GearSim Software Description

Rapid Modeling and Simulation for
Landing Gear Systems and Ground Loads Analysis

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EXECUTIVE SUMMARY

The purpose of this software description document is to introduce GearSim, a high fidelity landing gear modeling software tool developed by SDI Engineering Inc. (SDI). GearSim can be used in applications ranging from a detailed system level landing gear analysis to the evaluation of aircraft ground loads. Technological advances in commercial and military aircraft have led to increased requirements on the landing gear system and increased demand for high fidelity analysis. SDI's integrated approach using GearSim will enable designers and loads engineers to meet these requirements while reducing program testing and certification costs.

Approach:

- Integrated modeling of landing gear and airframe structural dynamics and nonlinear subsystems, such as the shock absorbers, tires, flight controls, steering, braking, antiskid, etc.
- Simulation of the entire aircraft, landing gear facility testing, or individual performance evaluation of landing gear components
- Shimmy and gear walk stability analysis, and tire wear evaluation
- Propulsion and flight control system modeling for realistic taxi, takeoff, and landing manuevers
- Batch processing for ground loads evaluation, subsystem design, or component wear evaluation
- Modular software architecture allows multiple levels of fidelity of built-in subsystem models, with provisions to include user's proprietary models
- Professional-quality user interface streamlines the modeling and analysis process; users can quickly create detailed, high-fidelity landing gear models
- Easily integrates with Nastran and other 3rd party structural modeling software

Anticipated Benefits:

- Versatile and robust software capable of efficient military and commercial aircraft simulations
- Design process improvement for reliable evaluations of integrated design and performance of landing gear components, structure, and subsystems
- Cost and timescale savings, with increased safety through reduced testing requirements and avoidance of hazardous test cases
- Enables the assessment of many additional flight and ground testing scenarios that previously have not been readily amenable to reliable evaluation
- Certification support for multiple flight cases and configurations

Potential Applications:

- SDI can tailor GearSim's modeling capability and user interface for custom requirements
- Detailed modeling of hydraulic actuation systems to assess takeoff and landing FCS performance
- Can be linked with CFD software for high-speed taxiing and improved ground effect modeling
- Import aircraft aeroelastic influence matrices from 3rd party aeroelastic software to enable extraction of airframe loads directly from simulation results
- Batch analysis and post-processing features to streamline the ground loads analysis process for certification efforts
- Improved tire and brake service life evaluations using GearSim's batch processing and advanced post-processing features

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1 INTRODUCTION

Aircraft landing gear consists of critical components that must be relied upon to function safely during the most challenging phases of flight. The landing gear consists of many coupled structures and systems, including the leg structure, shock absorber, steering, and braking systems. The industry standard methods for the prediction of loads during ground operations are typically accurate only at low speed taxi conditions, and tend to neglect the effects of important integrated systems such as steering and braking. Similarly, the design and analysis of landing gear subsystems often neglects the dynamic response of the landing gear and aircraft structures. The certification process for landing gear therefore usually involves flight testing and can require significant cost and time. Modeling and simulation is being increasingly utilized to analyze the load-carrying capability and dynamic response of these complicated systems.

2 HIGH FIDELITY LANDING GEAR SOFTWARE

GearSim is an accurate and user-friendly simulation tool for predictive ground loads and landing gear subsystem analysis. It can be used to simulate selected test points to reduce the extent of required ground loads tests, or in parametric studies to understand critical subsystem interactions. This software combines a high fidelity, nonlinear 6-DOF landing gear system modeling tool with variable fidelity aircraft simulation tools, in order to produce an efficient and accurate integrated simulation.

2.1 Background of the Software

GearSim was originally developed in Fortran in the early 1990s to support various ground loads and landing gear projects, and has a long development and validation history. Starting in 2006, SDI Engineering transitioned the engineering software into a commercial software package for generic dynamic simulations of landing gear systems. The aim of this package was to represent dynamic interactions between all of the important landing gear subsystems and the whole aircraft flexible flight dynamics in order to evaluate static and dynamic loads. GearSim's simulation models include an accurate representation of the aircraft, the landing gear flexibilities, the nonlinear subsystems, and the tire-runway interaction.

