

AVT-297 Development of a Framework for Validation of Computational Tools

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Design of aerospace vehicles relies on system models. These models rely on validation data to ensure accurate representation of the system. This paper provides an introduction to the problem and an overview of a NATO STO Activity, AVT-297, which developed a framework to determine validation experiments required to support system level models. The goals of the research group were to develop a process to identify a validation database for intended uses of a vehicle system, demonstrate the process on vehicles and document the process. Applying this process to multiple intended uses and collecting this set of validation databases identifies a set of validation experiments that could be applied to the design of multiple vehicles, further reducing the cost and time to develop air and naval vehicles. Four subgroup teams focused on different aspects of the validation database process: two focused on different aspects of a missile, and two focused on different aspects of a fixed-wing mobility transport class vehicle. This resulted in three different processes to decompose the multi-disciplinary problem to identify critical validation data. All four of the teams demonstrated their process on a sample problem demonstrating the benefit of the process.

I. Introduction

The situation for the warfighter – physical, operational, political, and even environmental – is continually changing and requires new support vehicles to meet the warfighter’s needs. The defence industrial complex requires the means to rapidly evolve systems to meet these needs so that new tools can be designed and delivered as conflicts evolve in real time. These demands are more difficult as they evolve in the context of the greater political climate. For example, political changes can add new constraints that defence systems are environmentally friendly, e.g., carbon neutral, or that the systems have limited capability such that they are defensive weapons and not perceived as an offensive threat. As the situation on the ground changes, it is more and more critical to field updated weapons systems in a timely fashion.

The development of aerospace vehicles has been characterized by complex, specialized platforms with long and costly development cycles. Future vehicle systems will require greater levels of modularity, adaptability and autonomy, must be resilient to new threats, have shorter development times, and be more affordable. Vehicle systems will require new technologies to meet new and evolving threats. Physics-based systems engineering has the potential to meet these needs reducing development time, evaluating new technologies, and facilitating risk analysis when simulations can be used to augment or replace some systems testing in the development process.

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One of the keys to enabling development of 21st century systems to meet new threats on shorter design cycles within affordable budgets is more reliance on physics-based simulation using evolving high performance computing systems. The time to test a new system can be a primary constraint to timely field new weapons systems. Two keys to meeting the time constraint are Digital Engineering and Certification/Qualification by Analysis. Digital Engineering can reduce the design/build time by more reliance on digital models. Certification/Qualification by Analysis can reduce testing time for system validation and acceptance.

However, accurate and reliable digital models are required to enable both Digital Engineering and Certification/Qualification by Analysis. While there are many existing models and system analysis tools for existing capabilities, new models and tools are required where new approaches are considered. These new models and tools require vetting – model verification and model validation. When multiple new technologies are considered, this model vetting can be both costly and require a large amount of time. The system designer must be able to identify a set of validation experiments to provide the model developers the confidence needed for model prediction.

Physics-based systems engineering facilitates risk analysis, analysis of alternatives, and integrated lifecycle engineering. High fidelity physics-based simulation has the potential to reduce cost and development time when simulations can be confidently used to augment or replace some systems testing (e.g., reduce flight testing) in the development process.

Models of physical processes require data for validation. Validation is the process of determining how well a model predicts a process, [Refs. 1-2] and requires data from the physical process to compare. From the beginning of modeling, the importance of physical data has been understood. NATO has had many activities focused on validation [Ref. 3]. Several of these activities created critical data for validation and collected existing data sets into compilations of data for use by modelers and code developers to validate their tools [Refs. 4-6]. Additionally, a large body of work has been developed on the process of validation [see, e.g., Refs. 1, 2, 7, 8].

However, none of these activities focused on a key question “how do we determine which validation experiments are needed for a given project?” AVT-297 brought together an international community to explore that question and propose processes to answer that question.

Designs for aerospace vehicles require validation data for each of the models used in the design, e.g., a system model would need validation data for flow physics, the structural response, the controls, etc. How do we decide between these needs? Fluids has validation data for a wide range of conditions, but not a lot of data for fluids coupled with flexible structures and even less coupled to control deflections. Validation data is typically focused on a single discipline, e.g. aerodynamics. Do we validate data for all conditions of a single discipline? And then all the disciplines coupled together? This would be a prohibitively expensive proposition. However, waiting until the system is complete and flight testing to verify system performance predictions can result in very expensive changes to the system and long schedule delays. Delays can be critical to the customer. How can we determine which validation data adds the most value to the prediction of the complete system response? Can we determine what validation data will be required early in the design process so that we can include the cost and schedule in planning to ensure we have the data when it is needed instead of delaying system development?

