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Object-Oriented Modelling: A Streamlined Approach to Simulate Landing Gear Drop Tests

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Abstract

Object-Oriented Modelling (OOM) is a simple, modern and yet a powerful and efficient approach for dynamic analysis of complex and integrated systems such as aircraft landing gear. It works by connecting premade components from domains such as mechanical, thermal and electrical in a graphical and hierarchical format. (i.e. the components are dragged from a readily available library, dropped into a working space, and connected in the same sequence as they would be physically connected in the real world). OOM can be used to streamline the typical dynamic analysis process which can be complex and time consuming because it requires good command in advanced mathematical operations including differential equations, integrations, Lagrange equations, and Laplace transformations. This study demonstrates the use of Dymola for OOM to model and simulate a limit drop test of a multi-degree-of-freedom landing gear of a General Aviation aircraft at 3 m/s (10 ft/s) descent velocity and a ⅔ lift-to-weight ratio. The certification basis for the aircraft is FAA FAR23 post Amendment 64. This study focuses specifically on the Main Landing Gear system. This consisted of a trailing link connecting the aircraft structure to the Oleo and the wheel. The oleo is the critical functional component of the system as this is where, in combination with the tire, the management of the energy absorption takes place. The oleo is a compressible mixed air/oil oleo shock absorber. Oleo air and oil forces generated during impact were calculated based on Polytropic Processes and Bernoulli's Equation, respectively. Tire forces generated during impact were calculated based on manufacturer's tire compressive force-deflection curves. The simulation results including tire vertical and spin-up drag load indicate promising and expected outcomes based on theoretical analysis and historic test data obtained from NACA Technical Note No. 863. Experimental drop tests will be performed in the future to further benchmark and validate the accuracy and reliability of the simulation data.

Keywords: drop test simulation, Dymola, dynamic analysis, landing gear, object-oriented modelling.

Introduction

Dynamic analysis plays a crucial role in landing gear design, enabling engineers to predict drop test and dynamic responses during landing prior to conducting physical experiments or flight tests. By leveraging dynamic analysis, the time and costs associated with manufacturing and testing physical prototypes can be significantly reduced.

However, performing dynamic analysis on aircraft landing gear is challenging due to its nature as a multi-degree-of-freedom (multi-DOF) system. Accurately modelling and solving the equations of motion involves complex methods such as differential equations, integration techniques, Lagrange equations, and Laplace transformations. This study presents validated results for a single-DOF mass-spring-damper model using the Object-Oriented Modelling (OOM) technique within the Dynamic Modelling Laboratory (Dymola), providing a foundation for more advanced analyses. The validated model is further extended to simulate drop tests of a multi-DOF Main Landing Gear (MLG), incorporating rigid links and the oleo acting as the shock absorber. The simulation replicates the FAA FAR23 (amendment 64) [1] limit drop test conditions for General Aviation, GA, aircraft, which require a descent velocity of 3 m/s (10 ft/s) and a lift-to-weight ratio of ⅔.

Single-DOF Analysis: Dymola Validation

The dynamic analysis in this section aims to predict the displacement over time of a mass connected to a spring and damper, as illustrated in Fig. 1. To understand the system's dynamic response, Laplace and inverse Laplace transformations are applied to obtain baseline results, which are subsequently used to validate the OOM technique within Dymola. The parameters required to analyse the system are provided in Table 1. These parameters are arbitrary and are used solely for the purposes of this analysis.

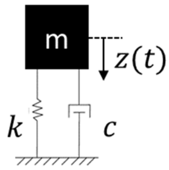

Fig. 1: Single-DOF mass-spring-damper model.

Table 1: Input parameters for dynamic analysis of the single-DOF mass-spring-damper.

Parameter	Value
Mass, m	1,600 kg (110 slug)
Initial Sink Velocity, v_{sink}	3 m/s (10 ft/s)
Spring Constant, k	73,000 N/m (5,000 lbf/ft)
Damping Coefficient, c	4,960 Ns/m (340 lbf s/ft)
Time Step, t_{step}	0.0001 s

The resulting displacements obtained from both methods are compared in Fig. 2. Despite the differing methodologies, both approaches yield identical results, validating the OOM approach in Dymola for this type of system. This validated approach is subsequently used to model drop test simulations for a multi-DOF MLG in the next section.

