Thermal simulation in aircraft development - a global approach, innovation into perspective

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Abstract
The aircraft thermal simulation techniques have evolved toward a global approach at the beginning of the decade. The current global aircraft models are developed under Finite Element technology, and include a physical modelling of major aircraft structures, fluids, equipment and system in order to predict temperatures and heat loads all along a typical flight mission.

This paper provides an overview of the state of the art in term of global aircraft thermal modelling, its known benefits and current limitations. It discusses the perspectives of evolution of such approaches in the aircraft industry, and the compromise between accuracy, representativeness, the cost and the complexity of global model developments.

1. Background and Introduction

The knowledge and determination of aircraft temperatures are part of the design process, as an essential enabler. Temperatures have many impacts on aircraft engineering : materials qualification temperature range (thus manufacturing processes and costs), thermal-stresses and deformations induced by temperature variation along the flight, temperature knockdown factor on materials, thermal ageing of hot structures, impact on engine, system and equipment performances and qualification, overheat protection devices, hot spot insulation and design precautions for hot system installation, cooling system design and sizing, assessment of temperature-driven reliability of equipment, etc.

Aircraft temperature prediction have started in the seventies by the use of analytical methods and lumped mass models. Thermal Finite elements/volumes techniques then emerged in the nineties, and allowed the temperature prediction up to the scale of an aircraft section (center fuselage, nose fuselage). The predicted temperature field was then mapped on load and stress models to accommodate from thermal effects into the structural sizing process, mainly due to the high Coefficient of Thermal Expansion [CTE] of aluminum structures. During the last decade, thermal aircraft thermal simulation techniques have evolved toward a global approach, with the ability to predict the temperature fields for a full aircraft [1]. The models are still developed under Finite Volumes/Elements technology, and include a physical modelling of major aircraft structures, fluids, equipment and system in order to predict temperatures and heat loads, for the whole aircraft. This approach was deployed on the A350XWB, with a delivered AirCraft Thermal Model [ACTM].

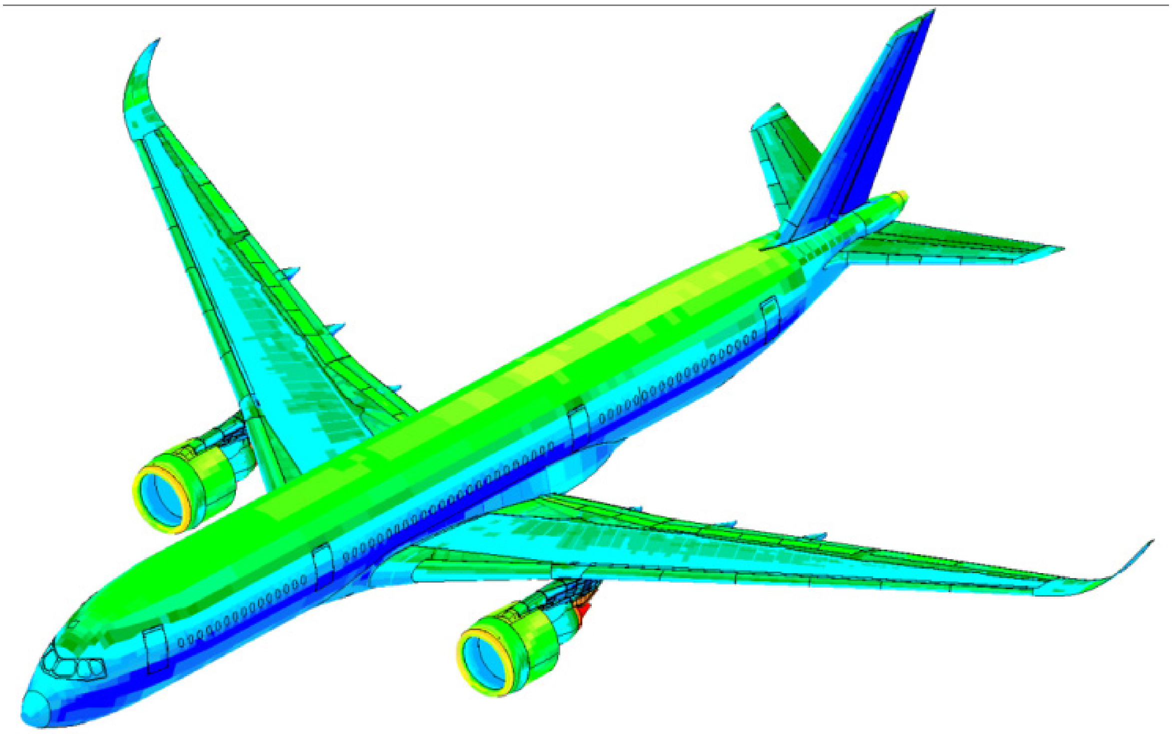

Figure 1: Aircraft global thermal model – A350XWB - ACTM

The development of such global techniques has been pushed forward by the variety of new thermal concerns raised by the innovative design of modern aircraft.

