33RD CONGRESS
OF THE INTERNATIONAL COUNCIL
OF THE AERONAUTICAL SCIENCES
STOCKHOLM, SWEDEN, 4-9 SEPTEMBER, 2022

A MODEL BASED SYSTEMS ENGINEERING APPROACH TO STREAMLINED NOISE CERTIFICATION OF TRANSPORT-TYPE AIRCRAFT

Daewoon Kim[1], Fatma Karagoz[1], Shireen Datta[1], Michael Balchanos[1], David H. Anvid[1], Evan D. Harrison[1] & Dimitri N. Mavris[1]

[1]Aerospace Systems Design Laboratory, Georgia Institute of Technology, Atlanta, GA, 30332, USA

Abstract

This paper presents an approach for a model-based system verification for the validation of system design applicable to the 14 CFR Part 36 Noise certification of transport aircraft. The goal is to present a streamlined process for certification utilizing a model-based verification through integration of system design model and current industry certification processes. The presented approach is demonstrated through a verification of a system under test (SUT), a transport-type aircraft block model, and a system verification model for the Federal Aviation Administration (FAA) 14 CFR Part 36 Noise Standards as a component of aircraft Type Certification. Both the aircraft and verification model are based on model-based systems engineering (MBSE) and utilizes systems modeling language (SysML). In order to implement the model into current practice of transport-type certification, the paper captures findings and inputs obtained by aircraft manufacturers, translates regulations to requirements, constrains requirements through modeled current procedures, verifies the SUT based on the constraints, and outputs the results as artifacts utilized in the current certification process. The integrated model enhances data integrity, communication between stakeholders, and assessment of current practices. To conclude the paper, the advantages and disadvantages of utilizing a model-based verification approach within an MBSE framework are discussed.

Keywords: MBSE, Aircraft Certification, Noise Certification, System Verification, Requirements

1. Nomenclature

MBSE	=	Model-Based Systems Engineering
EPNL	=	Effective Perceived Noise Level
SUT	=	System Under Test
SPL	=	Sound Pressure Level
PNL	=	Perceived Noise Level
CFR	=	Code of Federal Regulations
OEM	=	Original Equipment Manufacturer
NAC	=	No Acoustic Change

2. Introduction

The U.S. Air Force credited Boeing T-7A Red Hawk as the leader of the digital revolution within the aviation industry on September 14, 2020. Boeing T-7A, designed to be the advanced pilot training system for fighter and bomber pilots for the next few decades, was developed utilizing digital threads from its concept phase to first flight. Digital thread is a framework that connects information, information flows, and relationships through the life cycle of the system. The framework for digital design enables integration of new concepts and capabilities onto the system because virtual testing decreases verification time and burns down technical risks earlier in the design life cycle. The impacts of this framework decision on the T-7A, compared to traditional aircraft development programs, were a 75% increase improvement in first-time engineering quality, an 80% reduction in assembly hours, and a 50% reduction in software development and verification time (5). This capability was a key contributor in the T-7A going from concept to first flight in just under three years.

Our approach is to build the aircraft's certification process within the digital thread environment based on external data, current industry practices, and system engineering validation plans. Digital thread captures information which were captured in individual silos into an integrated environment. This connected data architecture becomes the authoritative source of information for the digital twin of an aircraft. Digital twins are defined as virtual representations of connected physical assets through the system life cycle. This virtual instance of the physical product creates a system that can be virtually tested and verified through inspection, demonstration, test, and analysis. A verification plan stemming from this environment can also represent an aircraft's certification process based on regulatory standards and industry practiced test plan standards. A verification plan built from digital threads will increase transparency between stakeholders and utilize the capability of rapid impact analysis of system design. Both of the benefits apply to the aircraft type and airworthiness certification process, leading to a streamlined certification process.

In this work, an integrated system verification and test environment was developed to merge the Federal Aviation Administration's (FAA) "Title 14 Code of Federal Regulations (CFR) Part 36 - Noise Standards: Aircraft Type and Airworthiness Certification", notional aircraft system model, and industry-accepted noise test standards and procedures. All these major components are translated into a System Modeling Language (SysML) and imported into a Model-Based Systems Engineering (MBSE) environment. This paper is organized as follows. In Section II, existing work on the model based design of commercial aircraft is discussed. In Section III, the current noise certification process from the perspective of the FAA regulators and aircraft manufacturers is discussed. In Section IV, an approach to an integrated system verification model is proposed. In Section V, the verification model is demonstrated with a requirement verification of instrumentation set-up and a verification-by-analysis of effective perceived noise level (EPNL), as according to FAA's 14 CFR Part 36 regulations. Finally, Section VI concludes the paper with discussion of future work and summary.

3. Background

Traditional aircraft certification processes pose difficulties due to their document-centric nature and out-dated reference and equipment incorporated processes. With emerging technologies and increased system complexity, manufacturers need to demonstrate compliance with equivalent procedures that are not explicitly described in the regulations. Therefore, a more streamlined certification process is needed to improve efficiency by reducing time and cost without compromising test effectiveness (3). Model-based approaches offer capabilities that supersede the document-centric approach, by building models in a systematic way for more explicit and less ambiguous verification process. Descriptive and executable models can be used to verify that the design meets requirements in earlier stages which could significantly reduce the time for certification process.

In the document-centric processes that are the current status quo, a Compliance Checklist for any kind of certification is normally compiled by manually reviewing all documents that make up the certification basis, applicable Means of Compliance (MoC), and methods of compliance. This has been found to be a non-trivial task due to the following reasons: MoCs are normally scattered across several different documents, an increasing number of amendments and guidance material (in the form of Advisory Circulars) are being added to regulatory documents as the industry evolves, and there is a complex network of cross-referencing across all documents that are involved in creating the Compliance Checklist (2). Spreadsheets are commonly employed as the medium for carrying out this process - due to their inherent decrease in efficiency as the document size becomes larger, this method often inhibits the ability to create a comprehensive enough mapping that is still easy to understand, navigate and collaborate on for the multiple parties that are involved. Lastly, the complex and non-modular nature of document-centric certification makes the process of updating any regulatory artefacts a significantly cumbersome one that is time-consuming, expensive and vulnerable to human error (2).

3.1 Industry Partner Feedback

The Aerospace Systems Design Laboratory at Georgia Institute of Technology led an industry expert panel workshop alongside our sponsor, the Federal Aviation Administration (FAA), to identify streamlining opportunities in the current transport noise certification process. The panel of experts composed of representation from six different aircraft OEMs.

To facilitate a directed discussion within the workshop, our research group produced questionnaires that were distributed to the participants prior to the respective meetings. A high-level summary of the questions is as follows:

- What is the current guidance provided by the FAA for noise certification?
- How does a company interact with the FAA to ensure that requirements and constraints related to noise regulations are satisfied and that the vehicle is compliant?
- How does the company perform the testing, internal processes, etc.?
- Can you identify procedures within flight testing that should be revised or updated to reflect capabilities of modern configurations? Are there any opportunities for improvement?
- Are existing certification procedures and methods sufficient to meet future configurations?
- Certification amendments due to type design changes—if a vehicle needs to be re-certified after making design changes, does your organization's approach change from the first round of certification?

The initial workshop along with the follow-on interview with the participants generated direct conclusions and insightful findings regarding the planning and methodological approach to system validation and testing. The key takeaways common across most OEM feedbacks are the following:

- Acoustical changes (AC's/NAC's) are challenging to navigate without standardized approval procedures - more detailed feedback would be useful for OEMs to propose suitable solutions.
- Test site selection is normally restricted by sound measurement technology and requirements (e.g., the lateral microphone component), by weather window options, and specific safety protocols of the applicant (e.g., only testing at approved airports).
- Conformity discussions can be significantly time/effort consuming, especially in cases where there is a need to justify changes that are unrelated to acoustics.
- Interactions between Part 36 and Part 25/23, as there seems to be a discontinuity between environmental and design standards, often leaving little space to apply acoustic improvements.
- Lack of consistency in calculating EPNL values from flight testing noise data can often make collaboration difficult - each OEM's methodology and code is different.