The landing gear software package was further developed with funding from the US Air Force Small Business Innovation Research (SBIR) program. These SBIR contracts were supported through the Air Force Test Center (AFTC), the Landing Gear Test Facility (LGTF), and in partnership with Airbus. Throughout the course of these contracts, the capability was expanded to perform integrated, fully coupled FE/CFD/landing gear simulations. The landing gear software was re-structured to improve the software maintainability and usability by providing modularized component blocks to construct the landing gear model. A graphical user interface (GUI) was also added to give users the ability to easily and quickly build landing gear models, run simulations, and analyze results.

GearSim has since been developed in cooperation with several industry partners in order to represent a wide range of commercial and military aircraft landing gear types. These relationships have also ensured that it adheres to industry-standard practices, standards, and quality procedures. Further benefits from these industry contacts have been in the specifications, requirements and validation from flight test data.

SDI continues to update GearSim according to customer requirements and as new validation efforts are completed. References 1 through 6 provide background details of the methodologies employed in the basic software and some examples of its usage.

2.2 Validation History

GearSim has been validated using several data sets from flight and ground test cases. References 7 through 10 contain examples of validation against test cases. The predicted loads and displacements were compared against the test data for parameters such as ground reactions, drag loads, shock absorber loads and travel, tire deflections, wheel spin speed, etc.

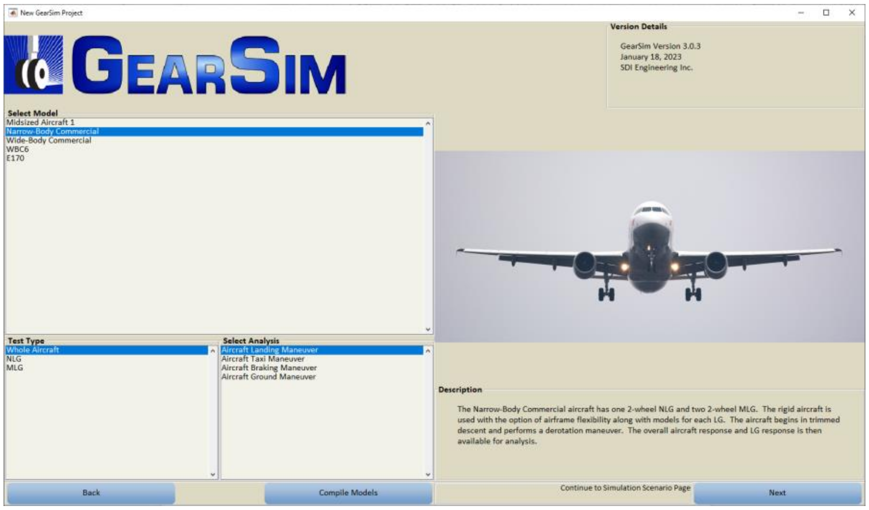
A recent partnership with a commercial aircraft manufacturer began with interest in GearSim as a comprehensive ground loads analysis tool. As part of the validation effort, the software needed to be connected with the aircraft manufacturer's in-house analysis software. GearSim was configured to allow coupling with externally-defined aircraft and subsystem models. This functionality allows users to import their own steering, braking, and antiskid system models into a GearSim landing gear model, and connect with 3rd party CFD or aeroelastic modeling tools to represent the aircraft dynamics.

The sponsorship through the LGTF provided the opportunity for validation and further development of GearSim. SDI has also validated the software against internal landing gear datasets. Validation activities included component-level testing, as well as full landing gear drop test, shimmy and gear walk investigations, and tire modeling. The major landing gear subsystem models were validated including the landing gear structure, oleo shock absorber, and wheel and tire dynamics.