For a structural viewpoint, the introduction of Glare and composite structures requires in-depth thermal investigation: the global hybrid concept of the new aircraft structures challenges the fine assessment of thermo-mechanical effects for both static and fatigue stress-sizing. The global hybridization of new structural concepts create global thermal loads due to the differences of CTE between metallic and composite structures, and local thermal stresses at hybrid junctions (or in case of local thermal gradients). The temperature distribution within structures has also been deeply modified by the introduction of composite materials, due to their low thermal conductivity properties (generally from 0.5 to 5 W/m/K) when compared to aluminum structures (around 120 W/m/K). Composite structures tend to confine the heat into the aircraft while the aluminum structures are evacuating the heat toward the external environment. Composite structures might be subjected to the decrease of mechanical properties in case of local overheat, for a given load case (buckling, compression) leading to low structural reserve factors. Optimization of the curing cycle and the manufacturing processes might also affect the performances of the composite materials to stand elevated temperatures when combined to loads. Due to this, special care is paid to the verification of temperature effect onto structures. This relies on a complex process, from the materials performances characterization versus the temperature, to the prediction of temperature fields in the structures and the assessment of knock down factors induced by the temperature, ending up by structural tests with temperature loadings in some cases, and aircraft climatic hot and cold tests.

Equipment technology is also changing. Electrical architectural concepts are emerging, where hydraulic and pneumatic technologies have been used on legacy aircraft. Combined to the performances development of electronic packages, these new concepts promote the increase of power electrical budgets, and thus the cooling demands for the electronic packages themselves. Power electronics equipment are not anymore installed in electrical bays only, but disseminated wherever it is optimum for their performance and installation. The installation of such packages out of thermally controlled bays raises several concerns. The thermal impact of system installation onto their performance and reliability encourages the competition (and benchmark) between the qualification constraints and the installation principles or the system cooling requirements. Thermal simulation is a recent tool enabling this kind of trade-off; by predicting the temperature distributions in the whole aircraft, it is possible to work at the construction of an optimized configuration, balancing the effects of hypothetical scenarios of equipment location, cooling system architecture and customized qualification constrains.

The cooling performance of an aircraft is also a key driver for its performance. Part of cooling requirements address the ground phases, in hot airports operations. As a result, active cooling systems are installed into the aircraft in order to evacuate the heat released by the hot equipment, which affects the weight of the designed aircraft and their complexity, and limits the growth potential for equipment to increase their heat dissipation and performances in some rare constraining hot cases. Of course, special care must be paid to redundancies of cooling equipment, in such a way that their eventual failure does not endanger the safety of ground/flight operations and the reliability of the aircraft. In-flight cooling requirements lead to consume external air through dedicated cooling inlets, which affects the aerodynamic performances of the aircraft by increasing the drag. Actuated air inlet/outlets are also used in order to improve the aerodynamic performance, at the price of added weight and complexity.