In certification planning and preparation, a paradigm shift from document-centric to model-based methods has the potential to eliminate unnecessary complexity and vulnerabilities and enable more effective collaboration. This is achieved mainly by introducing standardization and modularity to various aspects of the process. The current work proposes a MBSE environment that demonstrates the application of this transition specifically to aircraft noise certification and attempts to resolve the need for standardization, which was assessed to be an underlying issue common to all of the takeaways listed above. The primary inflection point in this transition away from the document-centric approach comes in the form of a single system model that receives and consolidates input from all involved parties and allows viewing of this information in several different formats that can be tailored to a user's needs (6). This centralized format also enables all sources of information to be linked together in a comprehensive network that makes the process of introducing and propagating changes more reliable and efficient. In its document-centric counterpart, any one information source is likely connected only in-part to the full network, thus forcing changes to travel along various different cross-referenced links with no reliable way of confirming that they were comprehensively implemented (6).

4. Current Noise Certification Process

Incorporation of new technologies have achieved significant noise reductions over the years. The main purpose of noise certification is to ensure the new technologies are incorporated into aircraft design process which leads to noise reduction around the airports. As new aircraft designs emerge and better technologies become available, noise standards are updated. Current noise certification processes are investigated in this paper to provide a better insight into potential improvements.

4.1 Overview

The research task to survey the current challenges of noise certification began with a review of the current regulatory standards, as shown in Figure 1. In coordination with 14 CFR Part 36 - Noise Standards for Aircraft Type and Airworthiness Certification", the FAA also releases advisory circulars (ACs) to provide addendum guidelines. As an example, AC-36-4D adds additional guidance on implementation of specific procedures covered within Part 36. These alternative methods of implementation are what are called "equivalent procedures". Equivalent procedures are alternative means of compliance, which add flexibility into how an OEM can lay out the certification plan. One specific procedure we will model as a step-by-step functional flow is the EPNL conversion process. This process includes a standardized value table for SPL versus frequency, which is outlined within Part 36. However, in accordance to the advisory circular, alternative set of perceived noise value tables can be implemented as an alternative for the calculation of EPNL (9).

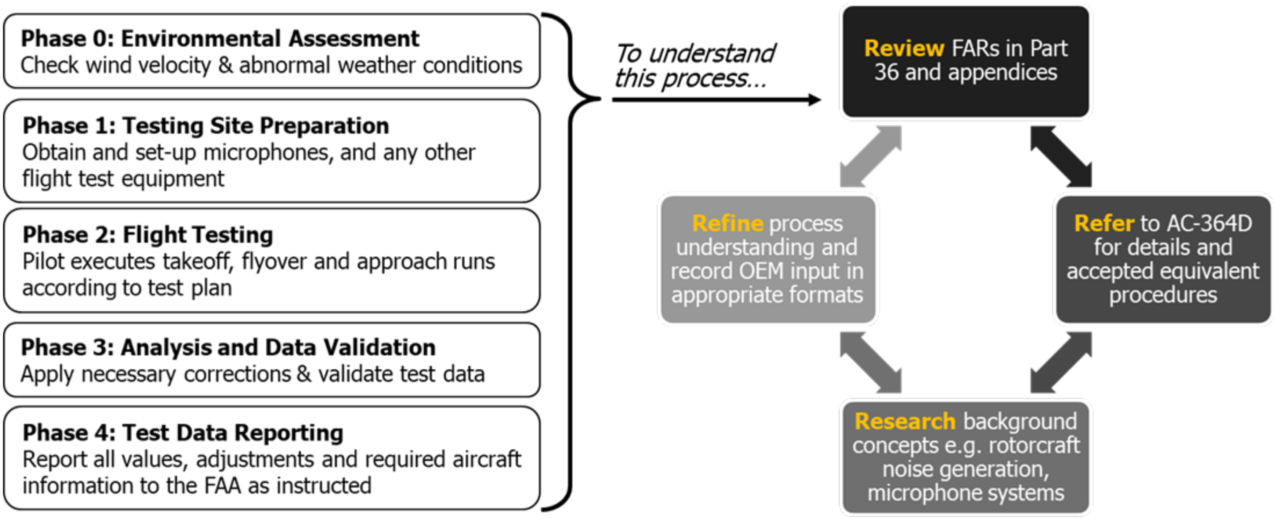

Figure 1 – Approach to modeling aircraft certification regulations

4.2 EPNL Conversion Process

Significant research effort has been conducted to determine the effects of noise on people (7). EPNL is an annoyance-based metric that is widely used in aircraft noise projections and based on prior loudness models. While loudness is considered the most effective contributor to the annoyance, other attributes such as sharpness, tonalness, roughness, fluctuation strength also may affect the annoyance perceived. FAA's EPNL metric considers intensity, tonalness, and duration of the aircraft noise. In this research, EPNL is used as the noise metric in order to demonstrate compliance with FAA's noise regulations.

A conversion process of the flight test data is required to obtain certification quality EPNdB, as it cannot be directly measured from raw test data. The standardized conversion process is described in ICAO Annex 16, which contains the aircraft noise standards. The EPNL calculation is performed utilizing the programs written by More (2010) (9), as per ICAO Annex 16.

Aircraft noise certification requires noise measurement typically at three reference points: flyover, lateral, and approach. Therefore, EPNL calculation is set up considering three different maximum permitted noise levels. The process is tested against a known flight data set from the industry partner for a transport aircraft that has been certified. The test data contains a spectral noise history of the aircraft at an unknown reference point, without the inclusion of background noise adjustment or reference condition corrections. The available data for the sound pressure levels, frequency distribution, and time variation measurements are used to evaluate EPNL (1) and validate the EPNL tool that is used in the verification model. The validation results are depicted in Figure 2 where the available flight test data is compared to the calculated values of perceived noise level (PNL). It can be depicted that perceived noise levels that are calculated from the sounds pressure levels align with the validation data, except a small peak between 20 and 25 seconds with a difference less than one percent. The corrected perceived noise levels are also depicted in the figure as a reference; however, these values could not be compared against a known data, as the given data set was limited to the uncorrected values. In Table 3, the resulting EPNL values are shown, along with the validation data which only considers uncorrected PNL values. Therefore, EPNL is calculated with both corrected and uncorrected PNL values. As results show, the EPNL tool used in the verification model is able to match the validation data. For comparison, the maximum noise levels from the requirements are also provided at flyover, lateral, and approach reference points. The data used to validate our EPNL conversion tool was sent by one of our industry partners and includes raw noise measurements from a previously certified transport aircraft. This data can be found in Appendix A of this paper.

