employment. Results indicate that both the stopping distance and cross track distance performance of the EHA are marginally better than the EMA. This is likely due to the fact that, for the same current input, the EHA is generally able to exert a higher normal force on the brake rotor disc and, thus, induce a higher braking force. The difference shown between the EMA and EHA braking behaviour demonstrates that the integration framework is able to capture the effects of implementing different system components on the aircraft dynamics. As the EHA seems to provide lower stopping distance and cross track distance, we choose the EHA as our brake actuator for the asymmetric braking and engine shutdown scenarios.

Scenario 1: Asymmetrical braking at rejected take-off
In this section, the effect of EHA brake degradation is illustrated. In this scenario, the engines are shutdown simultaneously after 26 seconds and the brakes are engaged. However, in this case, the right gear brakes are assumed to be worn and 5% less effective than those on the left gear which induces a yawing moment on the aircraft. Figure 7 shows the lateral acceleration of the aircraft Centre of Gravity (CG) for the cases of normal brakes (without degradation), right main gear brake degraded, and right main gear degraded with a fixed rudder deflection of 2 degrees. Figure 8 shows the stopping distance for the first two cases and the cross track distance for the three cases. Results indicate that, on one hand, the stopping distance is not strongly affected by asymmetric braking. The overall longitudinal braking performance is still effective. On the other hand, having a worn right brake increases significantly the cross track distance as the comparison of the three cases shows. The effect of the lateral wind and the lateral stability of the aircraft can be seen. For the second case (brake degraded), the aircraft CG lateral acceleration increases significantly, due to the yawing moment caused by asymmetric braking. This non-zero lateral acceleration is reflected in a considerable increase of the cross track distance compared to the normal case. Similarly in the third case (brake degraded with rudder deflection), the effect of the rudder deflection on the lateral acceleration as well as on the cross track distance is shown. It can be seen that when the brakes are engaged and the associated yawing moment acts on the aircraft, the lateral acceleration increases significantly as in the previous case. This scenario clearly shows the capabilities of the integration framework to capture a system level aspect (e.g. brake degradation) at aircraft level (e.g. aircraft dynamics).

Scenario 2: Asymmetric Engine Shutdown
This scenario serves to validate the SUT performance under aircraft impact (embodied by engine asymmetric shutdown) on system performance. This scenario assumes that shutdown dynamics of the two engines are slightly different with the right engine shutting down 0.9 seconds faster than the left engine. This causes a net non-zero yawing moment that acts on the aircraft until both engines are completely shut down. Figure 9 shows the stopping distance for the cases

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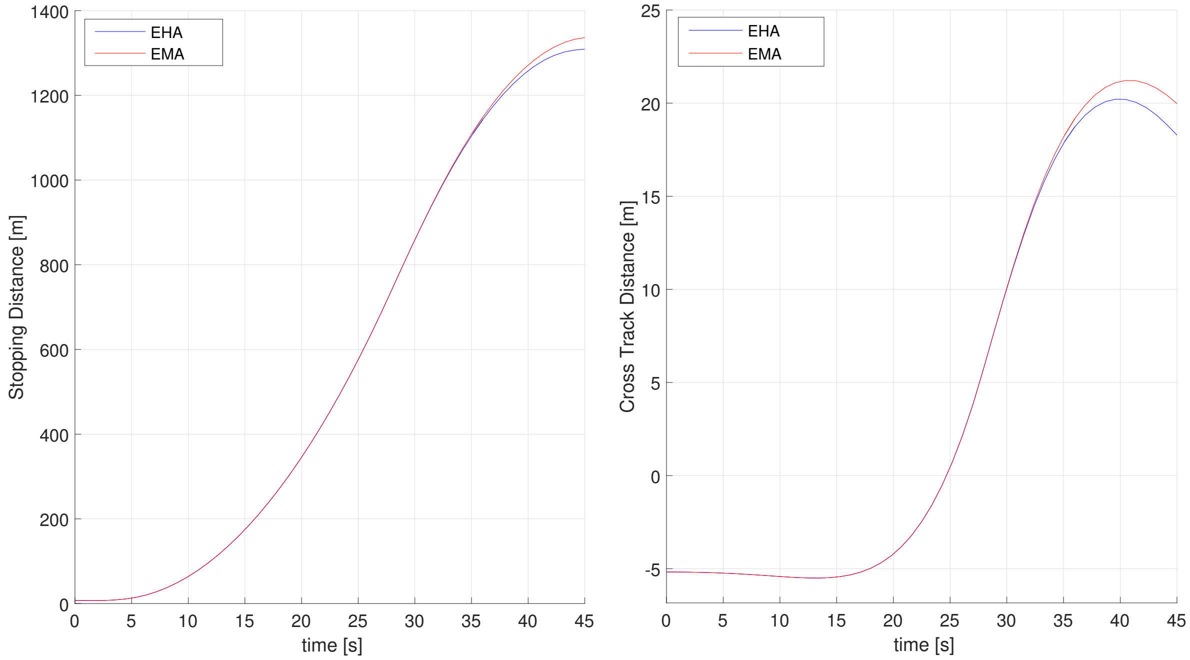

Figure 6: Stopping Distance and left Main Gear Cross Track Distance. The EHA seems to offer a marginally better performance than the EMA.

