

Multi-Physics Design and Optimization of a Complex Radar System

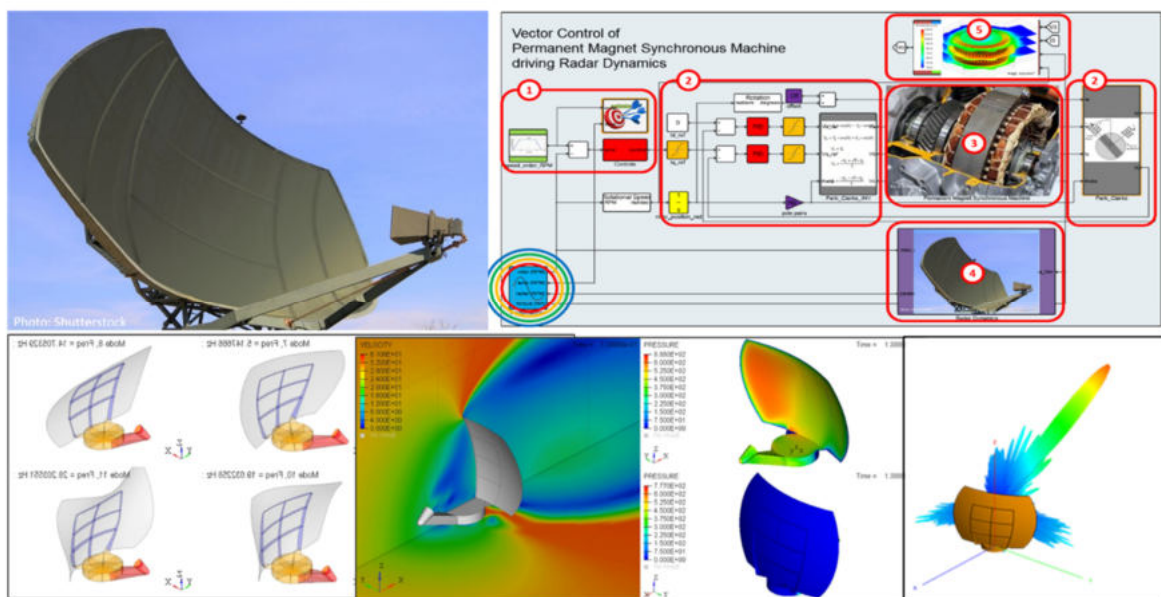
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Introduction

Today, most products are complex mechatronic combinations of advanced technologies, mixing electrical parts with controllers and embedded software. To efficiently manage innovative products, organizations are turning to a Model-Based Development approach for concept studies, control design, multi-domain system simulation and optimization. To meet this demand, Altair's simulation and optimization suite aims to transform design and decision-making throughout product lifecycles with their multi-disciplinary software tools and consultancy services.

Modern radar systems are a good example of a complex product - comprising electrical, mechanical and structural components. The overall radar performance, as measured by the electromagnetic (EM) radiation profile, is influenced by each subsystem – both individually and collectively – under a range of hostile, environmental conditions.

In this case study, an integrated multi-discipline design approach is presented for a typical terrestrial radar configuration to illustrate how the use of Altair's simulation tools throughout the entire V-cycle process – from conception to mapping radar beam profiles - aid design and ensure an optimized, robust final product.



Efficient Global Design thanks to Model-Based Development

Overview

To efficiently manage complex, innovative products organizations turn to a Model-Based Development approach for concept, trade-off studies, control design, multi-domain system simulation and optimization.

Basic Requirements

The radar pre-sizing and environmental drivers for this case study are:

- Antenna: 4m wide x 3m tall; 2m focal distance
- Rotational speed: 12 rpm (constant)
- Effect of environment on the structure (hurricane-level wind speeds, up to 120 km/h).

To accurately predict the electromagnetic (EM) performance, the effects on the structure, mechanism, motor, actuation, along with thermal losses need to be taken in account in a coherent manner. The aim of simulation is to design or select the most suitable components for the system that give the best performance in terms of quality of reception, lifetime, energy consumption whilst under various environmental conditions. These can be easily extended to include other constraints.

Multi-Physics Simulation Enablers

Techniques to enable multi-physics simulation of increasing complexity, can be summarized as:

- Chaining: « provider » solver compiles independent variables, such as time or Design of Experiment (DoE) parameters into Look-up Tables (LuT) of either time-based or surface responses that « client » solver uses during its own simulation.
- Coupling: « provider » solver produces linear equations (LSE: Linear State Equations) – e.g. import of a structure into a mechanism model - or non-linear equations (GSE: General State Equations) – e.g. import of actuator dynamics into a mechanism model - to « master » solver that integrates all states.
- Co-simulation (Co-Sim): « first » and « second » solvers are synchronized to exchange inputs/outputs at regular time intervals whilst both integrating separately their own states.

V-cycle Approach

From the identification of market requirements to the final product, the design-development process forms several steps that describe the overall system architecture, subsystem topology, component design, integration and validation. Together these form the radar V-cycle shown in Figure 1.