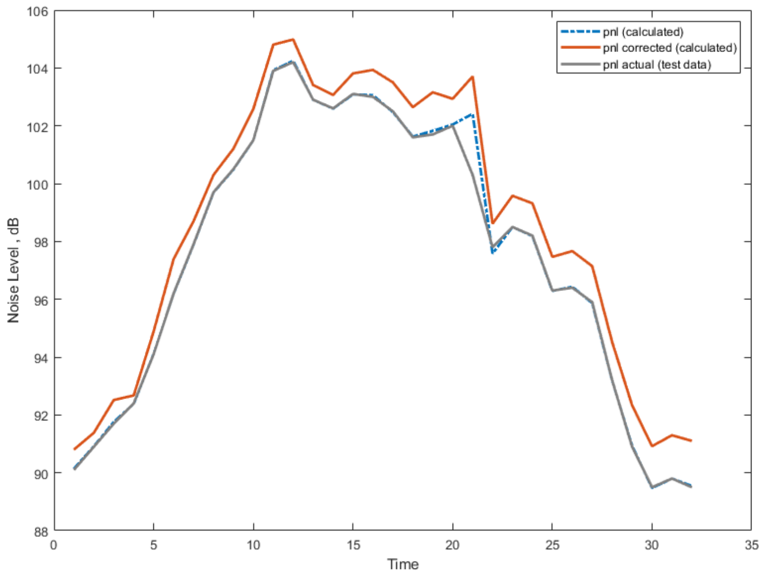

Figure 2 – EPNL Tool Validation

Table 1 – Comparison of EPNL Values

Noise Level (EPNLdB)					
Uncorrected (Test data)	Uncorrected (Calculated)	Corrected (Calculated)	Max Noise Level (Requirements)		
			Flyover	Lateral	Approach
101.5	101.5	102.4	98.6	101.3	104.7

5. System Verification Model

An immediate benefit from the digital thread verification model is the increased transparency of system design at any stage of development. This benefit can also be utilized to build trust amongst stakeholders with a shared design view to instill common knowledge of the system. The current limitations for the certification process include keeping up with the rapidly changing aircraft systems and technologies. As new technologies emerge, the systems become more and more interconnected.

For this reason, there is a need for greater agility in the certification process for adapting to a fast pace dynamic environment. In order to enable reusability and effectively expedite steps through digital modeling and process execution, MBSE shifts the representation of systems from documents to explicit representation of systems via models, hence it merges product information and engineering models. It provides a consistent system model that everyone can 'view', maintaining a shared system model as the authoritative source of information, a feature that is helpful in preserving common understanding for people with different roles, responsibilities.

The system verification model utilizes external inputs from present-day certification procedures to build an interconnected model for the system under test (SUT) aircraft model. Specifically for FAA's 14 CFR Part 36 Noise Certification, the regulations (Appendix A - Aircraft Noise Measurement and Evaluation and Appendix B - Noise Levels for Transport Category and Jet Airplanes) are imported as text blocks into the verification model, translated into verifiable requirements, and linked together to establish a data thread. In order to verify these regulatory requirements, specific test artifacts are brought into the verification model as procedural guidelines for testing. As an example, Department of Transportation's guide for "Validation Protocol for Instruments used in Aircraft Noise-Certification Testing" is imported into the model as logical and behavioral elements. This build up process is shown below in Figure 3. The result is a system verification model that is a build up of four interconnected models: Aircraft Model, Requirement Model, Logical Model, and Behavioral Model. All of these models support test and verification specific to 14 CFR Part 36 Noise Certification testing. The development of each model is further explained in the subsections below.

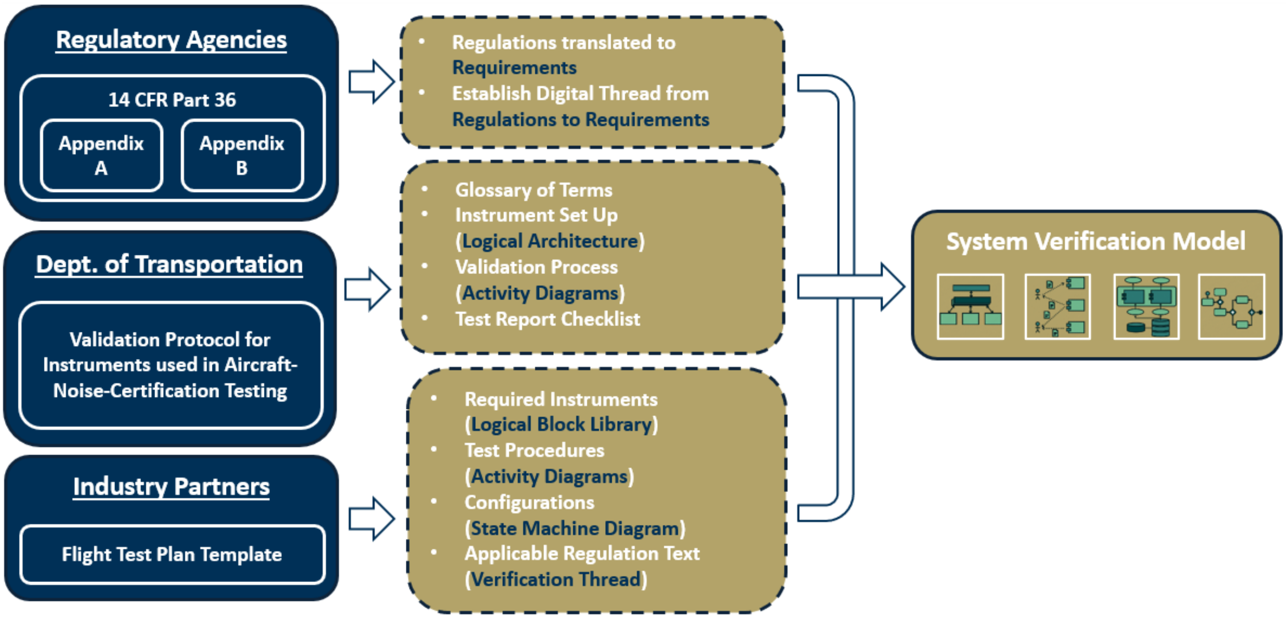

Figure 3 – System Verification Model Build-up

The model is developed for the main purpose of verifying the system under test (SUT). In this example, a notional aircraft model representing a transport-type Boeing 787 MBSE model is used as the SUT. This aircraft model is represented with the system verification model as a logical block that holds values pertinent to noise testing (e.g., max takeoff weight, flyover decibel, flyover speed). These value properties owned by the SUT is what is verified by the requirements derived from the regulations. This is setting up for a verification by analysis, as this aircraft model is the framework to input test and analysis data into the MBSE environment to be verified by requirements and constraints, also within the MBSE environment. Once the elements are connected, the system verification model constrains the Aircraft Model through the regulatory constraints of the Requirement Model. The test instruments and environment to be used for testing are defined by the Logical Model. Finally, the test and analysis procedures of noise measurements are defined by the Behavioral Model. All elements of the system verification model help to build a test and verification environment that leverages digital engineering driven design of the aircraft and digital verification for certification. If further reports outside of the MBSE environment are required for certification, automatically generated reports can be exported from the model using Document Wizard toolkit built into MBSE modeling tools such as Magicdraw. This interconnection of models is shown below in Figure 4.