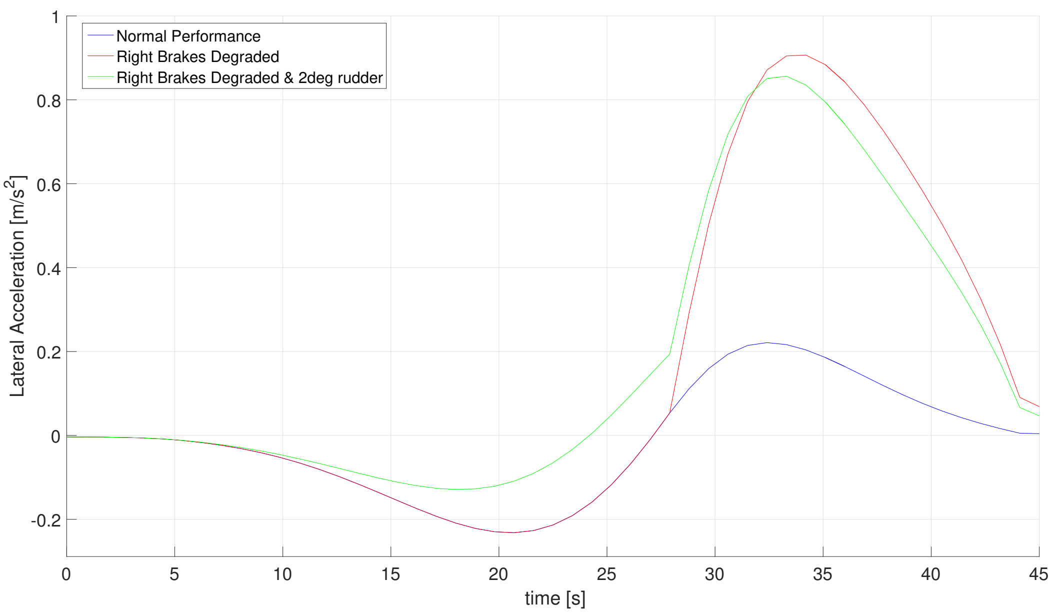

Figure 7: Lateral Acceleration of the aircraft Centre of Gravity. Significant increase due to brake degradation.

of symmetric engine shutdown, asymmetric shutdown and asymmetric shutdown with a fixed rudder deflection of 2 degrees. The figure indicates that the stopping distance is not strongly affected by asymmetric engine shutdown. The overall thrust and, therefore, aircraft velocity profile is similar in all three cases. On the other hand, having different engine shutdown dynamics increases significantly the cross track distance. With symmetric engine dynamics, the cross track distance is, as expected, identical to the previous scenario. For the second and third cases, the behaviour is similar to the brake degradation scenario: i.e. after 26 seconds, there is a nonzero yawing moment (due to engines' thrust difference), which causes a high lateral acceleration and, consequently, a high cross track distance. In this scenario, the final cross track distance is lower than the previous scenario. However the comparison between scenarios

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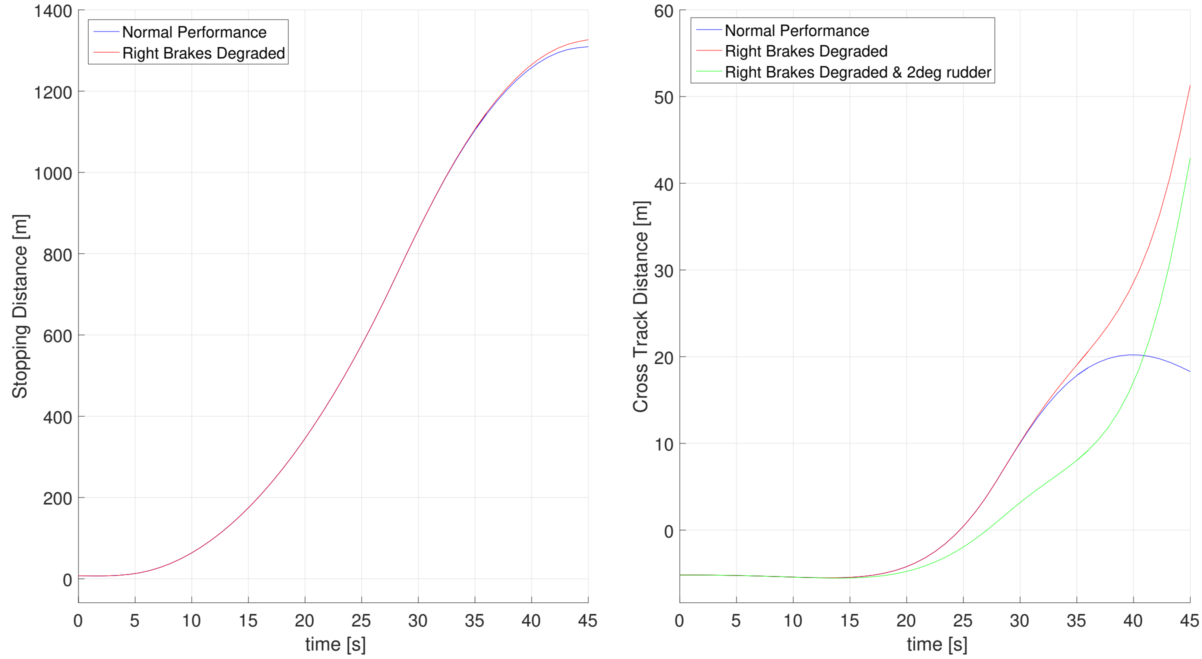