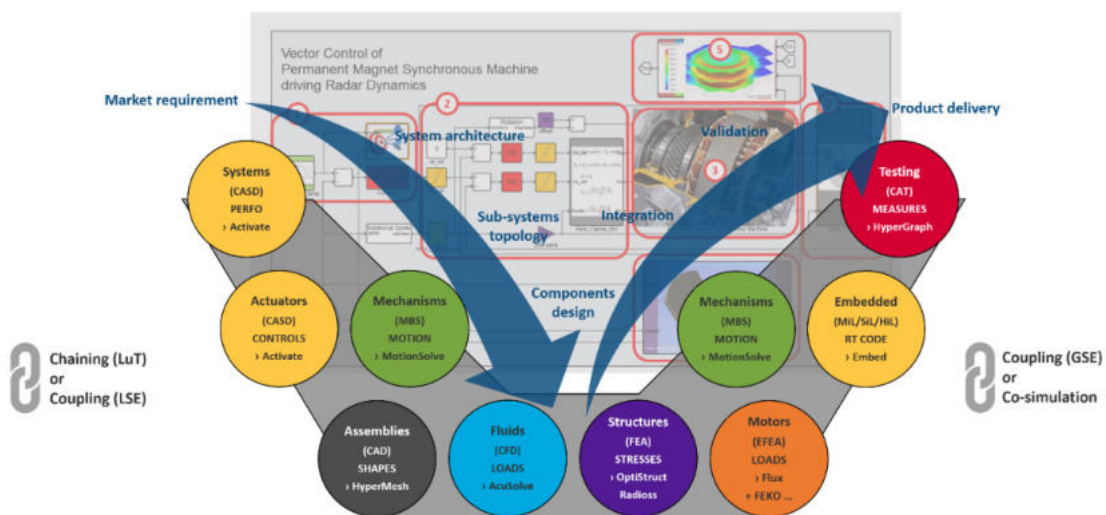
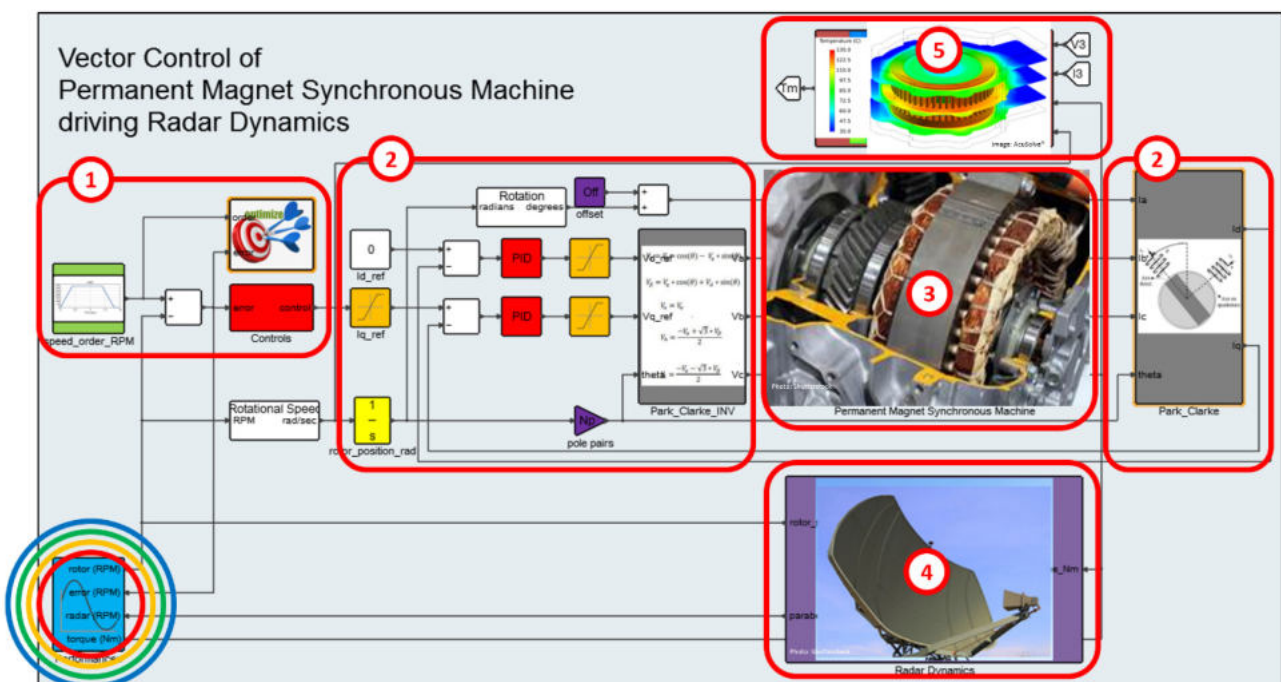


Figure 1: Radar Design V-cycle - From Identification of Market Requirement to Final Product

Different simulation disciplines and solutions are considered and applied to the various subsystems – motors, actuators, mechanisms and structure – to become the multi-physics design approach described in this case study. In general, the more accurate simulation solutions are applied later in the V-cycle to attain the necessary precision.

Global Integration into a System Model

As shown in Figure 2, **Altair Activate™** - Model-based Development of Systems Solution - is used very early in the design cycle to describe the radar system model, as divided into different but interrelated subsystems (numbered 1 to 5). Each of these can be simulated in a separate model by applying appropriate solvers at different stages to enable the overall radar EM performance to be measured and prove the robustness of the analysis.



Key: ① Rotor speed control; ② Electric command; ③ Electric actuation; ④ Mechanical plant; ⑤ Thermal loss

Figure 2: Radar System Model - Main Subsystems

Multi-Physics Integration

Implementing an Efficient Electric Command depending on Rotor Speed

By applying classic design processes, in particular PID control factors, the rotor control simulation results are shown in Figure 3, with rotor speed and error, antenna speed and torque v time shown graphically.

The initial curve comprises an acceleration, constant speed region, then deceleration to stop which is applied to the radar system. The last curve illustrates that under the imposed rotor speed profile, the torque curve fluctuates because of aerodynamic loads on the antenna due to the high wind speed. This will need to be considered during further studies and optimization.