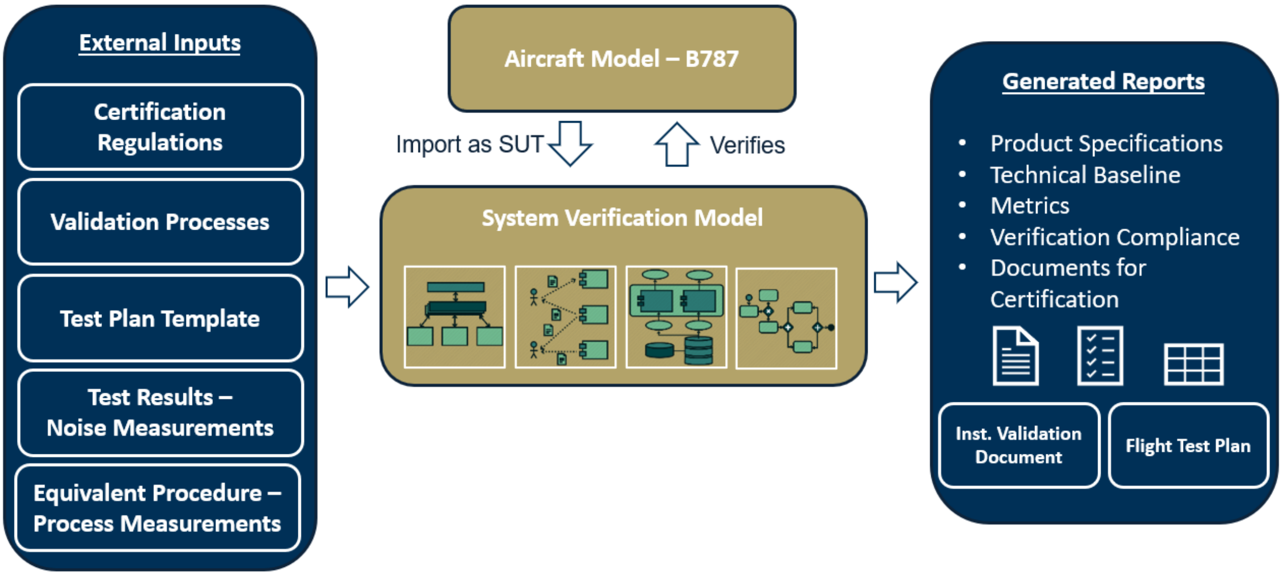

Figure 4 – System Verification Model inputs and outputs

5.1 Aircraft Model

The assumption here is that the aircraft design (since concept) has been developed within MBSE. This is pivotal to enabling a digital thread design that can best utilize the verification model. At the level of noise testing, the aircraft is abstracted to a singular system block. In combination with its engine, they make up the System Under Test as shown in Figure 5. These blocks themselves can comprise of much more than the notional values as shown in the figure. Given design occurred within MBSE, the aircraft would decompose to its subsystems then further decompose into components at its lowest level. However, because our application of verification is only at the level of complete vehicle noise output, lower level design is not captured. However, if the example was verification of lower level subsystems (e.g., landing gear, interior cabin, hydraulic system), then the Aircraft Model would have to decompose down to the level that matches to what is being tested to more accurately represent the System Under Test.

5.2 Requirement Model

Creating and managing a set of good requirements is essential to the design, development and operation of any product or system. In this case, building a requirement model was one of the first steps to representing the current noise certification process in a model-based environment. An existing set of relevant Federal Aviation Regulations (14 CFR Part 36, Noise Standards: Aircraft Type and Airworthiness Certification), acts as the primary reference for requirements that are placed on aircraft noise certification processes and equipment. These are normally published by the FAA in a solely document-based format, which needed to be migrated into a requirement model in MagicDraw for the purposes of the current work. This section begins by introducing the main features of the requirements themselves, before discussing the difference between 'regulations' and 'requirements' and the process of converting from the former to the latter. Finally, requirement verification and the associated linkages between requirements and other model elements are discussed.

Within the Systems Engineering Handbook (SEH) published by NASA (4), Appendix C describes various types of requirements and includes a validation checklist of features that 'good' requirements should have, e.g. completeness, conciseness, clarity, traceability, and verifiability. Each of the FARs in Part 36, as currently written, do not always appear to comply fully with these accepted writing standards. Therefore, the first step in building a requirement model was to select relevant subsets of FARs

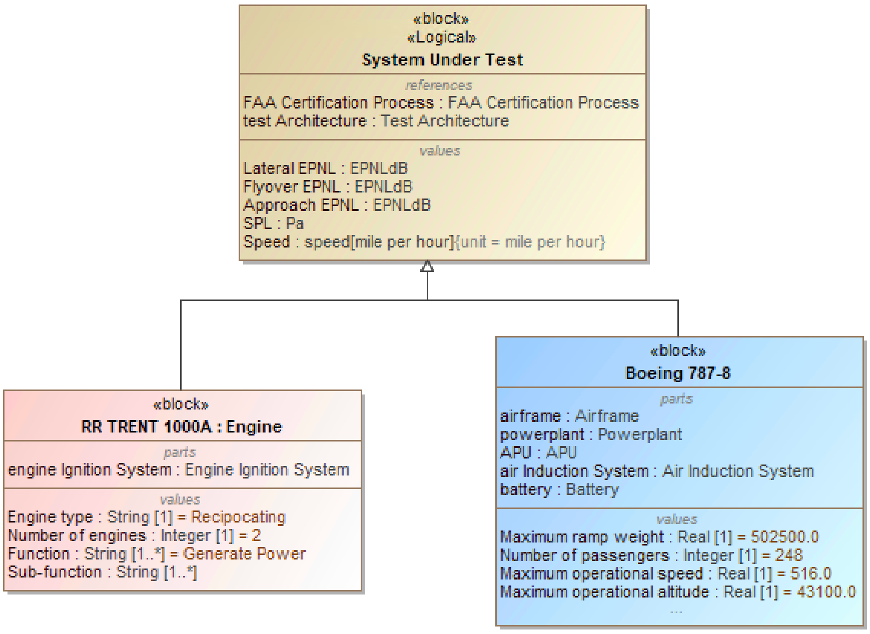

Figure 5 – Aircraft and Engine represented as System Under Test

and process them thoroughly using the SEH as a reference. This yielded individual requirements that are clearly associated with various parts of the noise certification 'system', and are compliant with well-known standards for requirement language.

ID:Name	Requirement Text	Owned By	Traced To	Satisfied By
40: Sudden Onset Response Sampling Instants	The analysis system shall have a response (to the sudden onset of a constant sinusoidal signal) that is measured at sampling instants 0.5, 1, 1.5 and 2 seconds after the onset.	Measurement System Requirements	A36.3.3.1 (1D), A36.3.7.1, A36.3.7.4	Sound pressure level response (Analysis System: Value Property)
41: Interruption Response Sampling Instants	The analysis system shall have a response (to the sudden interruption of a constant sinusoidal signal) that is measured at sampling instants 0.5 and 1 second after the onset.	Same as ID 40	Same as ID 40	Same as ID 40
42: Rising Response Limits	The analysis system shall have a rising response that conforms to these dB values at each sampling instant (relative to the steady-state level): -4+/-1 dB at 0.5s, -1.75+/-0.75 dB at 1s, -1+/-0.5 dB at 1.5s and -0.5+/-0.5 dB at 2s.	Same as ID 40	Same as ID 40	Same as ID 40
43: Falling Response Limits	The analysis system shall have a falling response such that the sum of the output signal levels is -6.5+/-1 dB, at both 0.5 and 1s (relative to the initial steady-state level, and to the corresponding rising response).	Same as ID 40	Same as ID 40	Same as ID 40
44: Sum of Rising and Falling Response	The analysis system shall have a sum of rising and falling responses less than or equal to -7.5dB (at subsequent times).	Same as ID 40	Same as ID 40	Same as ID 40

Table 2 – Five requirements formed from one regulation in 14 CFR Part 36 Appendix A.

A standard requirement normally includes an ID, a name and the main requirement text, in addition to features that relate it to other elements, as shown in Table 2. For example, a requirement can be "owned by" a larger set of requirements, can be "traced to" an original source, and can be "satisfied by" a verification element. In the current work, one of the capabilities that MBSE is leveraged for is the ease of representing such links between requirements and various certification elements, and creating traces to regulations where the requirements originated. This ability to represent a fully connected verification model can be very useful in addressing common issues that arise during certification audits, e.g., requirement traceability, configuration management, document control, and change impact analysis. The five requirements in Table 2 were extracted from regulation number A36.3.7.4, the text of which is copied below exactly as written in Appendix A of 14 CFR Part 36:

> A36.3.7.4 When slow time averaging is performed in the analyzer, the response of the one-third octave band analysis system to a sudden onset or interruption of a constant sinusoidal signal at the respective one-third octave nominal midband frequency, must be measured at sampling instants 0.5, 1, 1.5 and 2 seconds(s) after the onset and 0.5 and 1s after interruption. The rising response must be -4+/-1 dB at 0.5s, -1.75+/-0.75 dB at 1s, -1+/-0.5 dB at 1.5s and -0.5+/-0.5 dB at 2s relative to the steady-state level. The falling response must be such that the sum of the output signal levels, relative to the initial steady-state level, and the corresponding rising response reading is -6.5+/-1 dB, at both 0.5 and 1s. At subsequent times the sum of the rising and falling responses must be -7.5 dB or less. This equates to an exponential averaging process (slow time-weighting) with a nominal 1s time constant (i.e.,0.2s averaging time).