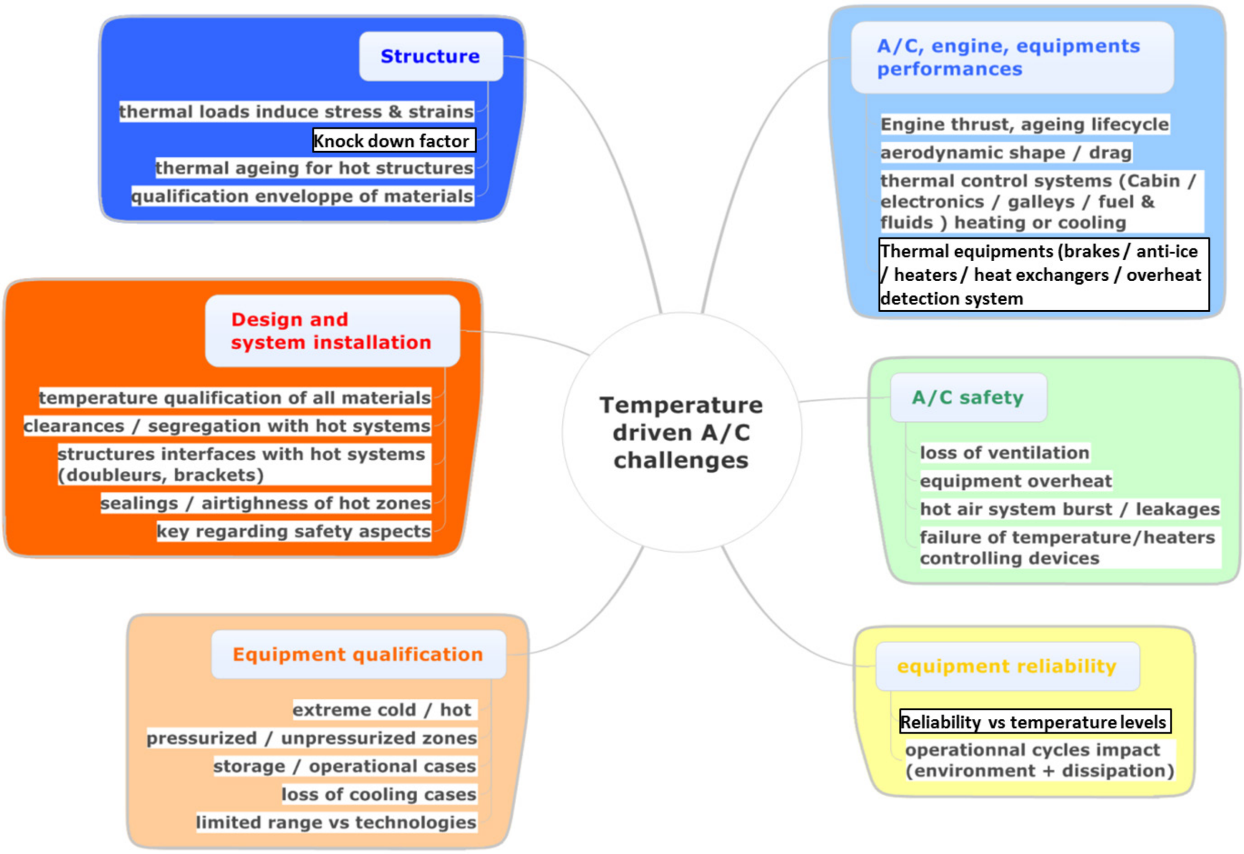

Figure 2: thermal challenges

The first part of this article deals with the state of the art of global thermal modelling techniques at Airbus. The second one demonstrates the benefits achieved today with such modelling techniques. The third one discusses the challenges and limitations met. The last part provides the perspective for future innovation, in the scope of the simulation methods, tools and processes and for the aircraft design itself.

2. State of the art

2.1 A fit–on-purpose model

As described in [1], the typical global aircraft thermal model relies on the assembly of several types of sub-models into a single one :

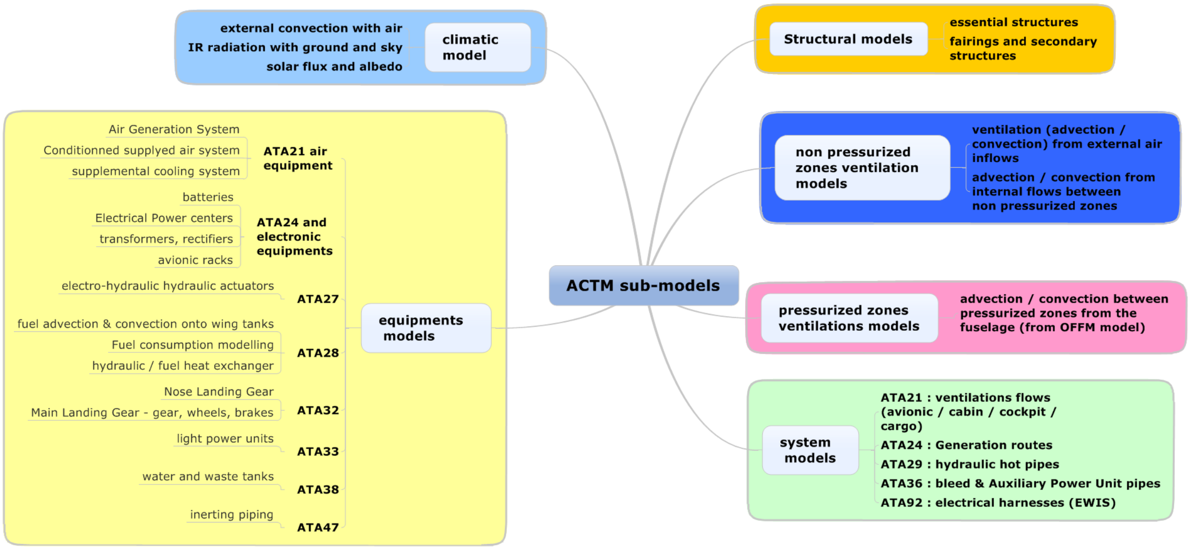

Figure 3: ACTM, a fit on purpose model

Thermal model of the aircraft provides a comprehensive and refined overview of the aircraft design. While the scope of stress models is limited to the essential structures, the scope of thermal model includes the fairings and internal minor structures, in a simplified way. This is required in order to model the closed compartments and bays and compartment properly, taking into account the external radiation and the interface between essential structures and fairings (example: the belly fairing shadows a large part of the fuselage skins). On the other way round, not all the essential structures are included in the model : fuselage and wing stringers thermal models are simplified, by representing physically only half or 30% of the stiffeners. The modelling of mechanical junctions (splices, fittings, and brackets) is also quite simple in the thermal model when compared to stress models. There, the thermal model is designed in order to properly capture the conductive losses at the junctions, through an average thermal contact resistance, which is generally less constraining for the meshing rules versus the stress models ones. Thick composite or sandwich structures require thermal modelling precautions in order to capture the through-thickness gradient. For this reason, 3D or special 2D (multilayered shell) elements are massively used.