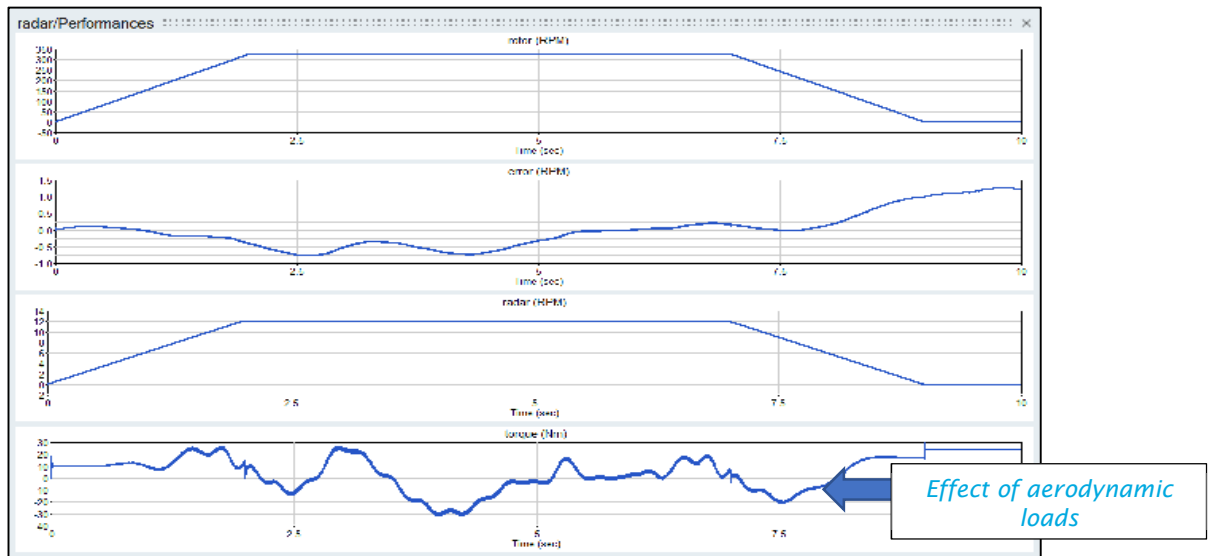


Figure 3: Radar Rotor Control Simulation

The classic procedures for the design of PID controllers are used in the simulation model, along with Park-Clarke theory commonly applied for control of three-phase to DC motors; as shown in Figure 4. The results, plot of the Park-Clarke currents v time, for each of the three phases identify a fluctuating current demand caused by the aerodynamic loads on the antenna.

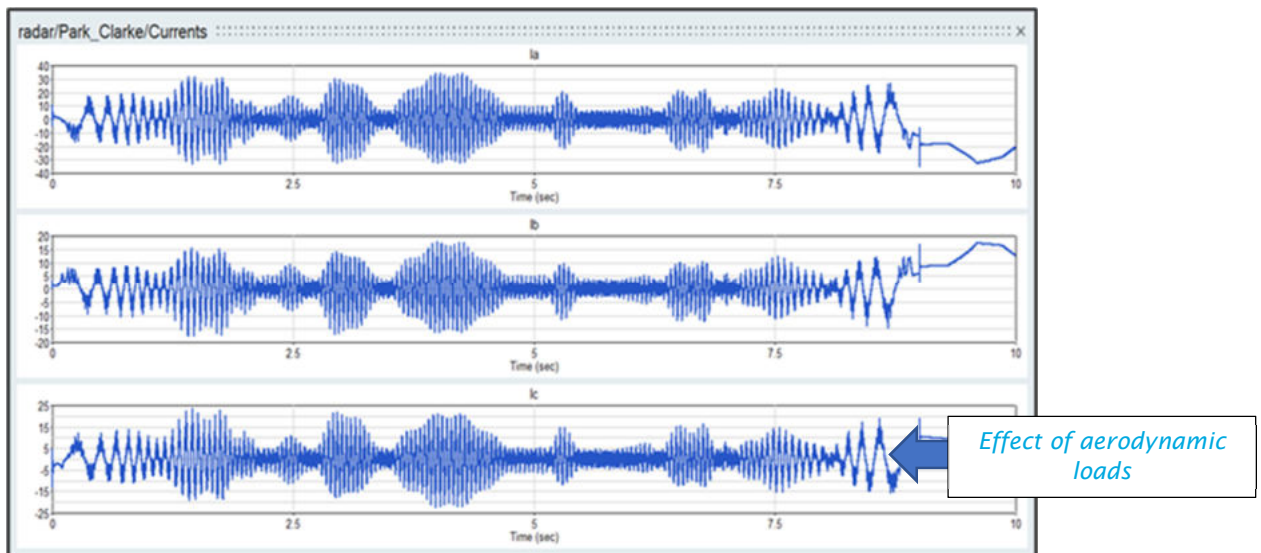


Figure 4: Radar Motor Current Simulation

Setting the System into Motion with Electric Motor Integration

Identified as “Permanent magnet synchronous machine” in Figure 2, the simulation of this electric motor is divided into 2 levels.

The chaining solution is applied very early in the design cycle. Extracted from either dedicated motor pre-design tool **Altair FluxMotor™**, or low frequency EM, electric and thermal simulations solution **Altair Flux™**, the look-up table offers a

magnetostatic representation with flux and torque generated by the motor in relation to the controller DC current and rotor position. These outputs can be directly incorporated into the radar model to be coupled with an appropriate Modelica description of the electric power supply, as shown in Figure 5. Such coupling enables evaluation of the performance of the machine, choice of one type or another from an existing range, or even design of a specifically-optimized motor dedicated to the application.

The more accurate capability to co-simulate with **Flux** is applied during the integration and verification steps to replace the magnetostatic look-up table used previously. Co-simulation offers a more accurate analysis of losses by taking into account saturation and Eddy currents, for instance.