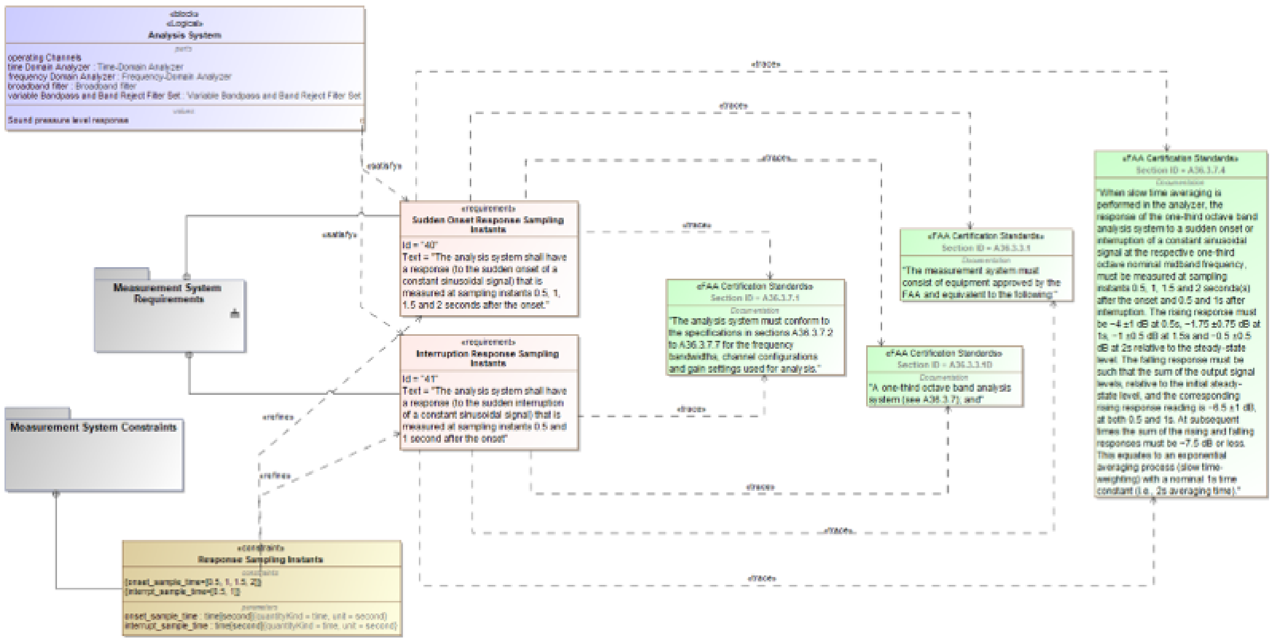

Figure 6 – Digital thread between requirements (light pink), logical model elements (purple), constraints (yellow) and original regulations (green)

For the purposes of the current work, regulations that are relevant to flight testing for aircraft noise were prioritized for the requirement writing process, selected from Appendices A and B of 14 CFR Part 36. Some of the considerations that were taken into account while building a good requirement model from the as-written regulations, were as follows:

- Every regulation did not need to be converted to a requirement.
- A single regulation often needed to be broken down into several requirements (e.g. Table 2)
- Multiple regulations often merged into a single requirement.
- The regulations did not always include all of the information needed to write a comprehensive requirement. Additional metrics and clarifying information were occasionally gathered from literature reviews and other regulatory documents referenced within Part 36.

- The verification method or element was not necessarily well defined for all regulations that yielded requirement. This was resolved primarily by referencing documentation from VOLPE that detailed the standard aircraft noise testing instrumentation setup.

The result of the first step of the requirement modeling process yielded a set of requirements that were aligned with an accepted writing standard, and were associated with their origin regulations and verification elements

In this context, a requirement normally represents a single design constraint, extracted from one or more regulations. A method of verification is required in order for this design constraint to be satisfied by the system under test. To provide this verification step, a constraint block is introduced as a verification mechanism by integrating engineering analysis into a model. In particular, with the use of a constraint block it is possible to quantify the textual requirement using mathematical and logical expressions only, while verification simulations which can determine if a certain metric passes or fails a requirement, can be enabled. Overall, the constraint block acts as the interface of linking a requirements model and the logical/physical model of a System under Test. An example of how a regulatory article can be imported as a requirement, linked to the verification model and be tested, is shown in Figure 7.

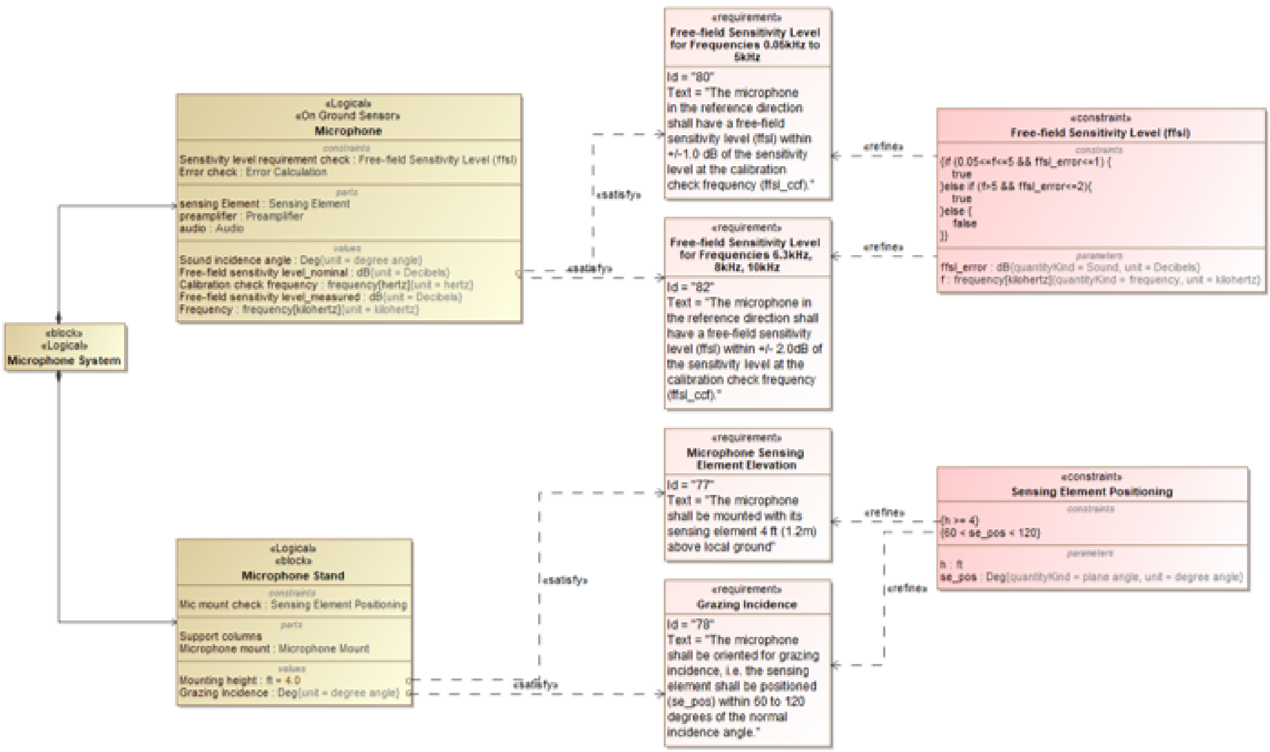

Figure 7 – Linkages from requirements (middle, light pink) to constraint blocks (right, pink) and verification elements (left, yellow) within the logical model

5.3 Logical Model

The verification model guides the engineers towards crucial information whether the requirements are satisfied for a specific system. The overall system representation is needed to provide a link between the system design and requirements, provide shared understanding of the system, and perform verification. Hence, logical system is defined to represent abstraction of physical solutions (11). This definition is achieved in a supplier agnostic way, from which a physical architecture can be established with different physical characteristics.