On the system/equipment modelling side, the aim of the thermal model is not to predict the performance of the system, but to reproduce its thermal effect onto the aircraft cell, or vise-versa, to assess the effect of the structure, cooling or adjacent equipment onto its temperature. Global thermal models of equipment and system need to be geometry based, in order to include convective, radiative, conductive heat transfer. In complement, these submodels are feed by performance data (boundary conditions) defining the thermal inertia, the electrical currents or heat dissipation, fluidic massflows and temperatures when relevant. The state of the art relies on a compilation of system and equipment that either dissipate a significant amount of heat into the A/C, or are critical (vulnerable / sensible) to the temperature, or to sink the heat (strong thermal inertia for instance), in the area they are installed.

The cabin and cockpit zones are modelled as a large compartment which temperature is set at the desired setting by the cabin crew (around 24°C, depending on the zone of the cabin). In order to keep a reasonable size of the model, the cabin layout and furnishing (galleys, oven, etc) have been de-scoped from the full aircraft thermal model. Airbus relies on a thermodynamic model of the cabin and pressurized fuselage zones ventilation named OFFM (Overall Fuselage Flow Model), which predicts the flow/humidity/temperature distribution in the cabin. Refer to [2], for the model description of the OFFM. This model includes the fine thermal control of these zones through the mixer unit and recirculation fans and the air Generation System. It also includes the heat dissipation generated by the passengers and the crew, as well as the cabin system (IFE, galleys, etc). Intermediate results from the OFFM are implemented into the global thermal aircraft model. The main objective of this model loose coupling is restricted to predict properly the crown, triangle and bilge ambient temperatures, that result from the heat balance between the cabin cooling system, the heat losses into the aircraft structures, the heat dissipation of the equipment installed in these compartments.

The external aerodynamic convective cooling is implemented into the model. The aim of the thermal model is not to predict the external heat transfer coefficients, as aerodynamic models are dedicated to, but to implement heat transfer and reference temperature mappings onto the external shell of the thermal model. The complexity of this model does not rely on the physical prediction of these coefficients but on the implementation of the full aircraft convective flux mappings, for a variety of mission points (ground, taxi, take-off, climb, cruise descent and landing) and thermal environments (ranging from extreme cold to extreme hot cases).

Unpressurized compartments of an aircraft (wings, landing gear bays, empennage, pylons) are generally not completely sealed, but are slightly ventilated by external air, entering and exhausting though small gaps, depending on the local pressure coefficients. Fluidic models are also used in order to predict the resulting flows, that are implemented into the aircraft thermal model.

As a summary, the aircraft thermal model is a fit-on-purpose model, which looks like an enriched structural model mesh, representing the whole structures of the aircraft, including fairings and secondary structures. Most of the significant equipment and system are included, should their heat dissipation or thermal inertia interact with the thermal behavior of the structure. Several of the equipment are modelled in order to capture their own temperature, in addition to the surrounding ambient air temperature, due to critical impact on their qualification or reliability.

The aircraft thermal model is at the cross-road of several performance models (fuel, hydraulic, electrical, ventilation systems), physical models (stress, aerodynamic), environmental climatic model. The model integrates many boundary conditions from these various engineering skills domains, which drives its complexity due to the high number and variety of boundary conditions to be gathered and implemented, and drives the robustness requirement of the thermal solver (ability and performance to solve conduction, convection, radiation for a large transient model).

2.2 Model fidelity

The definition of the model fidelity is dealing with

- The proper representation of all the aircraft components and pieces (exhaustive representation) : for practical reasons, it is not possible to model all the pieces. A number of simplification is implemented and some parts are neglected, reducing the fidelity of the model versus the design.
- The right temperature assessment of each component represented by the model. Depending on the component, phase of flight and climatic case, the real distribution of temperature per component can be more or less heterogeneous. The finite elements(/volumes) technique subdivides the part into isothermal nodes (/cells), for which temperatures are predicted.

How to set the right fidelity target ? The model fidelity requirement is driven by two main questions:

- What is to be included in order to predict correct ambient air temperatures and correct spatial-average temperatures ? How accurately shall be predicted the hot and cold spots ?
- What is the scope and degree of refinement of the stress models on which the resulting temperature fields are to be mapped ?

Increasing the fidelity of the model leads to increase the number of structures and equipment represented, and to reduce the characteristic size of elements. As a numerical effect, this leads to increase the total number of elements and the number of boundary conditions managed by the model. Not only the pre-processing tasks suffer from such an increase (meshing, BC management, checking), but also the CPU time to obtain a solution, and the post-processing tasks (bigger files management). The usual trap is to focus energy and time on very local mesh areas, which temperatures have finally low impact on the stress models or equipment, but have large impact on the industrial process, cost and lead time to solution.