2.3 Software Structure

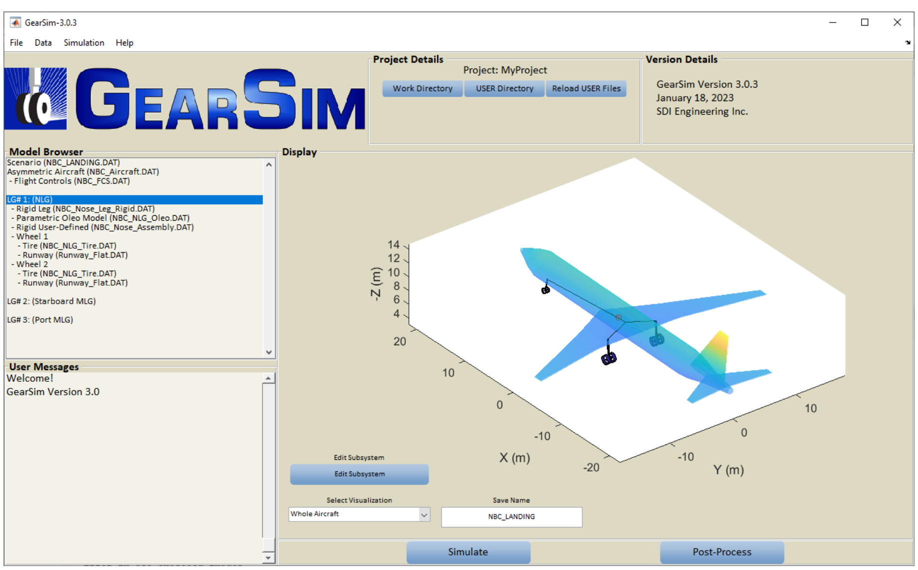
GearSim is based in MATLAB/Simulink, which provides access to a wide variety of industry standard engineering tools. The software has a modular modeling architecture, with the different subsystem models represented by Simulink blocks. This modular architecture enables a variable-fidelity approach to be taken with respect to the subsystem modeling, such as basic models for initial design, and high-fidelity models for detailed analysis. Users can also connect their own proprietary analysis tools, allowing full control over the definition of specific subsystems.

A library of landing gear examples is available within GearSim that serves as a starting point for each analysis. The aircraft types that can be procured include several military aircraft examples, narrow-body, and wide-body commercial aircraft. For experimental aircraft or aircraft with novel landing gear configurations, SDI can work with users to add additional library examples to cover each scenario.



Users start with a landing gear library example that is closest to the landing gear being analyzed, and then input specific data to update the model. This greatly reduces the modeling effort, as users do not have to start from scratch when developing their own landing gear models. The individual landing gear test analysis types are then useful for ensuring the performance of the landing gear model matches the relevant test data.

The main GUI consists of a series of menus that guide the user through the landing gear configuration and definition of all relevant subsystems. Subsystems such as the leg structure and bracing, oleo, and steering and braking systems are defined by engineering parameters readily available from the relevant drawings and specifications. The simulation is then run and post-processed within the GUI, providing relevant loads and stability results at the click of a button.



GearSim's efficient analysis models can perform runs over many load cases or parametric trade studies in "batch mode." This configuration is suitable for trade studies where hundreds or even thousands of design points need to be analyzed. This feature increases the applicability and ease of use of GearSim, allowing users to tailor subsystems to new aircraft models, calculate the sensitivities of relevant results with respect to the modeling inputs, or conduct uncertainty analyses.

2.4 Modeling Capability

The software provides a detailed nonlinear simulation of an aircraft, its landing gear, and all associated subsystems. The applications include take-off, landing, ground roll, braking, steering, taxiing and the general ground maneuvering phases. The subsystem models incorporate numerous levels of detail so that a user can build up simulations over the landing gear development program, from the initial specification to in-service problem solving.

The current simulation software capability has different subsystems that can be coupled together to build models that are suitable for the integrated analysis of specific scenarios. Analysis scenarios range from single landing gear, which can be used to examine drop or dynamometer tests; to complete aircraft formulated to examine all phases of take-off, landing, and ground maneuvering.