System simulations must be validated for the intended use to ensure the results of simulations will accurately model the system. For systems that are derivatives of legacy systems, it may be possible to validate simulations against the legacy systems or get additional experimental data for validation. However, for systems that are unique or involve new technologies not previously used on a legacy system, no legacy hardware exists for validation. Building a prototype system and testing it adds time and cost to the development cycle. A method is required to validate system simulations to mitigate the risk of making decisions based on simulations. This method will require a validation database that encompasses the physics applicable to the design requirements.

The goals of the work are to develop a process to identify a validation database for intended uses of a vehicle system, demonstrate the process on vehicles and document the process. Applying this process to multiple intended uses and collecting this set of validation databases can identify a set of validation experiments that could be applied to the design of multiple vehicles, further reducing the cost and time to develop air and naval vehicles.

II. Challenges

Consider a need to transport materiel to the warfighter. This could require a range of vehicles with large transport class of vehicles to move materiel from host countries to the conflict region and small to mid-size transport to move materiel from a safe location to the warfighter. The transport could be manned or unmanned and the field of conflict would define the best system architecture. Larger political forces can add additional constraints that the system is

environmentally friendly or has reduced capability to not be seen as an offensive threat. The scope of the conflict region could put limitations on power sources – a degraded infrastructure could limit access to electric power and/or aviation fuel requiring the designer to look for alternative fuel options.

As a further example, transports are required to move materiel – troops or weapons – around the world. This need requires a system of transports including long-range transports and shorter-range transports closer to the theatre of operations. The long-range transports need to consider alternate configurations and technologies to meet operational goals, e.g., fuel efficiency, range, payload, payload size. Figure 1 shows a blended wing body as a possible alternate technology to evaluate compared to existing tube-and-wing configurations that are in operation today. Similarly, short-range transports could include revolutionary distributed propulsion like the tilt-wing shown in Figure 2. Additionally, today's political climate could place requirements to use alternative fuels instead of aviation fuel. This could be a sustainable aviation fuel (SAF), hydrogen, or electric vehicles (battery electric, hybrid electric, or other options). The need for close support could drive the need for short take-off and landing (STOL) or vertical take-off and landing (VTOL). The designer must consider new technologies across the vehicle design to meet these different needs. Support for alternate fuels will impact system sizing, the lift system for short field length, material design of the system, and stability and control. The need for STOL or VTOL can drive the designer to look at radical high-lift systems and powered take-off/landing. The system designer requires accurate and vetted tools to make system trades in the design process including configuration effects and individual technologies that are proposed.



Fig. 1 Blended wing-body concept (NASA)

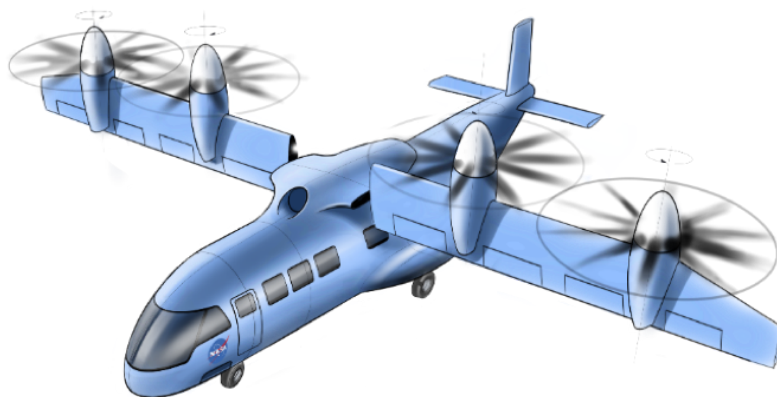


Fig. 2 Tilt-wing concept (NASA)

The system designer will break the problem down to identify these key issues in the design. For the subject transport, four of the key areas to study are: high-lift technology, vertical take-off/landing (VTOL) technology, alternate engine technology, and additive manufacturing technology. Each of these technologies will have modelling and validation challenges. The subject matter experts in each of these areas will identify those modelling and validation challenges and provide that to the designer.

The high-lift subject matter expert may identify various high-lift technologies to apply to the blended wing-body or other advanced configuration. They will identify various high-lift validation experiments and separation experiments that are important to the high-lift modelling and validation. Four of these recent validation experiments are shown in Fig. 3: the AIAA High-Lift Prediction Workshop, the High-Lift Common Research Model, the AIAA Drag Prediction Workshops, and the NASA Juncture Flow Experiment. Additional validation needs may be identified as the design matures to final design.