The logical architecture representation is described hierarchically, where the system decomposition level is dictated by the requirements. The necessary sensors for a flight test are realized by their logical block, typed with the «logical» stereotype in SysML.The instrumentation architecture is further characterized by the types of sensors used, e.g. the two types of sensors: «On Ground Sensor», and «On A/C Sensor». An example view of the logical architecture in provided in Figure 8 where different levels of decomposition is depicted for the measurement system and microphone system with their constraints and part properties.

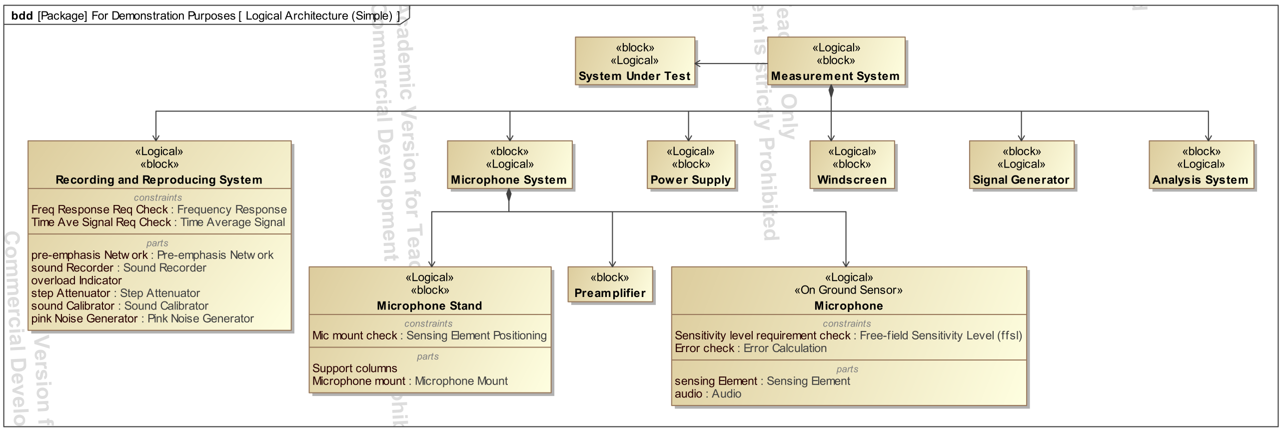

Figure 8 – An example logical architecture view in SysML for flight test instruments

5.4 Behavioral Model

This model is a representation of specific test procedures and guidelines as prescribed in the regulatory standards, industry accepted practices, and OEM test procedures. In all of these sources, procedures are written in text (bullet points, numbered lists, etc.). This makes roles and responsibilities vague and functional allocation to actors/systems are not clearly defined. Thus, the behavioral model translates these texts to functional flow diagrams comprised of singularly executable functions, allocation of functions to systems, and exchange of information between systems.

In order to better understand and demonstrate how this process functions in practice, an example is provided in Figure 9. The purpose of the example test function is to establish known reference noise level (in dB), with steps of the process listed in text format (indicated to the left side of the figure). Starting from the phase 1 of the implementation (at the top of the figure), the first process step indicates that a 1) sound calibrator is applied to the microphone system. What this means in the behavioral process model is that three system blocks from the instrument architecture library are used, namely the sound calibrator, the microphone system and the recording system. In terms of process steps, a connection of the sound calibrator to the microphone system must be established and the calibrator then to apply the calibration sound to the microphone. Looking at the next phase of steps (Phase 2 at the bottom part of figure), there is instruction to 2) connect microphone system to recording system, 3) adjust recording system's level-range-control to record the sound level calibration signal and 4) record the sound level calibration signal for 30 sec. All these process steps are then populated to the process model on the right side of the figure, and mapped accordingly to the system blocks. The resultant diagram in SysML is shown in Figure 10.

6. Demonstration of Requirement Verification

6.1 Executable Model

Analytical capability is needed for verifying requirements by analysis in the MBSE environment. For the calculation of EPNL, executable means are used to perform numerical computations externally, and interface with the MBSE framework. While a direct computation in the MBSE environment itself was possible, performing external computations were more straightforward with the added benefit of broad applicability. Therefore, MATLAB (8) integration with MagicDraw 19.0 is chosen for the execution capability with the assistance of Cameo Simulation Toolkit (CST) (10). The values that are calculated within the MATLAB environment made their way back to the system model automatically for requirements verification without manual processing. The analysis representation for EPNL calculation within the system model is depicted in Figure 11. This analysis included three noise