2.4.1 Typical Scenarios

GearSim contains a variety of different test scenarios for both the individual landing gears, and the full aircraft to provide insight into landing gear behavior under common aircraft operations. The different analysis types are detailed in the following table. The drop and rig tests are individual landing gear simulations, and the whole aircraft cases are models including three or more landing gear, the aircraft, and any other subsystems such as hydraulic actuation system, flight control system, or propulsion.

Analysis Type	**Description**
Aircraft Landing	The aircraft begins in trimmed descent and performs a derotation maneuver. Models for the aircraft's airframe and all landing gear are included along with the dimensions and aerodynamic constraints of the aircraft.
Aircraft Ground Roll	This option is used for simple taxi scenarios and begins with the aircraft traveling along the runway. Models for the aircraft's airframe and all landing gear are included along with the dimensions and aerodynamic constraints of the aircraft.
Aircraft Braking	The aircraft performs a landing or ground roll, and then a braking command is activated. Default scenario files for a braking ground roll case are also included. Models for the aircraft's airframe and all landing gear are included along with the dimensions and aerodynamic constraints of the aircraft.
Aircraft Taxi	The aircraft begins at a ground roll and a steering and braking command is activated. The user can input a desired aircraft path and velocity profile, from which the required thrust, braking, and steering angle commands are predicted as a function of time. This module also includes a basic taxi pilot steering model utilizing proportional-integral-derivative (PID) control to provide thrust and braking commands (Reference 4).
Carrier Operations	Carrier operations have also been demonstrated with GearSim's aircraft landing model, realistic deck motion and arrested landing (Reference 6).
LG Drop Test	The landing gear starts at a predefined distance above a surface. Depending on the nature of the drop test, the landing gear can also start at an initial velocity. The drop test is force-controlled; that is, it uses a dynamic model of "the testing fixture" that can react to the loads on the landing gear.
NLG Steering Test	The landing gear position, displacement, and velocity are all predefined by the user. The user also specifies the roll, pitch, and yaw angle of the landing gear leg as a function of time. A steering angle is commanded and the subsystem response is measured.
MLG Braking Test	The landing gear position, displacement, and velocity are all predefined by the user. The user also specifies the roll, pitch, and yaw angle of the landing gear leg as a function of time. A braking command is commanded and the subsystem response is measured.
NLG/MLG Bench Test	The bench test module is applied to any testing of the landing gear that is displacement controlled. This testing would include tire properties, leg structure, steering, shimmy, and a variety of other tests that may be conducted on an individual landing gear in a laboratory setting. In the bench test module, the user prescribes the time history of the landing gear displacement.

Analysis of landing gear shimmy is possible using the Aircraft Taxi and NLG/MLG Bench Test analysis types, with a force applied to the landing gear of interest to excite the lateral vibrations, if necessary. Hard landings and accident investigations can be conducted using the whole aircraft analysis types: Aircraft Landing, Aircraft Ground Roll, Aircraft Braking, and Aircraft Taxi. For Aircraft Braking and Aircraft Taxi, steering and braking models are included.

The software can provide a high fidelity integrated model that consists of an airframe, control surfaces, flight control system, engines and landing gear; with full nonlinear, 6-DOF and flexible dynamics. The modular software architecture of GearSim includes many different subsystem variants, enabling simulations for a wide variety of landing gear designs. The subsystems that are modeled are listed below, with a short description of each.