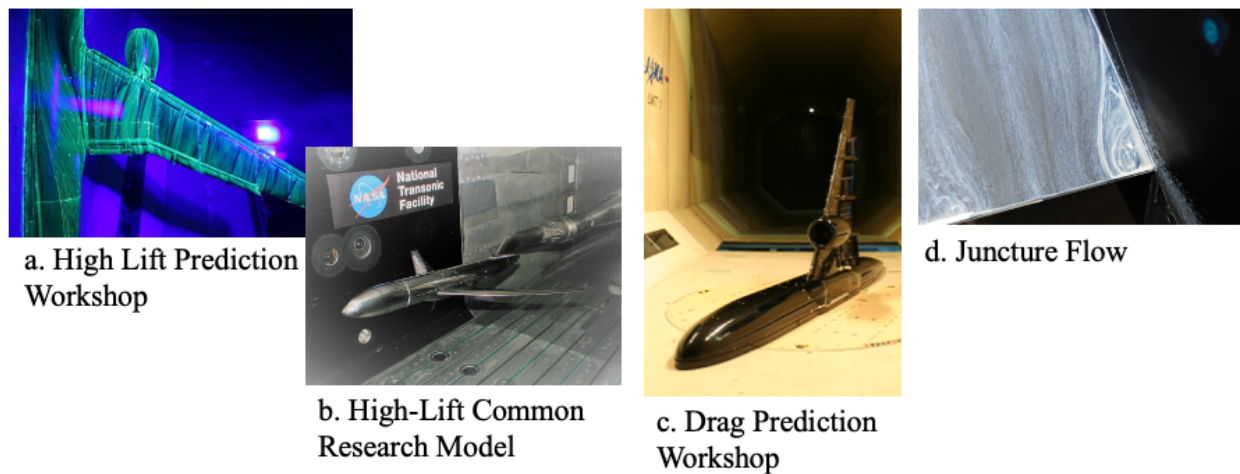


Fig. 3 High-Lift Technology Validation Experiments (photos courtesy NASA)

The VTOL subject expert may identify jet flows and cooling as key issues as shown in Fig. 4. The jet flow is broken down into components of free jet, wall jet, curvature flow, and stagnation each of which could require its own validation experiment. Similarly, the cooling challenge, Fig. 5, identifies ribs, pin fins, pressure side cutback film cooling, discrete hole film cooling, showerhead film cooling, and internal impingement and critical validation experiments.

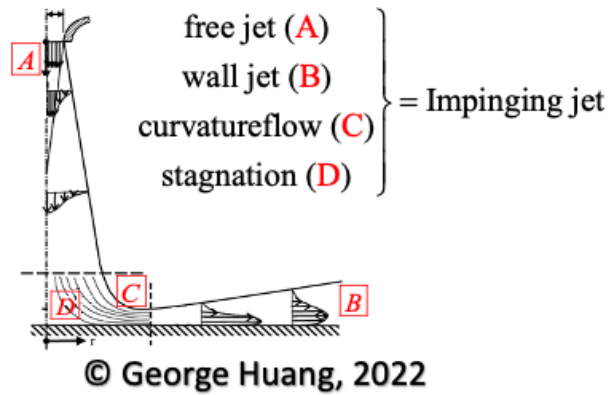


Fig. 4 VTOL Technology physic-based decomposition, [Ref. 9].