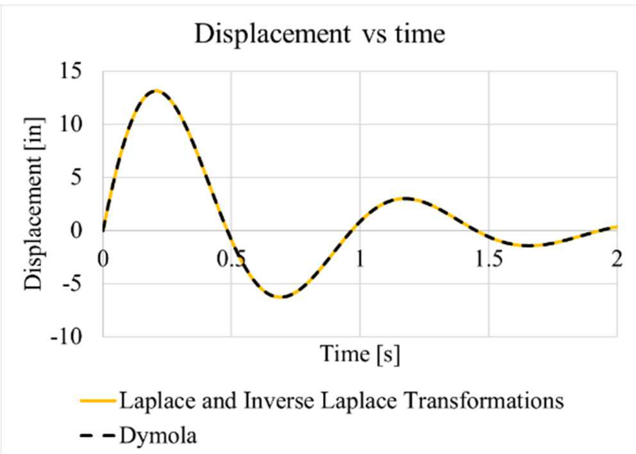

Fig. 2: Displacement results obtained from various calculation methodologies.

Multi-DOF Analysis: Landing Gear Drop Test Simulations

The dynamic analysis in this section aims to predict key dynamic responses—including displacement, velocity, acceleration, and forces—of each component within a single MLG of a GA aircraft. The landing gear simulation begins at touchdown, with the gear subsequently dropped under gravity onto a fixed and rigid ground plane and subjected to the following limit drop test conditions as per FAR23 guidelines [1]: an impact velocity of 3 m/s (10 ft/s) and a lift-to-weight ratio of ⅔. The landing gear model incorporates the following components:

The first component is the weight, which includes both sprung and unsprung masses. The sprung mass consists of the portion of the weight of the aircraft supported by the MLG and the weight of the oleo cylinder, while the unsprung mass includes the weight of the wheel assembly, axle, trailing link, and oleo piston. The model also includes rigid links representing the effective lengths of the trailing link and axle. These links are assumed to be non-deformable, so any force applied at one end is fully transferred to the other end. Additionally, pin and spherical bearing joints are embedded in the model to allow for movement within certain degrees of freedom. Together, these components are connected in the same sequence as they would be physically connected in the real world. They capture the physical and geometrical properties of the landing gear.

The next component represents the physics governing the mixed air/oil oleo shock absorber. Since air and oil forces are generated simultaneously during oleo operation, they are modelled as parallel components in Dymola. When the oleo is compressed or extended, the air pressure increases and decreases, respectively, meaning that it acts as a spring, resisting compression while supporting extension. The opposing and supportive air forces (F_{air}, Eqn 1) are calculated based on Polytropic Processes following methods detailed in [2]. The air force depends on atmospheric pressure (P_{atm} of 101,325 Pa or 14.7 psi), the air gauge pressure ($P_{g,fully\ extended}$) and isothermal air volume ($V_{iso,fully\ extended}$) when the oleo is fully extended, the isothermal air volume at any oleo displaced stroke ($V_{iso,z}$, Eqn 2), and the polytropic index (n_p).

$$F_{air} = \left(\frac{\left(P_{g,fully\ extended} + P_{atm}\right)\left(V_{iso,fully\ extended}^{n_p}\right)}{\left(V_{iso,z}^{n_p}\right)} - P_{atm} \right) \pi r_{outer,piston}^2 \tag{1}$$

$$V_{iso,z} = \begin{cases} \dfrac{V_{iso,fully\ extended} - V_{iso,fully\ compressed}}{-Z_{total}} \times Z_{total} + V_{iso,fully\ extended}, & Z_{oleo} \geq Z_{total} \\ \dfrac{V_{iso,fully\ extended} - V_{iso,fully\ compressed}}{-Z_{total}} \times Z_{oleo} + V_{iso,fully\ extended}, & 0 \leq Z_{oleo} < Z_{total} \end{cases} \tag{2}$$

where $r_{outer,piston}$ is the outer radius of the oleo piston, $V_{iso,fully\ compressed}$ is the isothermal air volume when the oleo is fully compressed, Z_{total} is the total stroke of the oleo, and Z_{oleo} is the oleo stroke at given time. Z_{oleo} is calculated by Dymola and depends on the overall landing gear system. When $Z_{oleo} = Z_{total}$, the oleo is fully compressed; when $Z_{oleo} = 0$ it is fully extended.