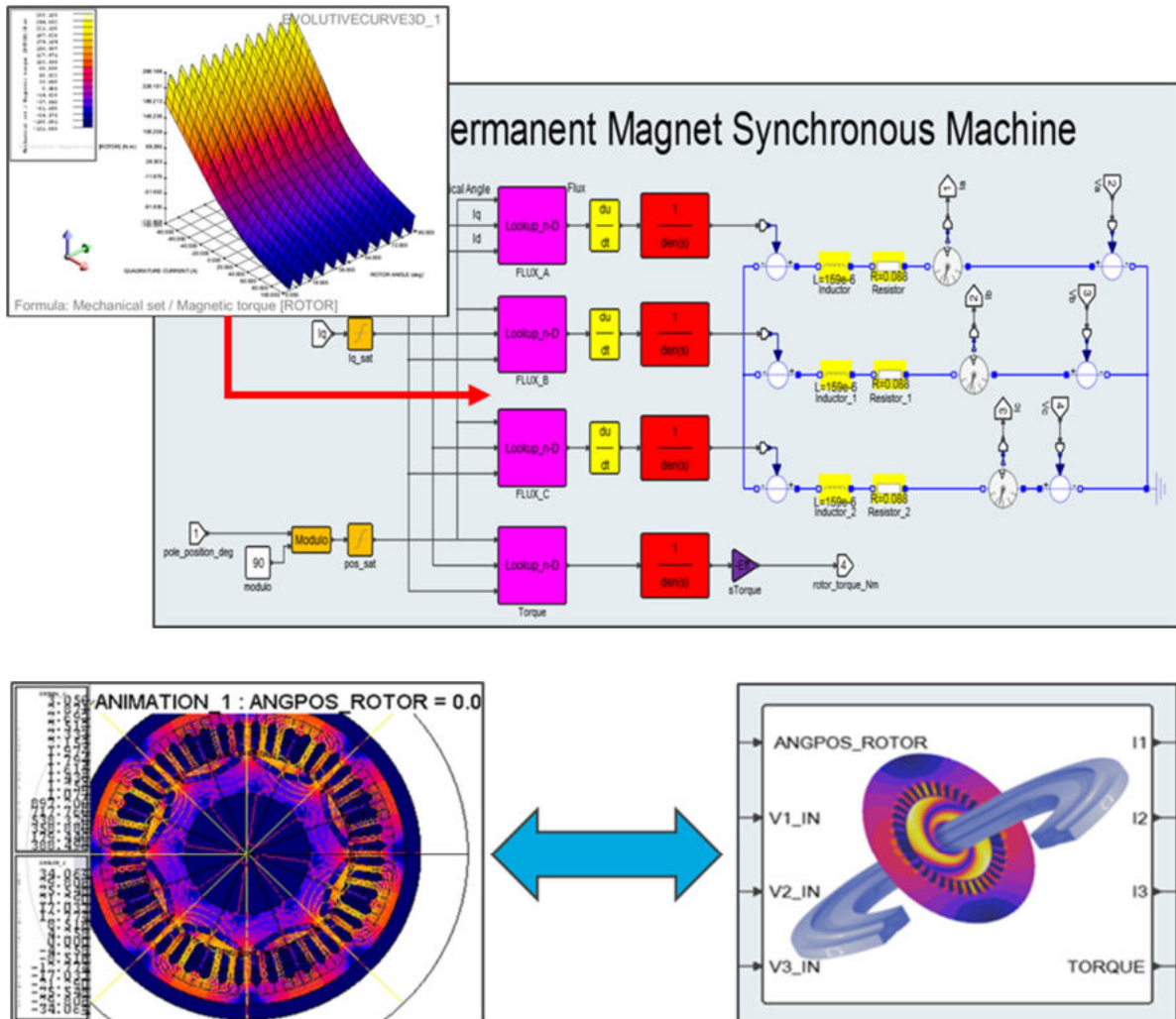


Figure 5: Electric Motor Simulation Steps and Integration into the Global System

Mechanical – Drive-Chain Loads

A general layout for the radar dynamics, given in Figure 6, shows the motor and 3 planetary gear sets necessary for speed reduction.

The first level applied early in the design cycle, uses Modelica equations for idealized gears and a rigid antenna structure. Computational Fluid Dynamics Solver **Altair AcuSolve™** produces a look-up table of results for aerodynamic loads, arising from high wind speeds, with respect to antenna position.

To determine more precise loads on the antenna, the next level retains the idealized gears, but replaces the rigid antenna with a flexible one using equations originating from structural analysis and optimization solver **Altair OptiStruct™** component mode synthesis.

The third level, applied later during integration and verification, uses the capability to co-simulate with **Altair MotionSolve™** multi-body dynamics simulation, for roller bearings, detail of gears and flexible antenna (from **OptiStruct** component mode synthesis equations) coupled with aerodynamic loads (from **Altair AcuSolve™** pressure results mapping).