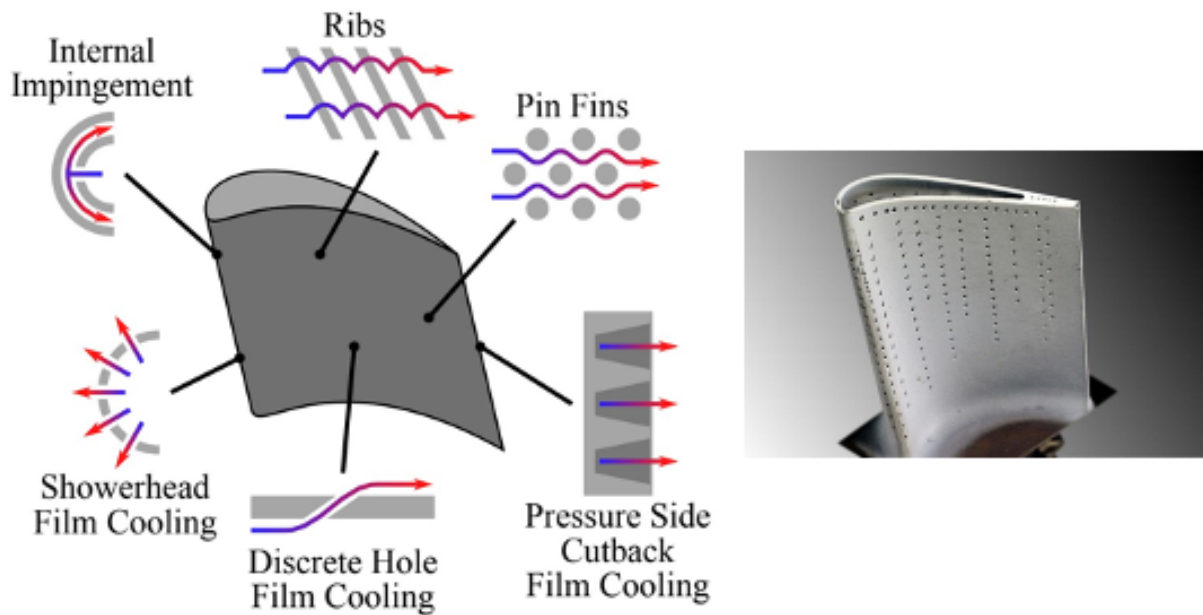


Fig. 5 Fin cooling physics-based decomposition [Ref. 10].

The additive manufacturing validation could be focused on processing and melt pool as shown in Fig. 6. Both processing and melt pool would require their separate validation studies designed to address each of the individual issues.

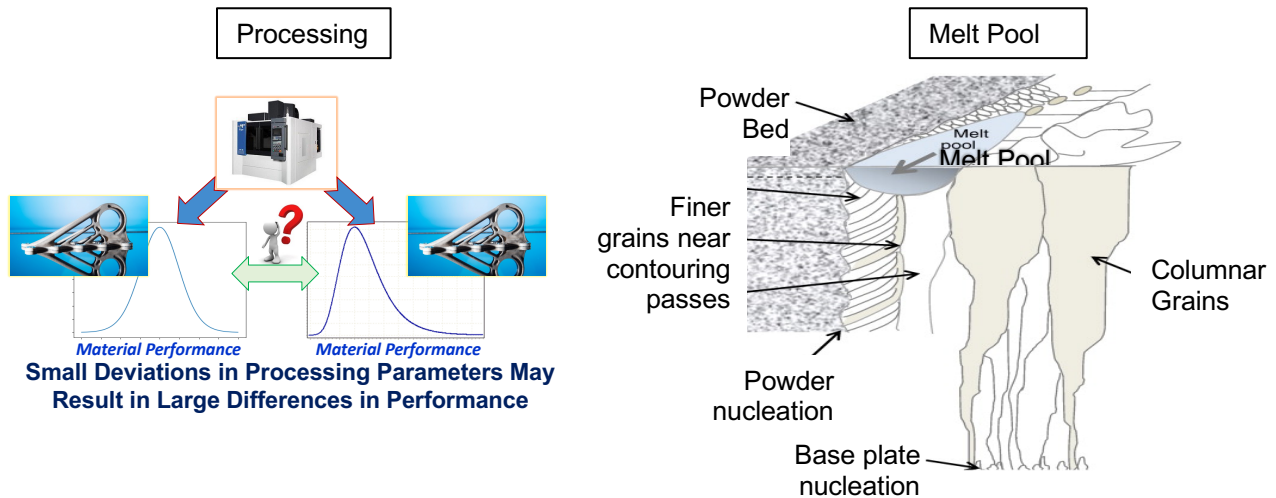


Fig. 6 Additive Manufacturing Technology – left Processing, [Ref. 11]; right Melt Pool, [Ref. 12].

The materials subject matter expert would propose the following hierarchy to validate new materials for use in this new application. There would have to be multiple development tests before the new material could be tested in structural elements and sub-components. The subject matter expert would probably recommend component level testing if this were a radically new material. All of these tests would require time and other resources.

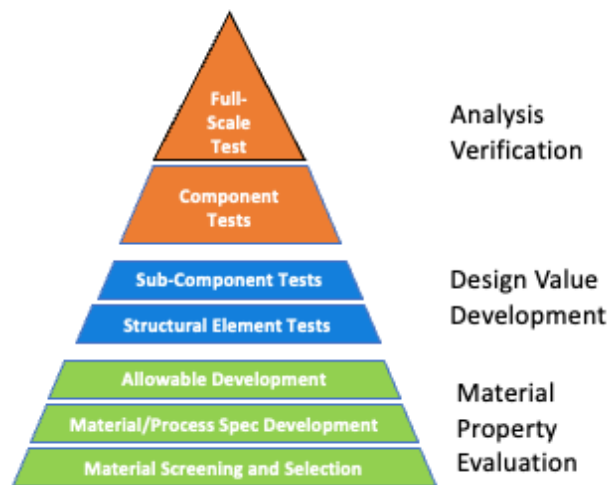


Fig. 7 Validation hierarchy for new material development (After [Ref. 13])

The designer then has to make decisions on which topics require what level of validation to do based on the resource constraints of the project. This process of identifying critical validation experiments and choosing which is the highest priority is the topic of AVT-297.