Subsystem	Variant	Description
Aircraft or Test	Drop test	1- or 2-DOF mass with lift simulation
	Rig test	Fixed displacement test for subsystem testing, shimmy analysis, etc.
	Rigid	Rigid aircraft with linear aerodynamic coefficients
	Flexible	Flexible airframe with Nastran normal modes solution and linear aerodynamic coefficients
	Taxi Module	Aircraft models can be reinforced with velocity and path control to follow a user-defined path
Leg	Rigid	Basic leg model to transfer forces and moments
	Flexible	Finite element description built from parametric leg inputs
Oleos	Lookup	Characteristics modeled through stiffness and damping lookup curves
Single Wheel	Shock tube	Shock absorber (oleo) contained inside leg (rigid or flexible)
	Levered	Levered suspension with oleo separate from leg (rigid or flexible)
Twin Wheel (Diablo)	Shock tube	Oleo contained inside leg (rigid or flexible)
	Levered	Levered suspension with oleo separate from leg (rigid or flexible)
Bogie/Trucks	4-Wheel	4 wheel with optional steering (rigid or flexible)
	6-Wheel	6 wheel with optional steering (rigid or flexible)
	Definable	Variable-geometry wheel assembly model with topology defined by user
Pitch Trimmer	Conventional	Pitch damper hydraulics
	Rocking truck	Special model of specific system
Steering	Torque	Applies torque input to steering collar based on steering angle input
	Rack/Pinion	Detailed rack-and-pinion steering model including hydraulic model
	Push-Pull	Detailed push-pull steering model including hydraulic model
	Aft-Wheel	For 6-wheel bogie models, aft two wheels are steerable
	Definable	Users can connect their own proprietary steering algorithm
Brake	Torque	Applies torque input to wheel and accounts for stator mode
	Hydraulic	Detailed friction and brake hydraulic model with actuators, stator mode, and hydraulic pipe transport delays via method of characteristics
	Definable	Users can connect their own proprietary braking algorithm

Subsystem	Variant	Description
Antiskid	Mark 1	Linear velocity error antiskid algorithm
	Mark 2	Nonlinear slip ratio feedback control antiskid algorithm
	Definable	Users connect their own proprietary antiskid algorithm
Tires	Simple	Point contact with lateral and longitudinal friction
	Brush Model	LuGre dynamic friction model for longitudinal friction
	Shimmy	Includes string theory and shimmy model for lateral friction
	Pacejka	Pacejka Magic Formula model
	Definable	Users connect their own proprietary tire algorithm
Runway	Simple	Large bumps and varying runway friction defined per tire or for all tires
	Rough	Runway surface irregularity introduced through random disturbances
Propulsion	Simple	Thrust reversers, asymmetric thrust, force and moments due to engine
	Nonlinear	Models each chamber of engine and connects to overall hydraulic system
Flight Control System	Simple	Flight control laws integrated with 6-DOF rigid aircraft Simulink model or coupled Nastran aeroelastic aircraft model
	Definable	Users can provide and connect their own proprietary flight control laws
Carrier Landing	Simple	6-DOF aircraft carrier deck motion model and arresting gear system that stops aircraft with tail hook in < 4 seconds
Hydraulic Actuation	Single-ram	Interconnected duplex system with up to 8 control surface actuators
	Dual-ram	Dual-ram or single-ram systems available for each control surface

Note that for many of these subsystems, a definable option enables the user to replace the subsystem with their own model. In this case, users develop a Dynamic Link Library (DLL) from their model in C/C++ based on an example provided by SDI. This option also enables hardware-in-the-loop integration of GearSim with subsystem testing by programming a DLL to manage the connection between GearSim and the hardware testing setup.

2.4.2 Simulation Input Variables

The GearSim GUI enables users to define all of the modeling parameters for each of the subsystems described above. Users also define the following inputs with respect to time, distance, or velocity:

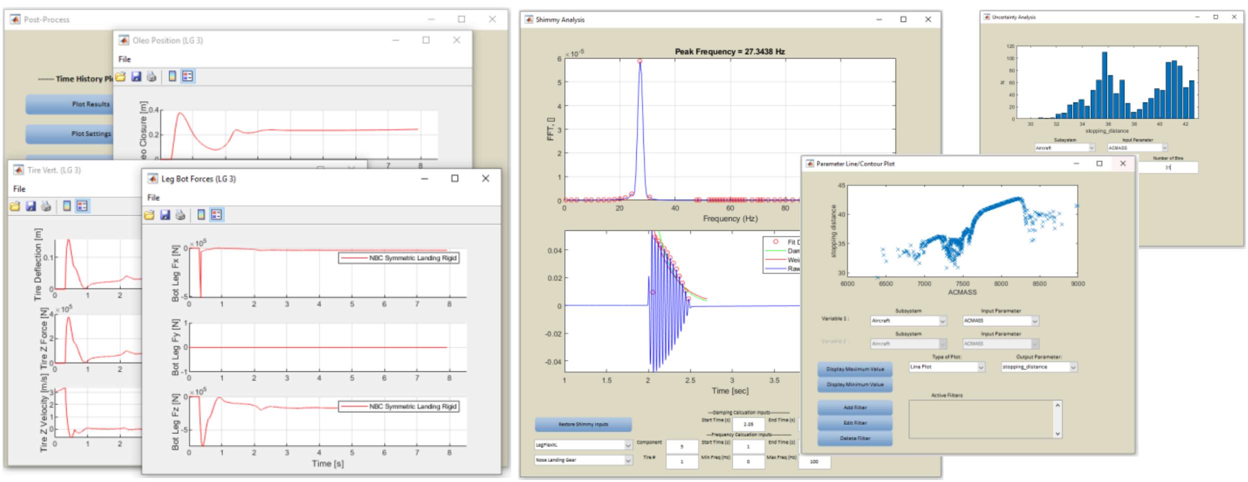
- Runway profile
- Runway friction
- Aerodynamic control surface deflections
- Engine thrust / reverse thrust
- Brake input; either brake pressure or antiskid demand
- Steering angle demand

2.4.3 Simulation Outputs

The list of model outputs includes, but is not limited to:

- Aircraft position and attitude response; aircraft aerodynamics
- System parameters; hydraulic pressures and flows, electrical variables
- Oleo gas pressures
- Brake temperatures and stator vibrations
- Frequency and stability analysis of shimmy and gear walk events
- Landing gear system positions and motions
- Landing gear system component loads
- Integrated loads for tire or brake energy absorption and tire wear analysis

GearSim includes a set of professional tools to post-process the simulation results. These include plotting of the important outputs from each subsystem and tools to post-process data from batch analysis runs. There are also frequency and damping post-processing capabilities built into GearSim for shimmy and gear walk analysis. For batch analysis runs, users can create their own result parameters for plotting or accessing the solution files and performing their own post-processing calculations.



2.4.4 Current Capability Compared with Common Ground Loads Practices

Many organizations use a classical ground loads analysis approach by using landing gear drop test data as the primary source of landing gear loads for design and certification. These landing gear loads are applied to an FE model of the airframe to estimate the resulting airframe and connection point loads. For steering and braking maneuvers, landing gear loads can be estimated through static balances of the aircraft with the appropriate simplifying assumptions.

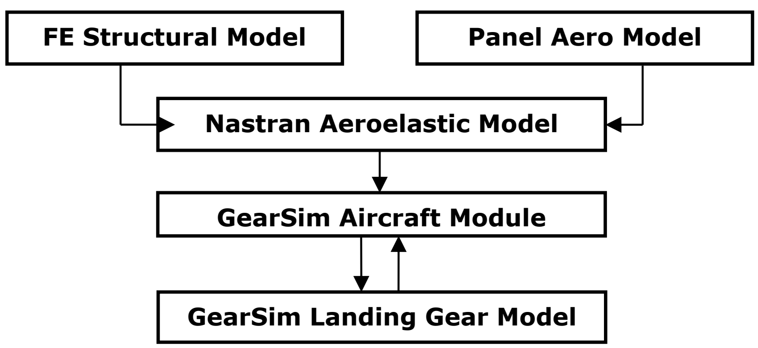
SDI has shown with GearSim that even for the carefully controlled conditions under which the drop test was conducted, airframe flexibility can alter the resulting landing gear loads. For a steady and level landing, landing gear loads will also be affected by the aircraft weight condition, CG location, and sink rate. These factors can be readily accounted for using GearSim, but would require further drop testing in the classical approach. For landings in crosswinds, GearSim enables a greater understanding of the flight control system and maneuver effects on the loads during the main and nose landing gear impact. This would not be possible using the classical ground loads approach without dedicated flight testing.