In addition to the mesh refinement simplification, boundary conditions are also simplified in comparison to the real physical phenomena. It has been explained that the model integrates a large number of data coming from several physical models (climatic, aerodynamic, etc). The current state of the art relies on a compromise that has been achieved by successive iterations, departing from a voluntary simple model, and refining areas of high temperature-impacts for the stress and design processes, keeping a reasonable performance to cope with industrial constrains, while modelling (or not) the relevant component, mastering the mesh size, and the physical phenomena that are modelled.

In order to provide an idea of the current fidelity of the model, typical size of finite elements mesh of the ACTM is ranging from 0.05 to 1 m. the total element number is around 200 000 elements, for modelling approximately 10 000 components (structures, equipment).

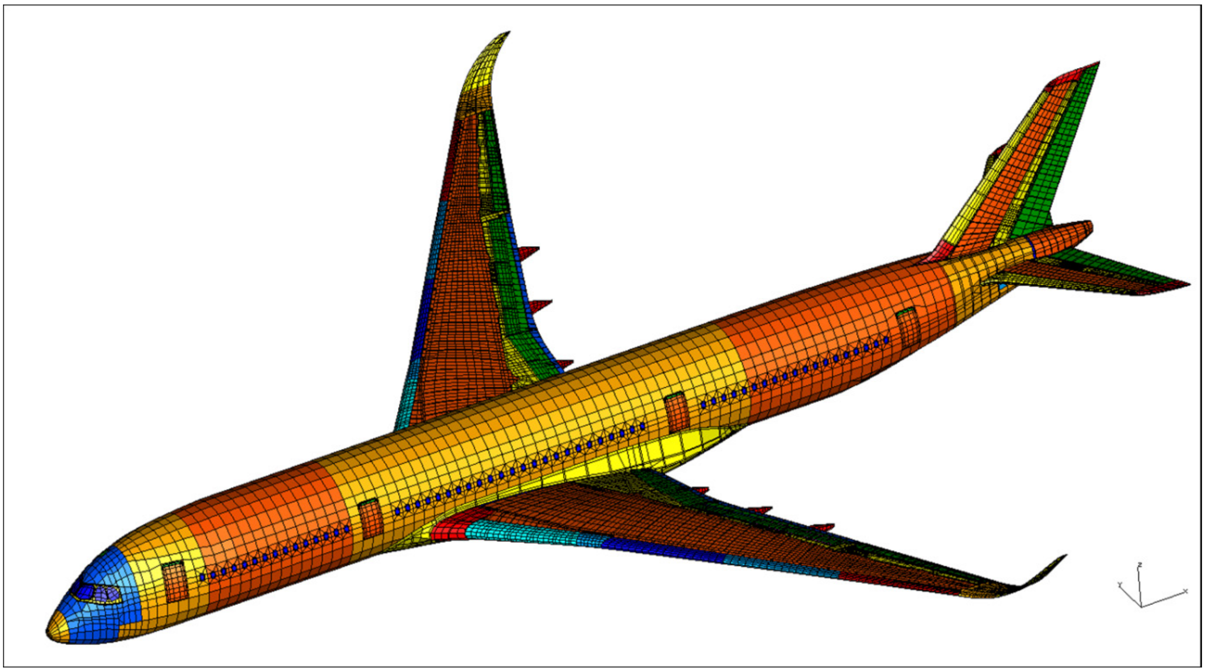

Figure 4 : ACTM model external shell mesh (without nacelle & pylon)

The direct assessment of the model fidelity (right first time) is part of improvement fields that are discussed further in this article.

2.3 Validation on flight tests

During the aircraft development, prototype test aircraft are produced, equipped with sensors and operated in order to assess the aircraft performances and to achieve the certification tests.

Figure 5 : A350XWB- flight tests (cold and hot)

During the test campaign, the test aircrafts are confronted to a variety of test scenarios that lead to characteristic temperature behavior of the aircraft structure and equipment (extreme hot cases, extreme cold cases, standard fatigue flights). One of the test aircraft has been massively equipped with flight test instrumentation that include temperature sensors (thermocouples, PT100), and temperatures were recorded for a large number of flight tests.

Thus the aircraft thermal model has been validated versus the flight test measurement, for a large envelope of real operating condition.

In details, the validation process of the aircraft thermal model is quite complex. Simulations rely on many settings that are based on theoretical specification and sizing case assumptions that are far from the real aircraft test data. The prototype test aircraft is not identical to the production aircraft design. Some components and equipment are also prototypes. Some test aircraft have no cabin layout, but a high number of flight test benches installed in the cabin floor. The paint livery of test aircraft differs from the ones that are used in the sizing processes. The thermal model validation process has thus started by adjusting the reference model to match with the test aircraft configuration, with a correct fidelity.