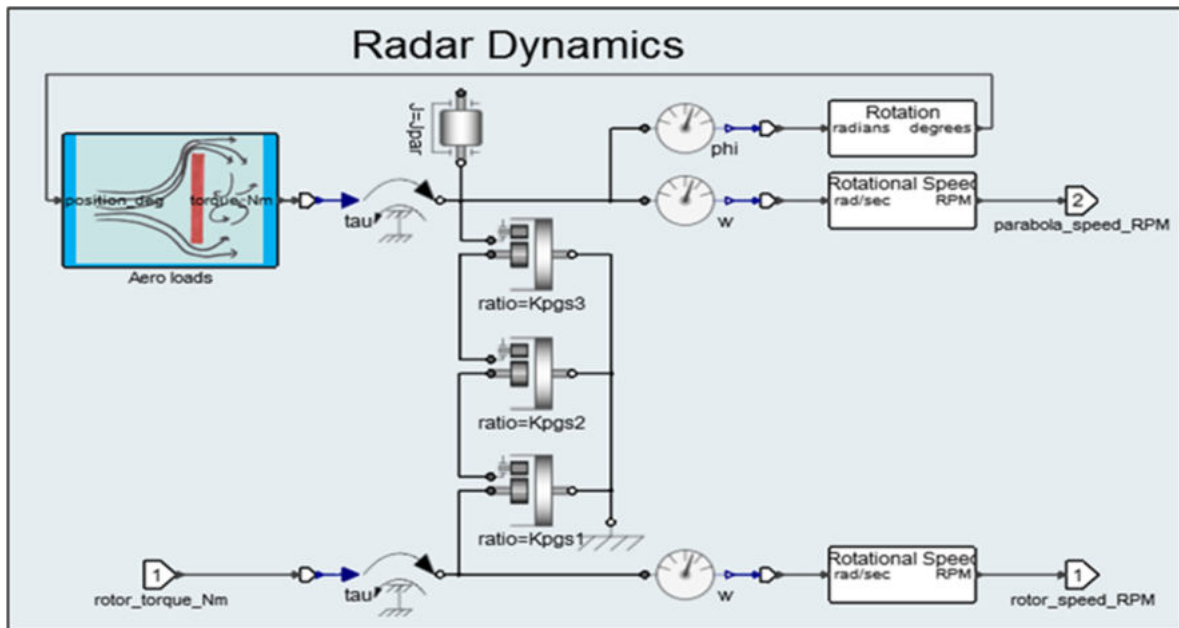


Figure 6: Radar Dynamics - General Layout

To establish the aerodynamics using **AcuSolve**, the antenna is rotated at the constant speed of 12 rpm under the influence of hurricane wind speeds (120 km/h). As shown in Figure 7, the results are a pressure map, on both front and back faces of the antenna related to the angle of attack of the wind direction. This determines precise environmental loads experienced by the radar antenna.

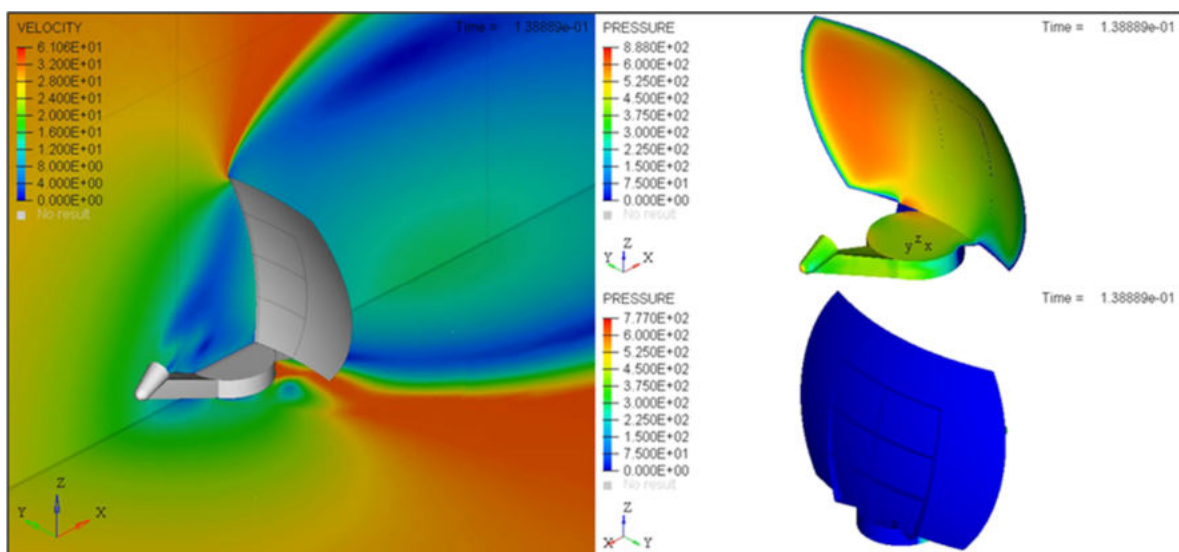


Figure 7: Radar Antenna - Aerodynamic Pressure Map of Front and Back Faces

To consider the effects of vibrations on the antenna assembly, a structural model from **OptiStruct** is used to determine the antenna deformation when the pressure map generated using **AcuSolve** is applied; as shown in Figure 8.