In contrast, oil serves as the dampening component within the oleo. It continuously generates a force that opposes the oleo's movement. When the oleo is compressed or extended, oil is forced to flow through a smaller area at the orifice compared to the larger piston or cylinder, causing the oil to accelerate. This acceleration results in a pressure drop, which in turn generates the oil force (F_{oil}, Eqn 3). The oil forces are calculated based on Bernoulli's Equation for orifices, as detailed in [3].

$$F_{oil} = \frac{\rho_{oil} \pi^3 r_{inner,piston}^6 v_{oleo}^2}{2g\left(n_{orifice} \pi r_{orifice}^2\right)^2 C_d^2} \tag{3}$$

where ρ_{oil} is the oil density, $r_{inner,piston}$ is the inner radius of the oleo piston, g is gravitational acceleration (9.81 m/s^2 or 32.2 ft/s^2), $n_{orifice}$ is the number of orifices, $r_{orifice}$ is the orifice radius,

C_d is the orifice discharge coefficient, and v_{oleo} is the velocity of the oleo during compression and/or extension at any given time (i.e. oleo closing velocity). v_{oleo} is calculated by Dymola and is dependent on the overall landing gear system.

The final key component is the tire, which is modelled to generate both vertical reaction force ($F_{vertical}$) and horizontal forces ($F_{horizontal}$), including spin-up (static) and kinetic drag loads. The vertical reaction force, governed by the tire's experimental force-displacement behaviour, is a function of the tire's vertical displacement, which is calculated by Dymola based on the overall landing gear system. This vertical reaction force drives the horizontal forces, which are conditionally calculated based on static (μ_{static}) and kinetic ($\mu_{kinetic}$) coefficients of friction, wheel assembly peripheral speed ($V_{peripheral}$), aircraft forward landing speed ($V_{forward}$), and the spin-up ceases factor (n_c) as expressed in Eqn 4. Here, n_c, which is less than or equal to one, reflects the condition where $V_{peripheral}$ approaches $V_{forward}$.

$$F_{horizontal} = \begin{cases} \mu_{static} F_{vertical}, & V_{peripheral} \leq n_c V_{forward}; Spin-up\ load \\ \mu_{kinetic} F_{vertical}, & V_{peripheral} > n_c V_{forward}; Kinetic\ drag\ load \end{cases} \tag{4}$$

Spin-up drag load is generated as the tire comes into contact with the ground and wheel assembly accelerates from a stationary state until $V_{peripheral}$ closely matches the $V_{forward}$. Consequently, $F_{horizontal}$ rapidly increases from zero to a maximum spin-up load within a very short period of time. According to [4], this transition can occur in as little as 0.2 seconds. After this, the spin-up load quickly diminishes due to its transient nature, transitioning into the kinetic drag load. Since this is a drop test simulation, $V_{forward}$ is manually set rather than calculated by Dymola, and it is assumed to be 1.2 times of the stall speed, as per FAR23 guidelines [1]. $V_{peripheral}$ is governed by Eqn 5.

$$V_{peripheral} = \omega r_{rolling} \tag{5}$$

$$\alpha = \frac{F_{horizontal} r_{rolling}}{I} = \frac{d\omega}{dt} \tag{6}$$

where ω and α represent the wheel assembly's rotational speed and acceleration, respectively; $r_{rolling}$ is the tire's rolling radius (i.e. the full tire radius, r_{tire}, minus vertical tire displacement); and I is the rotational mass moment of inertia of the wheel assembly.