GearSim includes a parametric airframe model to account for airframe flexible deflections resulting from the landing gear loads. Users can alternatively import a normal modes solution from a 3rd party structural modeling software. Airframe flexible deflections due to aeroelastics and controls are not included in GearSim's simulation, so airframe ground loads cannot be obtained directly from GearSim's airframe model. To obtain airframe ground loads including aeroelastics and flight control systems, GearSim's landing loads results can be applied to an aeroelastic model (e.g., Nastran) of the airframe as a post-process. GearSim's landing gear structural model is capable of outputting loads at the various structural attachment locations (upper leg tube, fixed and folding stays) by post-processing the simulation results.

For taxi, steering, and braking maneuvers, GearSim can provide realistic landing gear and ground loads through simulation of complicated maneuvers. GearSim's Taxi Module and Taxi Pilot Module are capable of following an arbitrary taxi path and velocity profile, defined through waypoints in the runway plane.

2.4.5 Incorporation of Aeroservoelastics with Nastran

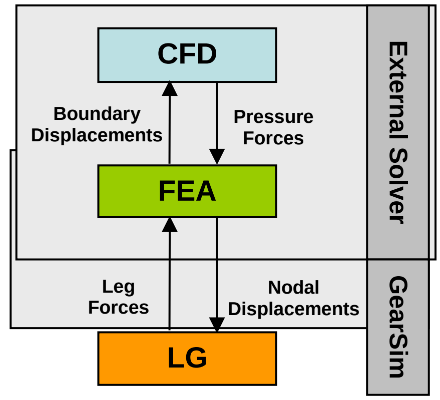
One way GearSim can account for airframe flexibility is to import a linear aeroelastic model from Nastran or a similar aeroelastic software package. In this case, the required aircraft structural and aerodynamic matrices are imported into GearSim, and a Reduced Order Model (ROM) is generated from the model in the time domain. GearSim's aircraft module then couples the landing gear model with the ROM and calculates the flexible aircraft dynamics along with the landing gear system.



In this approach, the majority of the user's time is spent preparing the FE and aerodynamic models. When the required modal and aerodynamic database is generated by Nastran, it is used directly by the GearSim aircraft module, and does not require additional Nastran runs. The airframe loads can then be obtained directly through a post-process of the GearSim results, instead of requiring an additional Nastran run as described in Section 2.4.4.

This approach was demonstrated as part of the previous SBIR efforts that were used to develop GearSim. SDI is working to develop a general, commercialized version of GearSim that includes this feature, and can work with current customers to develop their own tailored version according to their requirements.

2.4.6 Solution with FE/CFD Code



GearSim can provide high-fidelity nonlinear aeroelastic solutions through the integration with external FE/CFD codes. The nonlinear landing gear analysis is coupled with the external FE/CFD solver by using a staggered simulation approach. In this approach, GearSim calculates the nonlinear landing gear behavior, and the external solver calculates the flexible aircraft dynamics and aerodynamic effects. This allows the various modules to communicate without requiring any significant modifications to the external solver. This approach has been validated and is applicable to any industry standard FE or CFD code.

This approach requires detailed FE modeling around the connection points between the aircraft and its landing gear, and is computationally expensive. Customers can work with SDI to integrate their own CFD software into a specialized version of GearSim, enabling simulation of events such as high-speed landing and takeoff maneuvers, understanding landing gear door opening and deployment aerodynamics and deployment, and for landing gear drag prediction.

3 COMMERCIAL OFFERING

GearSim is commercially available in a modular approach, with each user's GearSim experience tailored to their requirements. The base software includes a specific landing gear type that is selectable by the user. This section provides a description of the various software features and modules that are available to empower GearSim for specific applications.