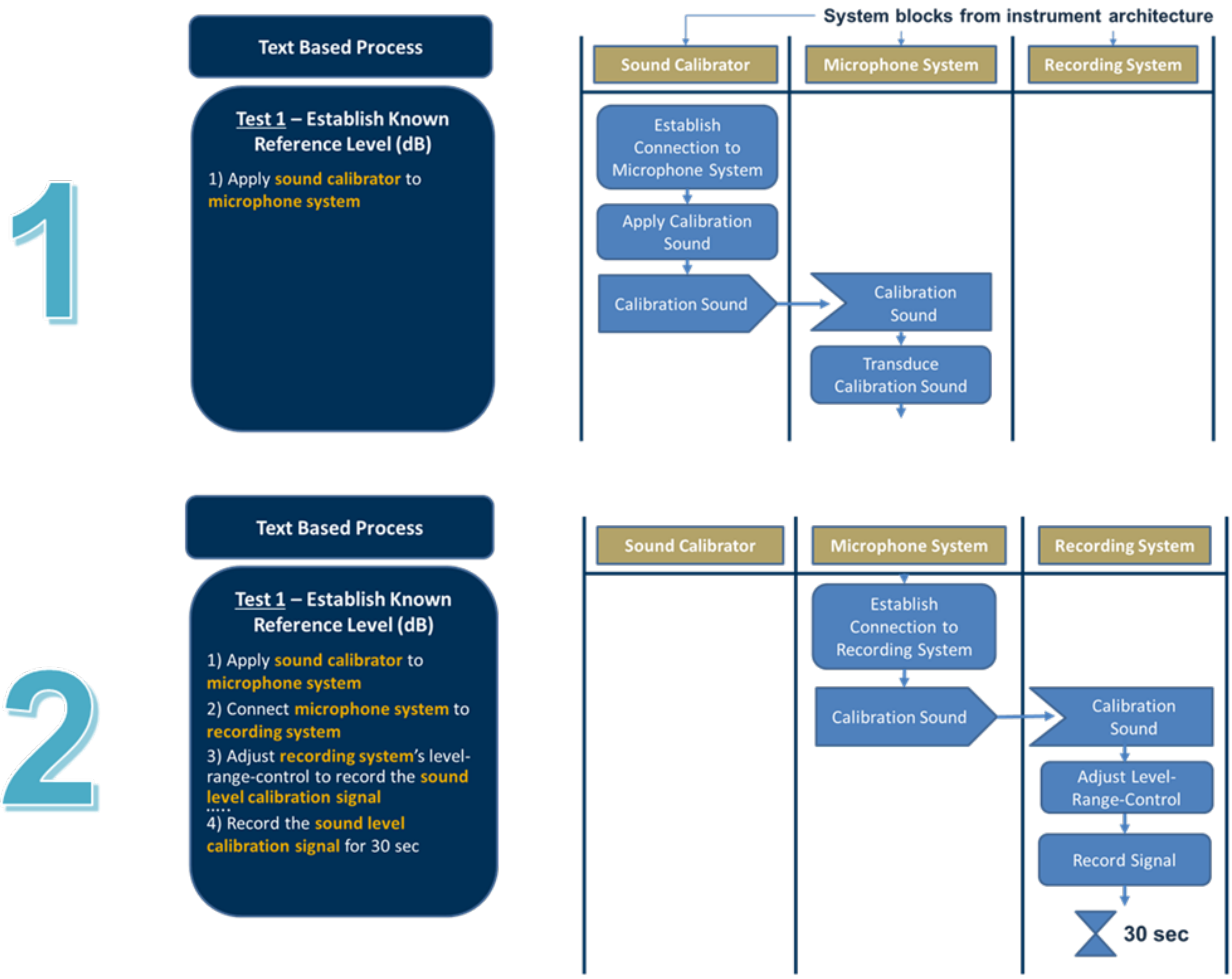

Figure 9 – Text based method translated to behavior based functional flows

level constraints for different reference points to show compliance with the regulations as well as the necessary input and output parameters as value properties within the analysis block.

6.2 Requirements Verification

After having necessary system parameters calculated, the results are checked against the requirements. Parametric diagrams are utilized to capture constraints and bind the parameters of the relevant constraints to the properties of the system architecture as shown in Figure 12. These constraints refine the requirements as described in previous sections, and mathematically describe a requirement. While some of these constraints can be mathematical or logical expressions that can be expressed with the built-in math functions, for more complex functions JavaScript is used to define the constraint expression. Parametric evaluations give the verdict on whether or not a requirements is satisfied. A commercially available MBSE simulation toolkit is used to analyze the associated scenarios and perform requirements verification automatically.

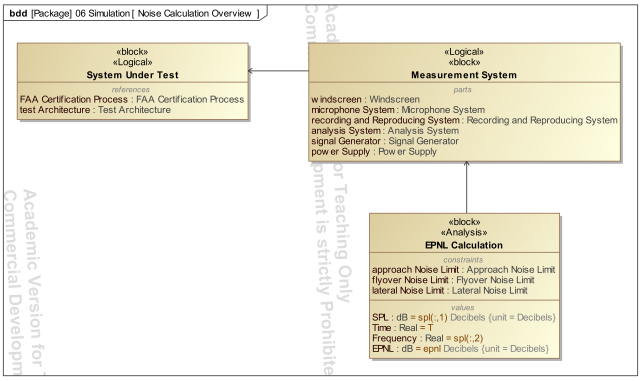

Figure 11 – Analysis Representation for EPNL Calculation

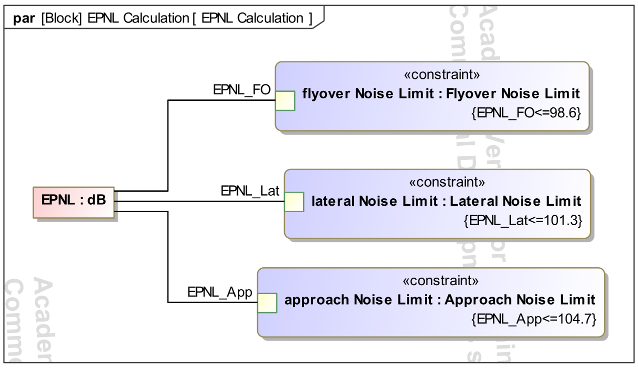

Figure 12 – Parametic Diagram Set-up for EPNL Limits

7. Future Work and Summary

This paper outlines an approach for noise certification of transport-type aircraft with a model-based systems engineering approach. Use of external tools such as MATLAB was found to be useful for showcasing re-usability of existing codes and broader applicability. Also, framing the system model and the external tools in an integrated way within the MBSE context enabled consistency across users, ensured end-to-end traceability of model elements, and provided a comprehensive view of the model for decision makers. This effort was accomplished through the documentation of current noise certification regulatory framework with input from literature and industry partner feedback. A working version of the verification model is able to lay out a test plan procedural document for certification and build a cert basis from data input to the system design model.

In the future, we will be integrating a functional evaluation model that will build discrete event simulations from behavioral models to assess change impact of certain steps (events) or procedures (equivalent procedures). This capability will build upon the working verification tool to find areas of improvement within an OEM's test plan, while ensuring that the alternative methods of testing are still compliant to regulatory standards.

8. Contact Author Email Address

For questions regarding the contents of this paper, please contact:

- Daewoon Kim: dkim780@gatech.edu
- Dimitri Mavris: dimitri.mavris@aerospace.gatech.edu