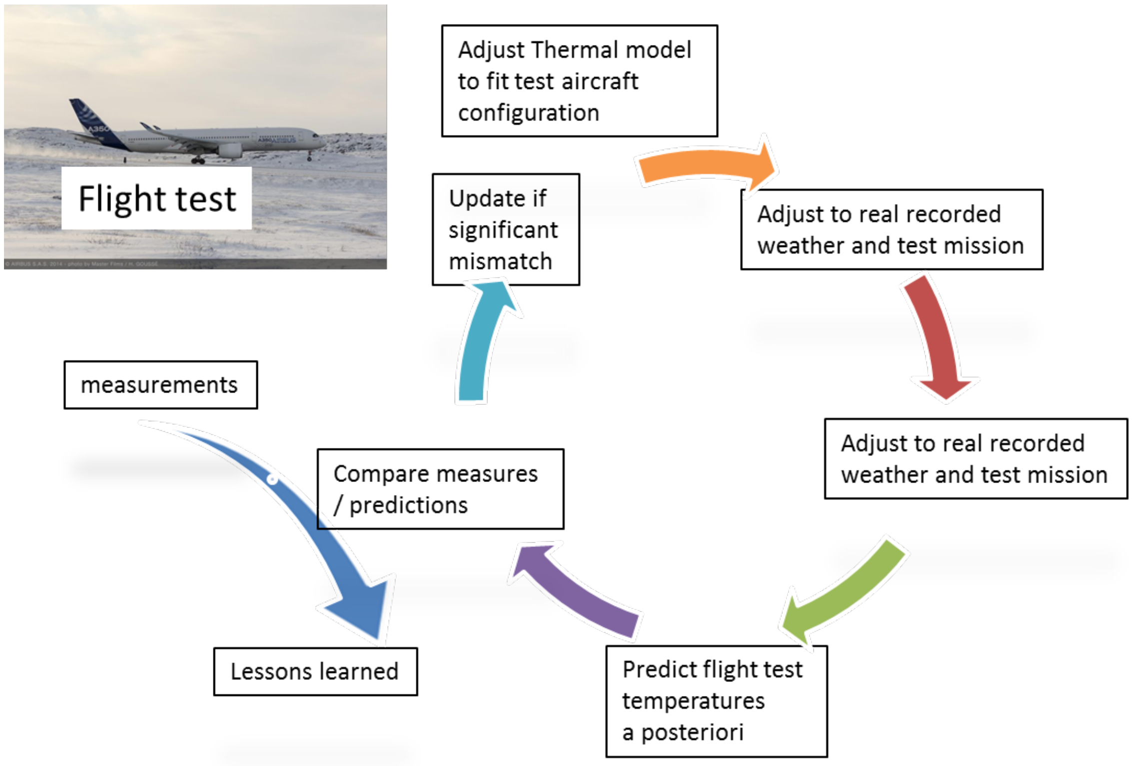

Figure 5 : Validation process overview

Flight test validation process applied to A350XWB has shown no major mismatch between measures and predictions, mainly due to the application of lessons learned from past Programs (A380, A400M). The most difficult comparison deals with the ambient air temperature. Where sensors provide a local measure of the air temperature in the compartments, the finite element model provides generally an average temperature of the air volume in this compartment. The same kind of difficulty might occur when sensors are located on structures where local thermal gradient are significant. Installation rules of the sensors are managed as such that no sensors are installed were gradients are expected by the model.

3. Benefits

The global aircraft thermal model offers benefits at several levels.

One of the obvious advantages is that this model feeds a large database of results, for many sizing cases covering the full scope of operations and climatic environment. Not only these results are issued from validated model by comparison to flight tests, but they are immediately available for the complete aircraft, at least with a minimum degree of fidelity.

For an aircraft development point of view, these model and results databases are probably the better answer to versatile demands of the engineering community, in order to solve and avoid thermal issues, may this be installation, structure, or equipment development concern. By covering the full aircraft zones, most of equipment and all the essential structures, this model allows a comprehensive answer to a variety of questions. For example, thanks to the capability development to map the computed temperatures on stress models, it is possible, at a late stage of development to focus on any structural area, where structural concern or local optimization could be assessed, and to provide thermal mappings quite rapidly. The availability of the results for a full database is a key benefit achieved by such a model development. It also allows reviewing rapidly, challenging and assessing the equipment and ambient temperature profiles, or temperature range when dealing with specific operations.

All along the aircraft development process, this model allows to investigate in a reasonable time-frame any question of change impact in the design, when this could affect its thermal behavior. It is an essential back-bone offering many trade-off possibilities, and up to final checks, requirement revisions and late challenges.