3.1 Aircraft Landing Gear Library Types

GearSim's library of landing gear types are starting points to rapidly develop a specific model for each application. The model can simulate individual landing gear and aircraft scenarios, with a detailed leg, tire, and shock absorber model for each landing gear; and an aircraft model including aerodynamics, flight control system (FCS), and airframe flexibility. The most popular aircraft library examples are described below. SDI can also work with customers to provide additional library examples for configurations not included. Example configurations include those with a different number of landing gear legs, tires, and including levered configurations.

Mid-Sized Aircraft Model: Single-wheel nose landing gear (NLG) and main landing gear (MLG), with the default example representative of a light business jet.

Narrow-Body Commercial Aircraft Model: Two-wheel NLG and MLG.

Wide-Body Commercial Aircraft Models: Two-wheel NLG, and four-wheel or six-wheel MLG with pitch trimming device. For the six-wheel case, an aft wheel MLG steering model is included (i.e. 777).

3.2 Additional Landing Gear Configurations

Additional landing gear types and the appropriate subsystem configurations can be added to the base GearSim package. SDI Engineering has worked with customers on a variety of landing gear types, including levered shock absorber arrangements, unique aircraft attachment details, and various numbers of wheels.

3.3 Specific Aircraft Models

Parameter inputs for a specific aircraft can be updated. The parameters are populated from data found in the public domain, estimated using engineering assumptions and analysis, and based on historical data with appropriate assumptions.

3.4 Validation and Tuning

Validation and tuning can be performed for various GearSim libraries. The validation is performed based on the user's data, with pricing based on the complexity of the subsystem being validated. SDI will provide a dedicated GearSim usage case to replicate the test data using the tuned model, and will provide expertise to adjust the modeling properties in order to validate a landing gear and aircraft model.

Drop Test Validation: The landing gear model's tire, shock absorber, and structural details can be determined through analysis of the landing gear geometry and comparison with drop test results.

Dynamometer Test Validation: Subsystems critical for successful ground operations, such as the steering and braking systems, can be tested using a dynamometer or other lab setup.

Flight Test Validation: SDI can recommend and participate in flight test activities to confirm GearSim's landing and takeoff performance predictions.

3.5 GearSim Dynamic Link Library (DLL) Integration

At the customer's request, DLL replacement of certain subsystems can be enabled. The DLL encompasses various landing gear related subsystems including but not limited to the shock absorber, tires, steering, brakes, and antiskid system.

In this module, the user can write a subsystem model in the form of a C/C++ library compiled to DLL. This enables users to create their own DLL that can be called by GearSim to calculate the subsystem (i.e. tires, brakes, steering, antiskid, etc.) response during the simulation. A set of example C files are provided as a guide to users.

3.6 Custom Requests

Custom GearSim package solutions are possible for customers. Examples include non-standard landing gear configurations, unique aircraft configurations, future design considerations, and expanded features to any purchased options, etc. User interface features oriented towards the customer's engineering goals can be integrated with the software to streamline its use and onboarding process.

4 CONCLUSION

GearSim is a landing gear loads, dynamics, and systems analysis software tool that has been developed over many years and supported by the US Department of Defense, commercial aircraft OEMs, landing gear suppliers, and universities. As a stand-alone validated software tool, it is capable of processing a comprehensive model of the landing gear system and simulating its dynamics efficiently and accurately. This commercial-quality software tool provides a platform for the integrated design and analysis of landing gear and all associated subsystems.

GearSim is an ideal platform for a variety of landing gear analysis programs. GearSim can be used to simulate test points that are required in the certification process, and therefore reduce the number of actual flight and ground tests performed. GearSim can also be used to explore the interactions between the complex, nonlinear subsystems that play an important role in adverse landing gear behaviors. GearSim can be coupled with aircraft models of varying complexity, so that a suitable fidelity can be selected for the specific type of problem.

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