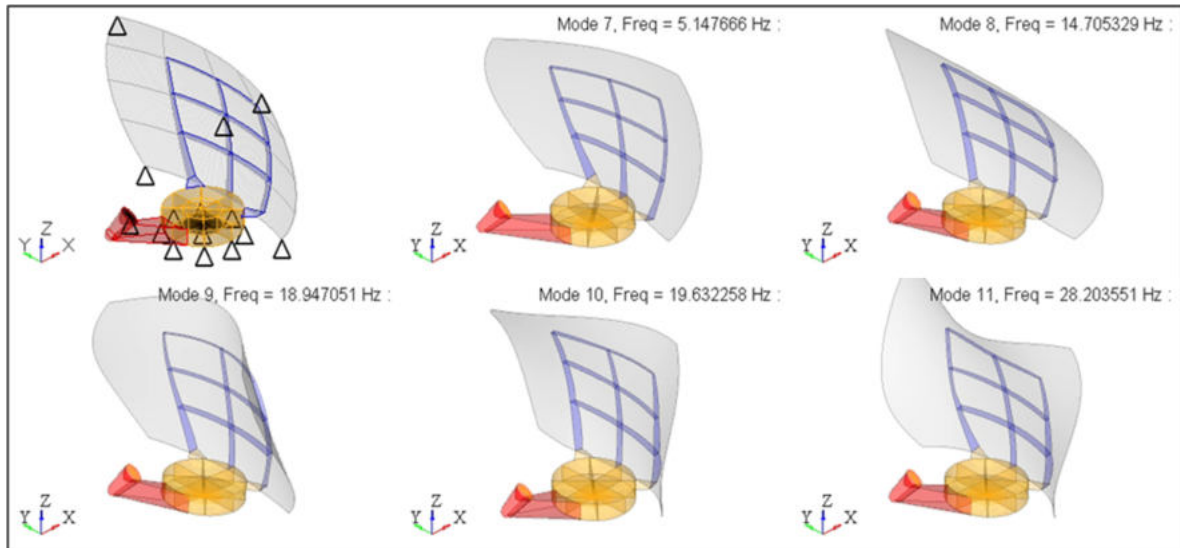


Figure 8: Radar Antenna - Effect of Vibrations and Deformations

To simulate the radar drive-chain, planetary gears and roller bearings, **MotionSolve** determines the wind loading on the bearing assembly as the antenna rotates; shown as red arrows in Figure 9.

In the graph of axle torque relative to antenna angle with time, the blue line represents the environmental loads on the antenna whereas the motor torque in red is to maintain the antenna rotation at the desired constant speed.

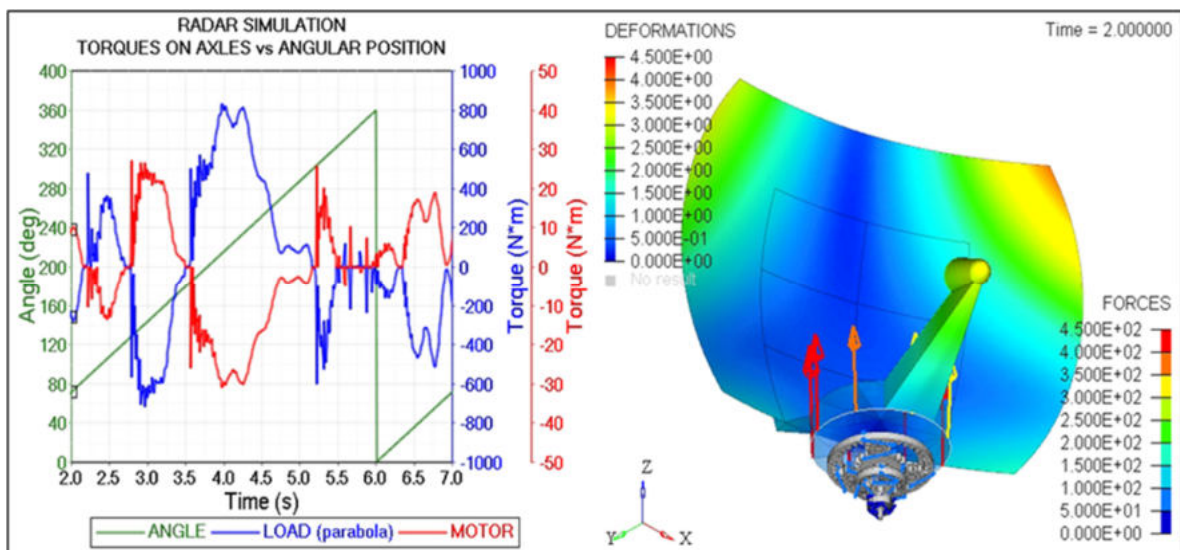


Figure 9: Radar Drive Chain - Aerodynamic Loading on Bearing Assembly

Comparing the results obtained at the different stages of simulation, in Figure 10 the electric motor torque (3rd trace) comprises a blue line obtained by Modelica with a superimposed red line from **MotionSolve**. Differences seen between the red and blue traces are due to the flexing of the antenna. In the motor speed error curve (2nd trace), the short-duration fluctuations are associated with a null point in motor torque and attributed to backlash in the gears.

Both these findings illustrate the importance of a multi-physics, integrated simulation approach to see factors that would be missed using the simpler, chaining solution.