The designer is left with three key questions:

1. How do we demonstrate to Certification/Qualification authority that results of analyses are equivalent to a flight test?
2. How do we ensure that our analyses don't miss any key system behaviour and the actual system will respond like the simulation across the full operational envelope? i.e., the analyses accurately model any emergent behaviour from a complex system or complex physics
3. How do we choose to apply resource – time, human, funding – to key tests to meet Objectives 1 and 2 when the systems, sub-systems, and disciplines have competing requirements?

AVT-297 sub-teams were challenged to approach the key questions, find a way to analyze the problem in a multi-disciplinary environment, and propose a way to identify critical validation needs.

III. Approach

To enable timely and cost effective validation of system simulations, the AVT-297 activity developed processes to identify a validation database. AVT-297 formed four teams to explore different aspects of the validation database process. Teams started their approaches with the hierarchical validation structure documented in the AIAA Guide [Ref. 1]. The AIAA Guide's hierarchy, Fig. 8, consists of four tiers: system, sub-system, component, and unit problem. The approaches used qualification requirements at the system tier and identify lower tier tests that could be used to validate the simulation at the sub-system, benchmark, and unit problem tiers. The system could be decomposed using a physical decomposition (hardware), a functional decomposition, or a physics-based decomposition. Each of the teams investigated the various decompositions to identify the best approach to handle the multi-disciplinary challenge.

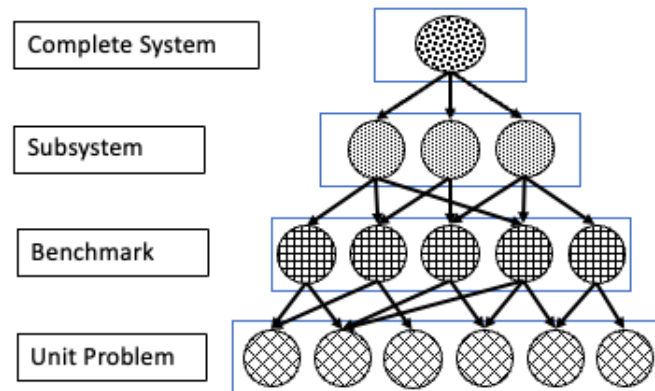


Fig. 8 Concept for Validation Hierarchy (After [Ref. 1])

For example, design of a mobility transport fixed wing aircraft could have a requirement for the stall speed. Stall speed is determined as the speed below which there is insufficient lift to maintain altitude. This is often caused by flow separation on the lifting surfaces. System level validation includes validation on similar or related vehicles at similar flow conditions. The system level tier would be decomposed to validation of separation prediction for the wing-body, separation initiated at the leading edge of the wing or high lift devices, separation initiated at the trailing edge of the wing or high lift devices, separation due to the speed brake, separation due to new technologies such as active flow control and deflection of the wing and high lift system in the presence of loads. Further, these sub-systems would be decomposed to component problems such as the wing-body juncture, wing alone, wing with high lift system, active flow control on wing alone with both rigid and deforming configurations. The component problems are further decomposed into boundary layer prediction on zero pressure gradient, boundary layer prediction in favourable or

adverse pressure gradients, smooth body separation in adverse pressure gradient, boundary layer transition and prediction of flow control devices. The build-up of validation from the unit problem through the sub-system increases confidence in the predictive capability of the physics-based simulations.

Some of the benefits could include:

- Reduced development risks through advances in validated high-fidelity physics-based simulations
- Reduced development costs through decreased reliance on full-scale testing
- Improved analysis of alternatives
- Designs with improved resilience to new threats.

IV. Results

The larger AVT-297 Team broke into four teams focused on different aspects of the validation database process: two focused on different aspects of a missile, and two focused on different aspects of a fixed-wing mobility transport class vehicle. Ref. [14] and [15] provide additional details of the model validation hierarchies and their application and Ref. [16] identifies requirements for physical referent data.