Figure 8: Effect of asymmetric brake degradation. No significant differences for the Stopping Distance. Cross Track Distance is strongly affected by asymmetric brake degradation.

is very sensitive to the conditions prescribed for them (rudder deflection, engine shutdown dynamics, brake degradation percentage etc.) A deeper sensitivity analysis on these factors is needed before final conclusions can be reached. This scenario shows the capability of the integration framework to capture aircraft level impact (asymmetric engine cut-off and rudder deflection) on system level performances (stopping distance and cross track distance).

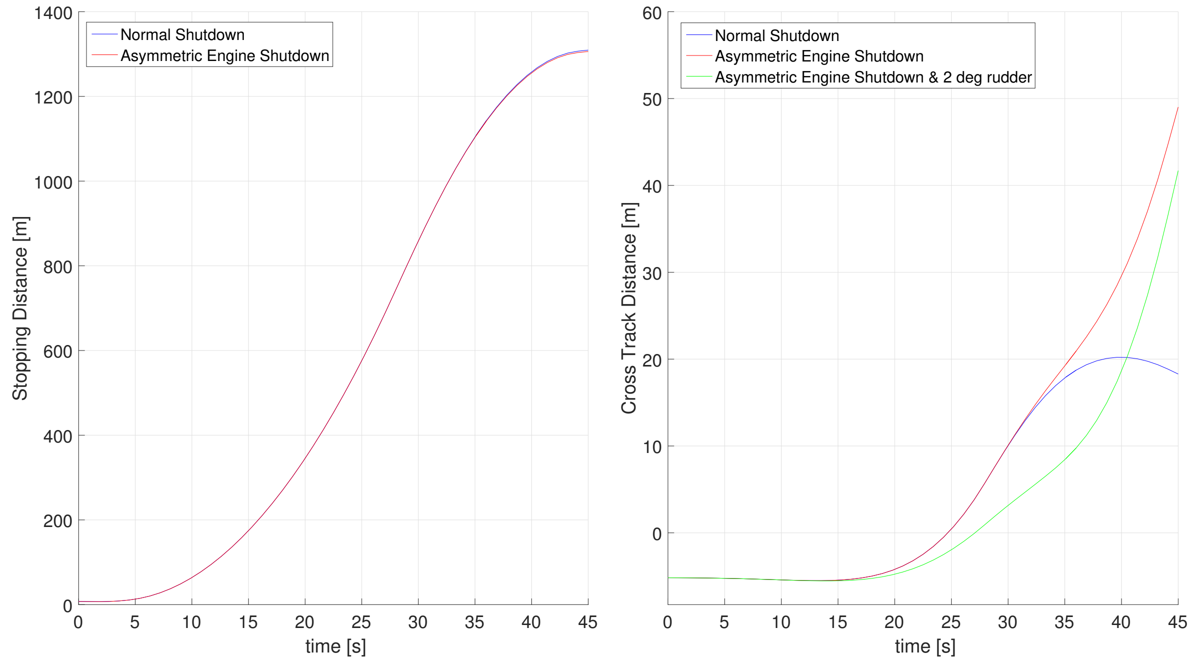

Figure 9: Effect of Asymmetric Engine shutdown. No significant difference for the Stopping Distance. Cross Track Distance is strongly affected by asymmetric engine shutdown.

Similarly, in addition to the effect of rudders, the effect of environment on braking such as cross wind or runway misalignment could be studied. Such an early interaction between different stakeholders such as aircraft and system

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designers will help in mitigating the risk of over or under sizing a system. In addition, an integrated framework such as this could also be used in design optimization where the brake design could, for example, be optimised with respect to power consumption or thermal constraints.

5. Conclusions

This paper has proposed a methodology to handle the integration between aircraft dynamics and system dynamics in the early phase of an aircraft design. We have modelled an aircraft system, namely the Landing Gear System, using an acausal modelling language (Modelica) and the simulation environment of our SUT, namely aircraft, atmosphere and runway, using a causal modelling language (Simulink). The models of the SUT and the environmental systems described in this paper are based on publicly available data. We have integrated the SUT and its simulation environment with the use of FMI standards. We demonstrated it for the Landing Gear System in the rejected take-off scenario, for the case of asymmetrical braking degradation and mismatched engines shutdown dynamics. We have demonstrated that the integration framework presented in this paper is able to capture the impact that events at system level have on the aircraft dynamics (asymmetric braking, EMA and EHA comparison) and vice versa (asymmetric engines shutdown). Future developments may include improving the fidelity of the constituent models.

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