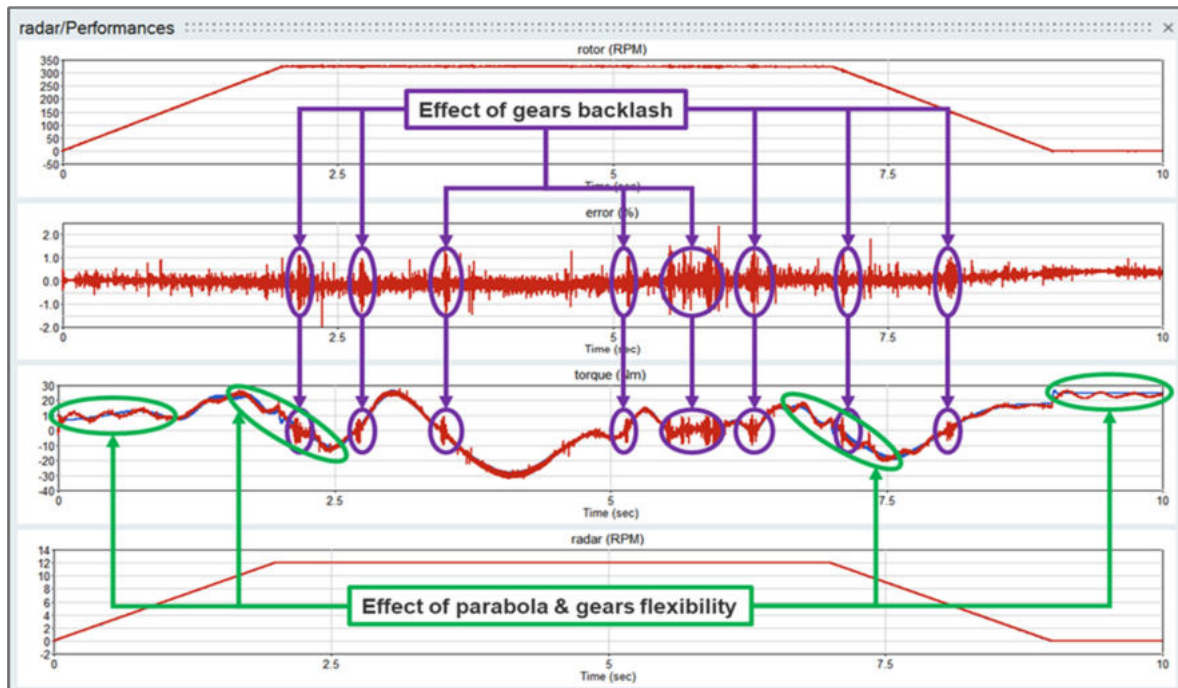


Figure 10: Radar Dynamics - Comparison between Results obtained by Modelica and MotionSolve®

Considering / Evaluating Global Thermal Loss (from Electrical and Mechanical Sources)

At the first level, Modelica library functions are used to calculate conduction, radiation and convection between component electro-mechanical parts (winding, stator, frame, rotor, magnets) and air-cooling effects. The overall aim is to predict the magnet temperature profiles which affect the electric motor performance. These results can then be integrated into **Flux** or **AcuSolve** to provide a more precise thermal simulation of the motor.

Predicting Antenna Electromagnetic Performance

The overall goal of the multi-physics simulation design approach is to predict in a reliable, robust manner the EM performance of the radar. This is simulated using Altair's high-frequency electromagnetics and antenna design software **Altair Feko™**. From the combined multi-physics models, the deformation of the antenna is now known for each position during 360° rotation caused by the combined contributions of the torque arising from components in the drive-chain, along with the aerodynamic loading from high wind speed.

The radar performance - EM mapping of field of view, side lobes, gain, overlapping of lobes, along with signal quality, can now be predicted throughout the rotation of the antenna; as illustrated in Figure 11.



Figure 11: Radar Performance - EM Mapping

Optimization and Robustness

Robustness analysis

Altair **HyperStudy**™ for Multi-Disciplinary Design Exploration and Optimization, can be applied to improve the robustness of the radar design. Figure 12 summarizes the individual solutions and their applications available under Altair's **HyperWorks** suite. Of these, **Feko** determines the EM performance whilst **OptiStruct** is applied for fatigue of the antenna assembly (structure, gears, bearings, attachment points).

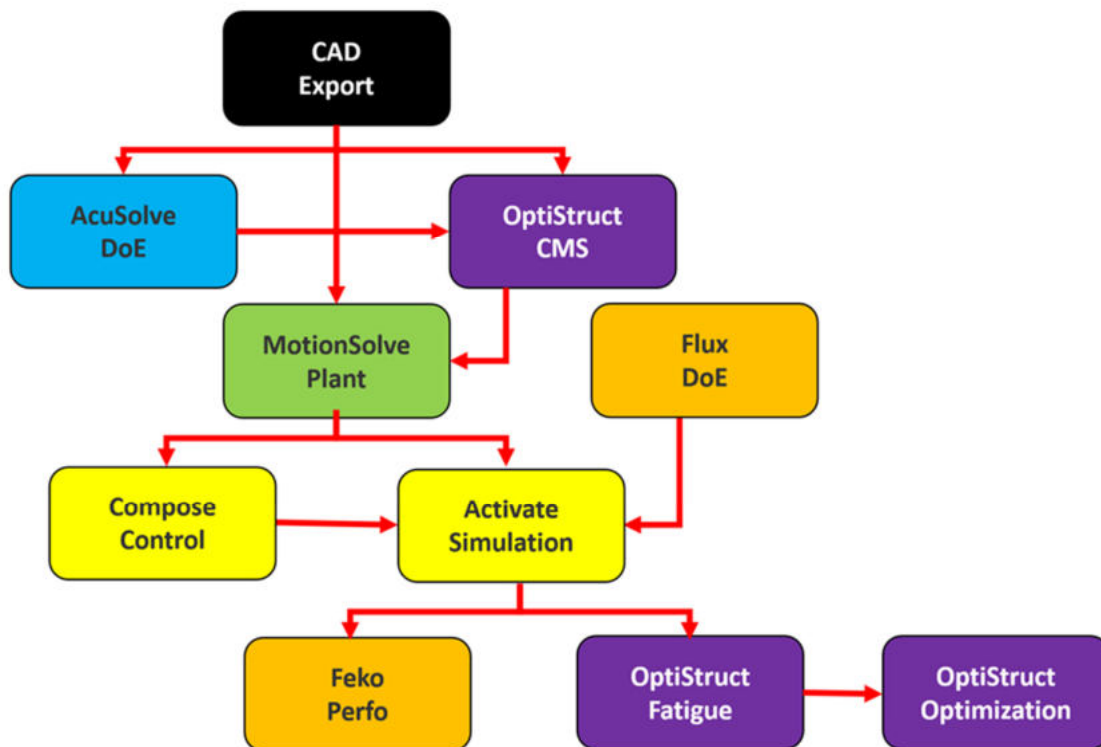


Figure 12: Altair HyperWorks Simulation Solutions for Robustness and Optimization

Optimizing the Global Design

To achieve an optimized design solution, certain design parameters can be systematically reassessed, including:

- **Activate**, e.g. rotor speed control, PID gains, see Figure 13.
- **MotionSolve** mechanism, e.g. friction effects in roller bearings, gears stiffness; see Figure 14.
- **OptiStruct** antenna construction, e.g. shell thickness; see Figure 15
- **Flux** electric actuation, e.g. slot shape, magnet temperature.