Another key benefit is dealing with the work and task-flow organization. Being global by essence, this model federates energies and synergies between engineering disciplines, because it centralizes a common delivery to the aircraft development teams, similarly to the digital mock-up. By giving a consistent overview of temperature fields on key components, addressing a large community of customer, it induces the convergence of efforts toward a common, concrete, and useful objective. It encourages the key contributors to broaden their investigation beyond their own activity, fostering innovative proposals. It also improves the communication between engineering disciplines simulation, by creating an essential cornerstone in the network of simulation models.

Thus it emulates the thermal development team and improves the network of contributions around such a model. Method and tools development projects have emerged in the recent years [3], in order to deliver more efficient tools facilitating the development and deployment of such a global approach, aiming at introducing earlier in the architecture trade-offs, the assessment of temperature effects onto the performance, equipment and structural design. Finally, this model improves the visibility of the thermal engineering team not only at Program level, but in the research and technology fields of investigations, as well as in tool development community.

4. Limitations & challenges

4.1 Physical interactions

Beyond the numerical challenge of gathering the massive number of required input data, to develop and run the model itself, and to synchronize its configuration to the aircraft configuration along the design cycle, the difficulty when applying this global methodology to a brand new Program development, is to guaranty that the model would stay predictive; in other words that the model would not significantly overestimate or underestimate the temperature, before any correction could be made from flight test learnings.

Many thermal consequences of physical interactions are difficult to predict. For example, the fuel loading and weight into the wing, balances with the aerodynamic pressures and structure flexibility, and has an effect on the global shape of the wing depending on the flight phase. The shape of the wing interacts with the fuel repartition into the wing, and the fuel free surface is pretty difficult to predict for all the flight operations that are thermally simulated. The position of the fuel free surface has a strong effect on the local temperature distribution of the wing internal structures, thus interacting with its flexibility (bathed structures are generally well hotter than the structures positioned above the fuel free surface, in flight). The described interaction is quite difficult to predict, cannot be managed today by a single numerical model but a network of models exchanging data and results between them. The robustness of such prediction would be difficult to guaranty because relying on several domain of expertise (aerodynamic, structure, fuel models) that include their own margins and propagate into the whole simulation network.

Other similar physical interactions are adding complexity in the simulation or could limit the ability of models to predict properly the temperature for some components:

- Structure deformations and local aerodynamic pressures have an effect on the local gaps and openings (holes, sealings, interfaces between movable structures, etc) into the external shell of the aircraft that influence the cooling ventilation flows in the non-pressurized areas.
- The strong electrical-thermal coupling is also difficult to predict accurately. The electrical system is a quite complex system to simulate, for a performance point of view, from the electrical generation, the distribution to consumers and the electrical structural network. The prediction of electrical load factor and the distribution of electrical currents into the complex electrical harnesses architecture are key to success (Electrical Wiring Interconnection System-EWIS). Once the electrical performance of the network is predicted, its interaction with the thermal model can be handled smoothly, but the complexity of this whole system exceed the capabilities of the current tools, leading to simplification, and margins in the simulation management.

- The drainage system creates internal flows in between the non-pressurized compartments. Here again, there is an obvious coupling between small geometrical factors (gaps between assemblies, sealants), and the simulation of the global phenomena in large compartments. This system is also in constant interaction with the ventilation systems, and the porosity of the external shell. The maturity for simulating these flows and their interaction with the compartments heat fluxes is a key challenge of success.
- Hot air system exhausts (heat exchangers ram air exhaust, ventilation exhaust, anti-ice system exhaust, engine plume exhaust) might impinge the external skin of the aircraft, producing local hot spots. This thermal load is currently approximated in the global model. They are generally modelled for the worst case of occurrence that leads to local design verification, and are quite simply modelled into the global aircraft one. The reason for this simplification is the high CPU time of the simulation (generally CPU) that is not compatible with the transient simulation and the high number of calculation cases needed for the global model.

4.2 Fidelity

As explained in the paragraph 2.2, the fidelity of the global thermal model is a major challenge, especially for assessing the compromise between the required level of detail to be meshed and modelled, the simplification that could be afforded in term of boundary conditions, and the expected performance of the simulation (keeping CPU time low enough for an industrial use of the model).

The background of this challenge is the intended use of the results. For instance, computed temperature results could be mapped on several kinds of mechanical models. Load models (like Global Finite Element Model - GFEM, reference [4]) are meshed with relatively coarse elements. Structural details are not represented through geometry based elements but through elements which equivalent stiffness represents its load transfer behavior.

On the other way round, detailed stress models (linear / non-linear) are geometry based up to an ultimate point of detail, brackets, rivets, bolts, etc.
Both of the model types are mapped with the aircraft thermal model, which means that its fidelity has to be defined accordingly to the most demanding mechanical model. But this does not mean that structural details are essentially meshed into the thermal model. They are meshed only when the local thermal gradients expected in these critical areas could lead to significant impact into the DFEM or GFEM, for a thermal-stress point of view. This limitation is today encompassed by the thermal mapping tools that offer the flexibility to map temperatures from a thermal to mechanical model, even with a large difference of mesh topology.