Missile Team 1 [Ref. 17] proposed a function-based system decomposition approach. In this approach, system-level requirements are decomposed down to unit test cases. They define four tiers of decomposition. In Tier 1, system level goals (i.e., mission goals) are defined. The system-level goals encompass the main system-level requirements clearly articulated. Tier 2 elaborates the system goal using mission requirements. A list of mission requirements necessary to accomplish the mission is developed in Tier 2. As the system goal is decomposed, the mission phases are explicitly defined. Tier 3 analyzes the mission requirements developed in Tier 2 and develops a list of functions which fulfill the mission requirements. Tier 4 decomposes the functions developed in Tier 3 down to well-defined physical phenomena. Tier 4 develops a list of physics to be modelled. Fig. 9 shows the sub-systems/components of an air-to-air missile derived in Tier 3 to guide the Tier 4 decomposition. A set of “performances” based on well-defined science branches, e.g., solid mechanics, such as structural performance, aerodynamic performance, thermal performance, etc. are used for this decomposition level. Tier 4 decomposes these performances down to unit problems where physics can be validated with simple and standardized tests. Each of these Tiers can have multiple layers in them.

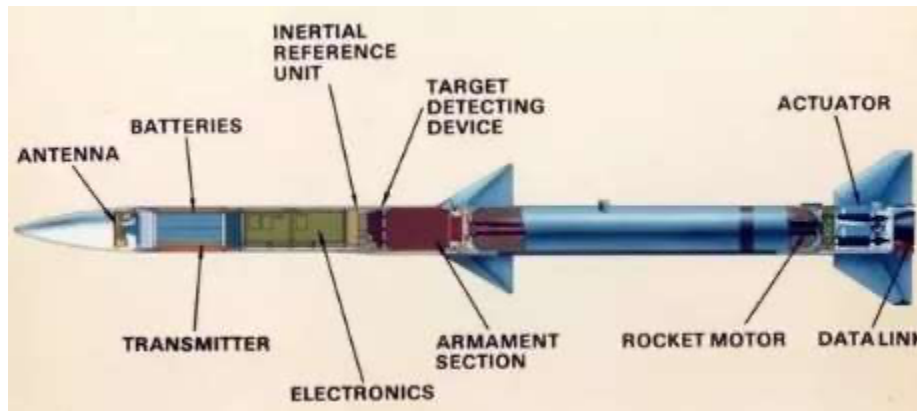


Fig. 9 Missile Team 1: Functional Decomposition of an Air-to-Air Missile [Ref. 17]

Missile Team 2 developed a hierarchy consisting of two hierarchy sections connected with a transition tier (see Fig 10). The top-level Systems Architecture tier focuses on system functionality. The bottom-level Physics Taxonomy focuses on physics modeling. The transition tier transitions from the focus on system functionality at the top-level to the physics modeling focus of the lowest levels of the hierarchy. This approach uses a combination of physical decomposition, function decomposition, and physics decomposition allowing great flexibility to re-use existing hierarchies developed in each discipline.

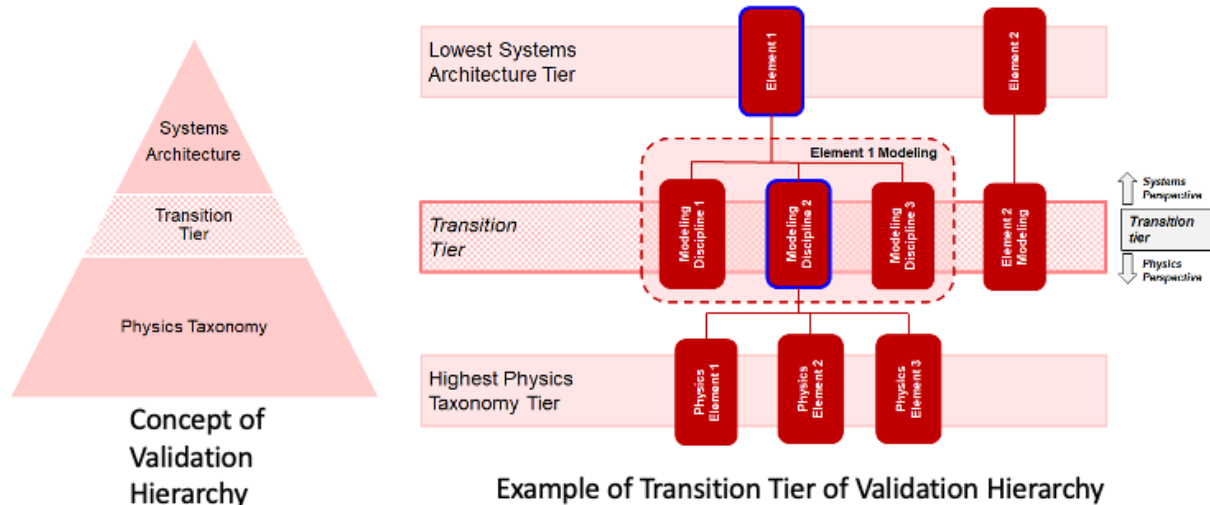


Fig. 10 Missile Team 2: System and Physics Validation Hierarchy [Ref. 14]