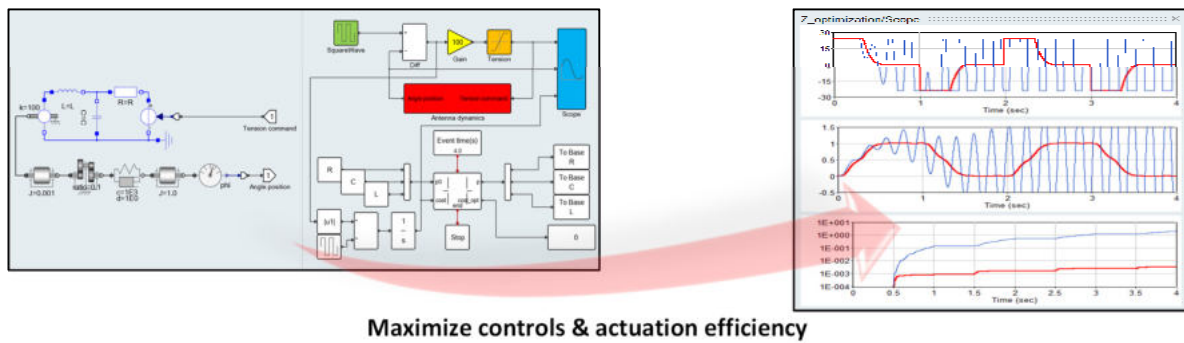


Figure 13: Activate - System Optimization, e.g. Rotor speed control, PID gains

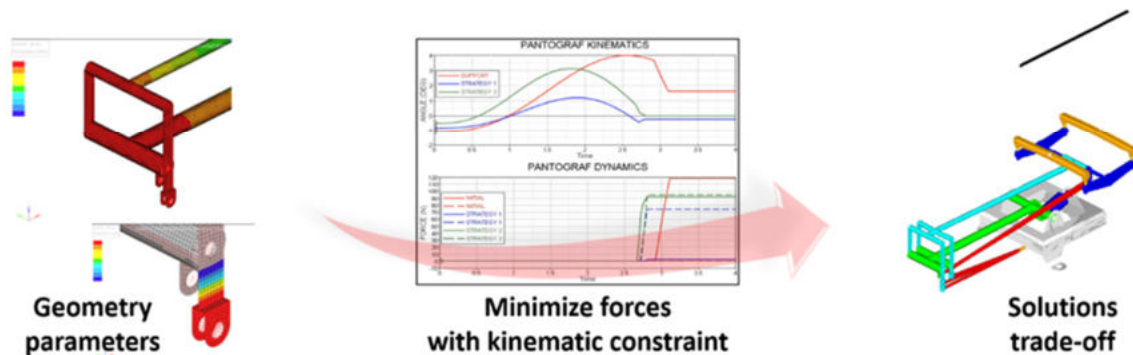


Figure 14: MotionSolve - Mechanisms Optimization, e.g. Friction Effects in Roller Bearings, Gear Stiffness

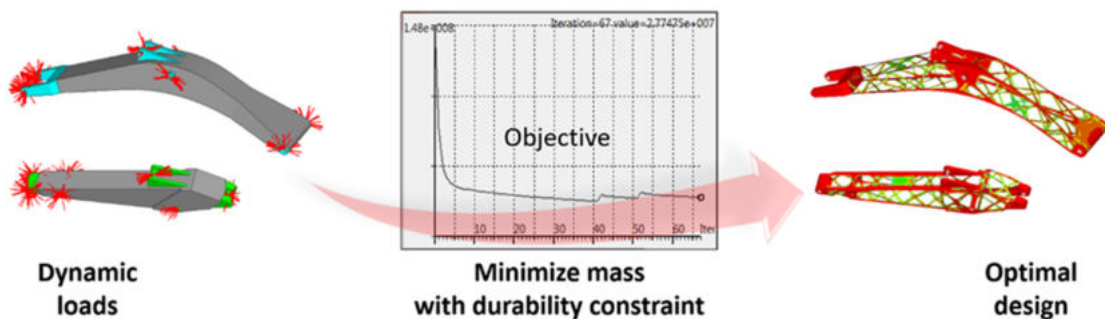


Figure 15: OptiStruct - Component, Structural Optimization, e.g. Antenna Construction, Shell Thickness

Conclusions

Under Altair's patented [HyperWorks](#) licensing model, multi-disciplinary tools are available to enable organizations to pool and centralize their global software investment to maximize utilization and accessibility throughout the entire company, therefore delivering far greater value than traditional licensing programs.

Such solutions, running multiple applications concurrently, along with the ease of access to a multitude of solvers are accessible for small to medium-sized companies and helps to foster multi-disciplinary team work.

An integrated multi-discipline design approach presented for a typical terrestrial radar configuration has demonstrated the value of applying Altair **HyperWorks** simulation software suite to address complex multi-physics problems; described as follows:

- Aerodynamic loads with [AcuSolve](#)
- Flexible bodies vibrations with [OptiStruct](#)
- Planetary gears and roller bearings with [MotionSolve](#)
- Electric actuation with [FluxMotor](#) or [Flux](#)
- Control design with [Altair Compose™](#) - Matrix-based Environment for Math Operations
- Electromagnetic radiation with [Feko](#)

The Model Based Development approach with [Altair Activate™](#) ensures the consistent progressive deployment of the many multi-physic simulation models throughout the system design V-cycle.

The process capture encapsulation with [HyperStudy](#) enables parametric sensitivity, multi-domain optimizations and robustness analysis, to efficiently achieve the best design first time.

Reference

This white paper is based on the presentation by Thierry Bernard, Senior Technical Specialist, Altair HyperWorks Support, given at [Simulation-Driven Innovation™ – Hannover Messe](#) – 23 to 27 April 2018