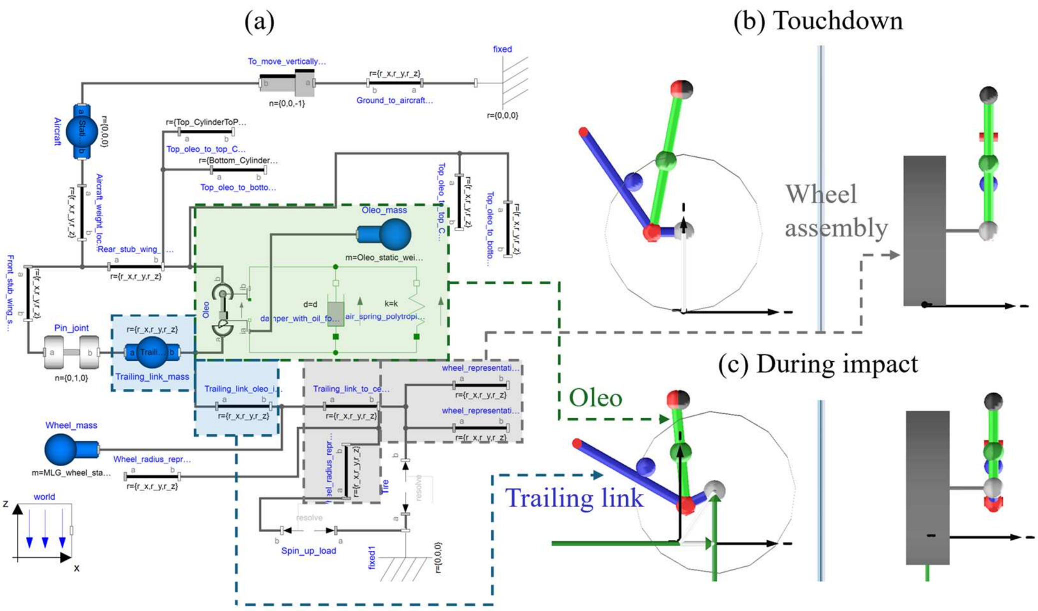

Fig. 3: (a) Multi-DOF single MLG modelled in Dymola. Side and back views of the simulated drop test animation at (b) Touchdown and (c) Maximum oleo deflection.

With all the physics and mathematics defined in the key components as outlined above, the Dymola objects are connected as shown in Fig. 3a. The side and back views of the simulated drop test animation at the beginning of the simulation (i.e. touchdown) and at the point of maximum oleo deflection are depicted in Fig. 3b and Fig. 3c, respectively. The inputs required to simulate the model are summarised in Table 2.

Table 2: Parameters required for drop test simulations.

Parameter	Unit
Physical and geometrical components	
Sprung and unsprung masses	kg (lbs)
Component dimensions	m (ft)
Tire component	
μ_{static}	-
$\mu_{kinetic}$	-
$V_{forward}$	m/s (ft/s)
I	kg m^2 (slug ft^2)
r_{tire}	m (ft)

Parameter	Unit
Oleo – Air component	
P_{atm}	Pa (psi)
$P_{g,fully\ extended}$	Pa (psi)
$V_{iso,fully\ extended}$	m^3 (ft^3)
$V_{iso,fully\ compressed}$	m^3 (ft^3)
n_p	-
Z_{total}	m (ft)
$r_{outer,piston}$	m (ft)
Oleo – Oil component	
ρ_{oil}	kg/m^3 (slug/ft^3)
g	m/s^2 (ft/s^2)
$n_{orifice}$	-
$r_{orifice}$	m (ft)
C_d	-
$r_{inner,piston}$	m (ft)