The goal of the hierarchy is to connect the system-level functionality with modeling and simulation to predict system performance. This leads to the need to split the hierarchy with the top-level portion of the hierarchy focused on systems-level functionality and the lower levels of the hierarchy focused on physics-based modeling and simulation. The number of tiers in each of these sections of the hierarchy is arbitrary and determined by the problem at hand and on the solution of interest. Validation experiments can be performed at any level of the hierarchy and are distinguished from other types of experiments; more information can be found in Oberkampf and Roy [Ref. 8].

The top-level Systems Architecture part of the Missile Team 2 hierarchy has a system level focus and follows a physical system or functional decomposition into components and sub-components using an arbitrary number of tiers. The lowest levels of the hierarchy, the Physical Taxonomy, focuses on highly complex physics which needs models and decomposes this into simpler problems using physical phenomena as its organizing principle. The decomposition breaks down the highly complex physics to unit problems using an arbitrary number of tiers.

One of the innovations in this hierarchy is the introduction of the Transition Tier between the System Architecture and the Physics Taxonomy sections. The Transition Tier transitions between the systems view in the Systems Architecture and the complex focused physics decomposition of the Physics Taxonomy section. The Transition Tier is a single tier. The Transition Tier focuses on modelling topics of the lowest tier of the Systems Architecture tier.

Another key innovation in this hierarchy is the introduction of coupling between disciplines. The hierarchy identifies the approach for coupling between components of the physical system, coupling between models, and coupling between phenomena. It is designed to work with both weak and strong coupling. These couplings often result in a separate discipline, e.g., coupling between unsteady aerodynamics and flexible structures lead to aero-elasticity. The approach is very general and can follow already established decompositions of existing disciplines.

Missile Team 2 exploited their strategy by modifying a PIRT analysis in what Shaw et al. [Ref. Shaw] refer to as a HELP Table that assists with gap identification and corresponding need for validation.

Mobility Team 1 [Ref. 19] consisted of a single researcher who worked with Missile Team 2 in developing their hierarchy. Mobility Team 1 applied the methodology developed by Missile Team 2 to the problem of a fixed wing mobility transport in high-lift configuration for take-off or landing in quiet air conditions. Fig. 11 shows the anatomy of the high-lift configuration that is used to develop the hierarchy and part of the hierarchy. The system tier is the Transport Aircraft and the sub-system tier is decomposed into Airframe System; Propulsion System; Guidance, Navigation, and Control System; and Internal Mechanical Systems using a functional decomposition. These sub-systems are further decomposed in the Physical Assembly Tier. This is further decomposed before the Transition Tier. The Transition Tier decomposes Airframe sub-systems into Aerodynamics; Structures; Acoustics; and Mechanisms and Kinematics. Each discipline of the Transition Tier is then decomposed using a physics-based decomposition from complex physics to unit problems.

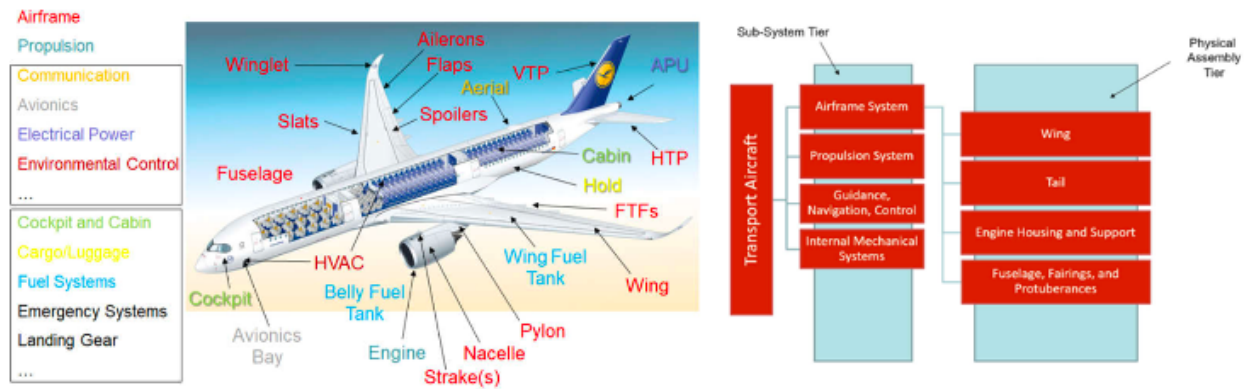


Fig. 11 Mobility Team 1: System and Physics Validation Hierarchy [Ref. 19]

Mobility Team 2, Ref. [15], constructed a framework for modeling and simulation environments to simulate the complete range of requirements using established principles of systems engineering. The Mission Decomposition is used to set requirements to construct functional and physical decompositions of the aircraft. A modelling infrastructure is then created from the Functional Decomposition and Physical Architecture, Fig. 12. The construction of the functional, physical, and modelling decompositions is iterative.