Yet local thermal models have not been completely removed from the global thermal simulation scope. It unfortunately occurs that the mapping tools fail to produce reliable results when the mesh topology are too large or too many components are not meshed in an area of structural interest, or structural deformations are such that the thermal model geometry differs significantly. Also detailed CFD model results are sometimes needed to assess the structure temperature local fields, which is not compatible with the global approach. Here again, the global thermal model is a powerful tool for improving these local models : it allows to determine the critical case in a large database of results, and to define boundary conditions from the global scale to the local area of focus. Vice versa, the results of local models could be condensed into equivalent conductances and thermal couplings, refining thus the global thermal model in local hot/cold spots. This approach is still in development, the principles of model condensation being not matured yet.

4.3 Standardization of climatic environment modelling and operations

Global thermal models are required in order to represent the full scope of climatic environment, within the flight envelope that extends generally from -55°C to +55°C in term of air atmospheric temperature. Airbus created its own internal standards to describe the extreme hot and cold conditions for these worst cases. Simulations are also dealing with the delivery to stress specialist of frequent mission temperatures, for fatigue and damage tolerance assessment. These conditions are generally ranging from polar to tropical climatic conditions, and are also part of the internal airbus standards.

Contrary to some other vehicles (cars, helicopters), the aircraft operations (mission description) could be standardized, for the intended use of the airlines. The grand majority of operators perform the following sequence for each flight : Ground stay at airport gate, boarding PAX, taxi to runway, take Off, climb, cruise descent, landing, taxi to airport gate, PAX disembarking.

The description of each phase can then be also standardized, per aircraft type, with an average duration per phase, a typical flight cruising altitude and Mach number, etc.

The use of a standard definition of an aircraft mission is an essential input data for the thermal analysis of the global aircraft and has a number of impacts. Difficulties arise when the climatic environmental conditions impact these standard operations. Due to high or low temperature operations, the performance of the engines and system might differ from the standard ones, leading to impact the standard mission description (altitude / mach / time mission profiles). Extreme climatic operations could also impact the preparation of the aircraft before boarding the PAX : cockpit and cabin pull-down(/-up) for extreme hot (/cold) operations, engine preparation, hot fuelling, de-icing. Airlines practices when dealing with hot or cold aircraft preparation are not codified. The description of the standard practices cannot be accurate, when compared to the variety of possible configurations.

The state of the art of this standardization is thus a conservative description of these operations combined to the climatic cases. Conservative means that the temperatures would be under-estimated for cold flights, and over-estimated for hot cases. Mastering the temperature margins resulting from the application of this standard, versus the real operations of airlines, and the real climatic conditions met worldwide, is one of the most tremendous challenge in front of us.

5. Perspectives and conclusions

In order to complete the challenges described in the previous paragraph, a number of improvement areas are discussed hereafter.

The initial development cost of a global aircraft thermal model for a new aircraft development can generally be considered slightly lower than the addition of costs, for the thermal models that we would have developed addressing separately each A/C section. However, the configuration management of this large model, in order to reflect the frequent aircraft design changes and improvements is still quite costly. The design evolution is followed-up through a complex process embedded into the digital mock-up (DMU). The thermal model, similarly to the other engineering models interfaced with it (system and equipment performances, stress and load models, aerodynamic), has poor dynamic link with this DMU configuration management. Creating a dynamic link within the complete simulation network is a long term objective. At mid-term, accelerating the detection of design changes, un-consistencies, the process of deciding for thermal model updates or not, will probably offer more flexibility and potential than an utopic automatic update.

The current architecture of the global thermal model rely on a centralized organization. A single team is responsible for its development, from the integration of all base-bricks (structural models, equipment models, OFFM, system models) into a single model, and addressing the whole interfaces with the relevant specialists for each brick. Thus base brick thermal models are fit on purpose for this integration. In parallel some equipment thermal models are developed outside this workflow, in order to assess in details the performance of the equipment itself and sometime including thermal data. Some saving could be obtained by a sharing of the models, in order that the performance models could be integrated (or co-simulated) with the global aircraft thermal model, in a decentralized approach. This area of improvement is key considering the knowledge management and the high skills that are mandatory today for running such an approach, and could then spread into the engineering domains the model is interconnected with. This is a long term perspective, which developments have started a few years ago in the frame of FP7 Crescendo and TOICA Projects [3].

At a last stage, the validation by test means for such a model, in parallel to the validation of the aircraft performances, is an essential milestone of any new aircraft development, relying on new technologies. Accelerating the verification process by the use of tests, and decreasing its cost, is also in the improvement roadmap for a near future.

For all of these topics, it can be concluded that the global thermal models approach will pull the innovation in the field of engineering simulation, for the coming years, not only on the aircraft development itself, but also on a tools perspective

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