The simulation (Fig. 3a) was conducted using an explicit Euler solver with a total simulation time of 1.0 second and a fixed time step of 0.0001 seconds (i.e. 10,000 data points). The fine time step was chosen to accurately capture the dynamic responses that occur almost instantaneously within the first second of impact. The simulation results, shown in Fig. 4a, include examples of linear accelerations induced by $F_{vertical}$ and $F_{horizontal}$. It is predicted and shown in Fig. 4a that landing or impact occurs in under 0.5 second. After impact, vertical acceleration rises almost linearly to a global peak of 2.1g, then fluctuates slightly before reaching a second peak of 1.9g. These peaks are typical and can be expected from a system with a mixed air/oil oleo. The first peak is dominated by oil force, occurring as the oleo starts deflecting, generating maximum closing velocity and therefore oil force. The second peak is dominated by air force, resulting from full oleo compression, which generates maximum air pressure. As for the horizontal linear acceleration, spin-up drag (caused by rapid wheel acceleration) induces the initial rise to the peak. As the wheel speed nears the aircraft ground speed, spin-up drag transitions to dynamic drag, seen as a vertical drop in horizontal acceleration. Consistent with real-world experience, such findings confirm the expected behaviour that it is unusual for both vertical and horizontal load maximums to occur simultaneously [5]. These responses similarly align with the vertical and horizontal linear accelerations reported in [4] (Fig. 4b). Specifically, the spin-up drag load ceases before the vertical reaction load reaches its global peak. However, a limitation of the $F_{horizontal}$ load model is its inability to predict the time required for the drag to transition from static to kinetic. For the purpose of this simulation, it was assumed that the drag transitions instantaneously (i.e. in a single time step) from static to kinetic. This is evident in Fig. 4a as a vertical and sudden drop in the spin-up drag load. To further validate the model, an experimental drop test following [6] is planned for future work. This test will involve replicating the simulated drop test conditions and collecting data on key landing gear responses. Comparisons will be made between the simulation and experimental results for critical characteristics, including tire force, oleo force, reaction factor (i.e. the ratio of vertical load transferred to the aircraft to its landing weight), and overall energy absorption. These comparisons will assess the accuracy of the model and its assumptions, providing insights into any discrepancies and potential areas for model refinement. Such validation is crucial to ensure the model's reliability and applicability for landing gear design and analysis across various operational scenarios.

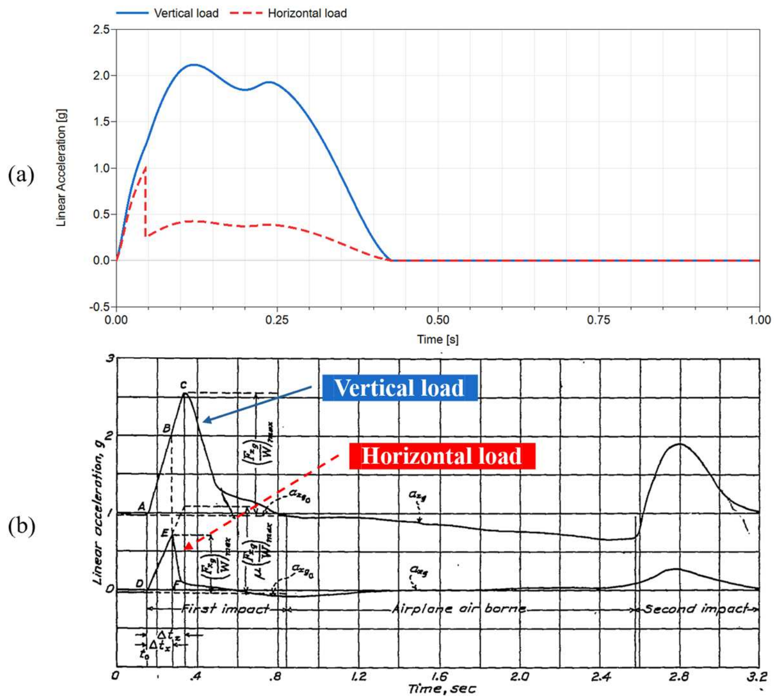

Fig. 4: (a) Predicted vertical and horizontal linear accelerations-time curves during the landing gear drop test. (b) Typical acceleration-time curves adapted from [4].

Conclusion

This study demonstrates the accuracy of using OOM in Dymola for analysing the dynamic behaviour of both single- and multi-DOF systems. The results show that Dymola can accurately predict the dynamic responses of a single-DOF mass-spring-damper system, matching those obtained using advanced mathematical methods such as Laplace and inverse Laplace transformations. Furthermore, Dymola effectively captures the dynamic responses of a more complex multi-DOF MLG system for a GA aircraft. Future work includes conducting an experimental drop test to validate and refine the Dymola models further. These findings suggest that Dymola, with its OOM approach, offers a modern yet powerful and efficient solution for the dynamic analysis of complex, integrated systems such as aircraft landing gear.

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