Fixed-wing mobility transports, like other aircraft, are typically designed for a specific mission. The mission has different segments that change the Physical Architecture (geometry) and Functional Decomposition of the system. For example, while the cruise segment will have slats and flaps stowed on the aircraft, the take-off, descent, and landing segments will have slats and flaps deployed at different settings, changing both the physical shape of the aircraft and the function. Different system requirements captured in the Mission Decomposition determine these physical and functional differences in various mission segments, Fig. 12.

A major innovation in the Mobility Team 2 framework is applying a multi-disciplinary design and optimization process to propagate uncertainty throughout the complete system model. Parameter uncertainties are propagated from lower-level components to the aircraft system level. The designer can then evaluate the effect of the uncertainties at any level of the framework on the system response metric. This provides a direct method to identify models or components that would have the greatest impact in reducing the overall system uncertainty and helps the designer and program manager in making decisions where to apply resources to improve the system.

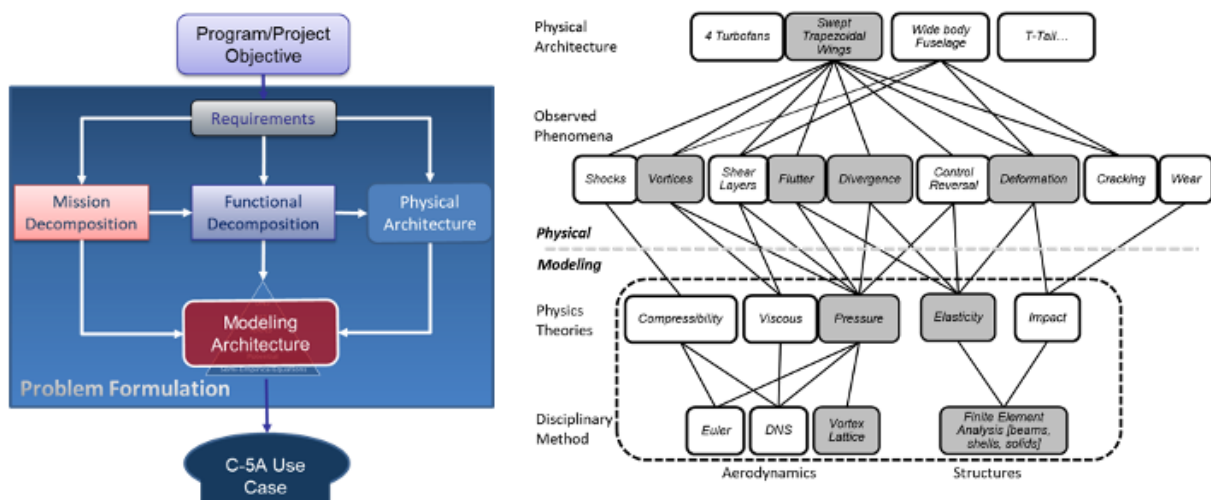


Fig. 12 Mobility Team 2: Functional, Physical, and Modeling Framework [Ref. 15]

V. Concluding Remarks

The larger AVT-297 Team broke into four teams focused on different aspects of the validation database process: two focused on different aspects of a missile, and two focused on different aspects of a fixed-wing mobility transport class vehicle. This resulted in three different processes to decompose the multi-disciplinary problem to identify critical validation data. All four of the teams demonstrated their process on a sample problem demonstrating the benefit of the process. One of the advantages of this as a formal process is that once it is done, it can be used as a starting point on a new problem. This helps to identify potential problems in a new design before the design matures. Additionally, each of these processes can be updated as the system changes – either in the design or operation phase. Applying any of these processes to new systems as they are in early design allows project managers to begin critical validation experiments well before the system design is complete. This is critical as validation experiments can take a long time to plan and execute. Identifying critical validation experiments early in the process is critical to have the data available when it is needed. This will be crucial as designers look at new configurations, new technologies, Certification by Analysis, and the complete Digital Transformation of system design.

While the various sub-teams took different approaches to the challenge problem, their various solutions did result in a degree of similarity. Future work in this area should be focused on the integration of the approaches to make use of the various innovations provided.

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