9. Copyright Statement

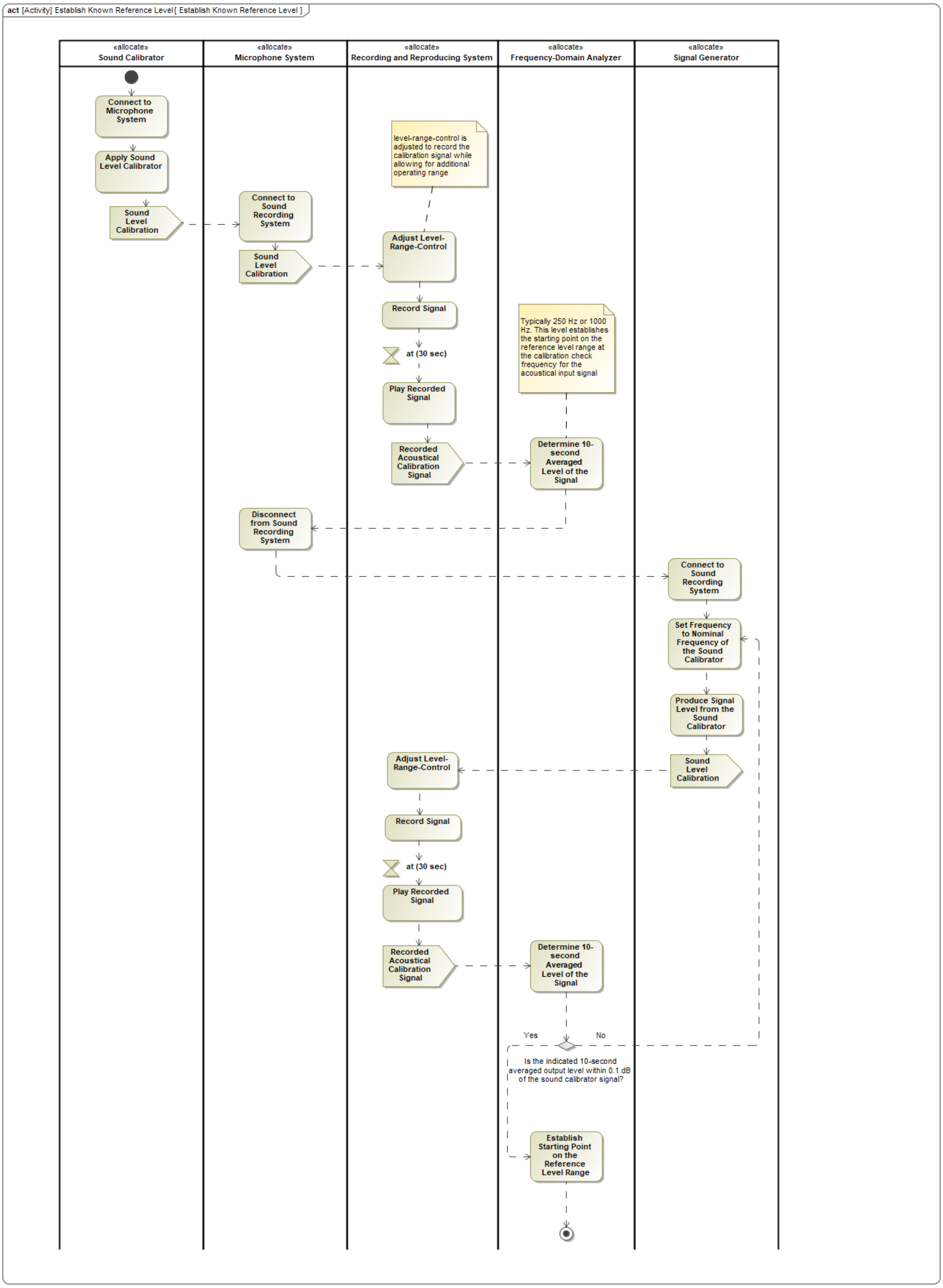

Figure 10 – An example of behavioral diagram for establishing Known Reference Level

References

[1] *Environmental Protection*, 8 ed., vol. 1. International Civil Aviation Organization, 2017.

[2] Bleu-Laine, M.-H., Bendarkar, M. V., Xie, J., Briceno, S. I., and Mavris, D. N. *A Model-Based System Engineering Approach to Normal Category Airplane Airworthiness Certification*.

[3] Cook, D., and Schindel, W. D. Utilizing mbse patterns to accelerate system verification. *Insight 20*, 1 (2017), 32–41.

[4] Dunbar, B. Nasa systems engineering handbook appendix c: How to write a good requirement, 2019.

[5] Jackson, R. Boeing t-7a red hawk trainer leads the way in digital engineering, 2020.

[6] Kim, D., Verberne, J., Sotiropoulos-Georgiopoulos, E., Harrison, E., and Mavris, D. N. *A Model-Based System Engineering Approach to the Certification of Transport Type Aircraft*.

[7] Kryter, K. *The handbook of hearing and the effects of noise: physiology, psychology, and public health*. Brill, 1994.

[8] The Mathworks, Inc. *MATLAB version 9.9.0.1467703 (R2020b)*. Natick, Massachusetts, 2020.

[9] More, S. R. *Aircraft noise characteristics and metrics*. PhD thesis, 2010.

[10] No Magic. *Integration with MATLAB*, 2021.

[11] Pearce, P., and Friedenthal, S. A practical approach for modelling submarine subsystem architecture in sysml. In *Submarine Institute of Australia Science, Technology & Engineering Conference* (2013), vol. 2013.

Appendix A

Table 3 – Test Data for Sound Pressure Levels

Time/ Freq.	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
37.5	66.6	66.7	67.7	63.8	64.9	69.9	75	75	72.4	70.8	75.7	72.7	73	72.2	70.7	69.2	66.4	62.8	55.7	47.6	42.6	30.3	11.4	-15.8
38	67.1	66.7	66.3	60.8	67.9	73.8	76.6	75.9	70.2	74	75	74.8	74.2	73.3	71.7	69.6	66.9	64.4	59	50.7	46	34.7	17.1	-8
38.5	66.7	66.8	65	56.8	68.7	74.1	76.9	75.2	71.8	77	73.1	76.2	75.4	74.4	72	69.4	67.6	64.5	59.9	51.5	47.2	36.7	20.4	-2.9
39	66.2	65.7	64.1	63.6	70.6	76.8	77.1	72.7	75.6	77.2	74.5	75.8	75.3	74.8	72.8	70.1	69	65.5	60.3	52.8	48.8	39	23.7	2
39.5	66.9	65.8	62.5	66.8	72.7	79.3	77.1	72.1	78.6	75.8	77.9	75.2	76.1	76.6	75.9	73	71.5	67.4	62.5	55.6	47.6	38.2	23.9	3.3
40	68.3	65.9	61.4	71.8	75	79.6	77.6	72.9	81.7	76.1	79.4	78.1	79.3	79.3	78.2	75.5	72.9	69.2	65.4	59.3	50.5	41.6	27.8	8.1
40.5	69	64.1	63.5	73.9	78.2	79.8	77.4	76.9	82.7	78.8	80.1	81.6	81.2	79.4	78.6	77	74.3	71.5	68.3	62.9	54	45.3	31.9	12.7
41	68.3	64.6	65.3	76.8	81	81.7	77.8	80.6	81.9	82.1	81.7	82.6	81.9	80.1	79	77.5	77.3	73.5	70	65.3	56.2	47.6	34.4	15.4
41.5	66.2	63.1	66	78.5	82.7	82.1	78	83.8	81	84.2	82	82.1	82.3	81.5	79.78	78.5	78	74.6	70.8	66	57.1	48.5	35.1	16
42	69.4	63.8	67.1	80	83.4	83.6	75.8	85.4	82	86	82.8	84.5	83.7	82.8	81.6	80.6	78	75.8	71.7	66.2	58.1	49.2	35.6	16.1
42.5	71.1	61.9	71.5	81	87.5	86.3	78.7	87.2	85.1	88	86.5	86.6	87	85.4	84.5	83.1	80.5	76.8	73.6	67.3	59.2	50.1	36	15.9
43	73.5	66.6	74.5	81.1	88.7	87.1	80.6	87.6	86.5	88.3	86.8	87.5	87.3	85.3	84.4	83.1	81	76.7	73.6	67.3	58.8	49.4	34.7	13.8
43.5	74.2	67.7	75.3	81.8	87.4	87.7	81.9	87.1	86.5	87	84.8	87.4	85.1	82.8	82.2	81	78.3	75.2	71.1	65.1	56.5	46.6	31.3	9.4
44	72.5	70	75.9	83	89.1	89.5	84.8	87	88.8	85.9	84.1	85.9	83.6	81.3	80.9	79.1	76.4	73.2	68.9	62.2	53.7	43.3	27.2	4.2
44.5	75.4	72.7	75.2	83.2	89.9	92.4	86.2	86.1	90.2	85.8	85.2	83.1	81.9	80.8	80.9	77.4	76.4	73.5	68.3	62	52.9	41.9	24.9	0.7
45	76.9	75.4	74.1	84	89.4	93.3	87.4	85.8	90.5	84.7	85.4	81.6	80.6	81.3	80.9	77.4	75.8	72.6	67.1	60.8	51.3	39.7	21.8	-3.8
45.5	81.9	78.8	74.7	87.2	90.6	92.7	89.7	84.8	90	82.9	84.2	82.2	79.5	79.9	78.6	76.3	73.7	69.1	64	57.1	47.6	35.4	16.6	-10.4
46	83.3	79.2	74	87.4	91.1	93	90.5	83.2	88.7	82	83.5	81.4	78.3	77.4	76.1	74	72.6	67.2	61.5	54.4	49.2	36.3	16.4	-12
46.5	81.6	80.3	74.4	84.9	91.1	92.7	91.4	83.4	87.5	82.2	82.3	80.4	78.3	78	76.9	75.1	73.2	68.3	67.2	54.1	48.6	35	14.1	-15.9
47	82.1	80.5	76.8	83	91.9	92.6	91.7	84.7	85.7	83.4	81	80.2	79.5	79.8	78.1	76.3	73.4	68.9	63.7	54.8	49	34.7	12.7	-18.7
47.5	85.7	80.6	78.2	79.5	90.2	91.8	89.1	83.2	81.8	82	78.4	78.5	78.4	79.1	76.8	74.2	70.7	66.7	61.5	52.4	46.3	31.4	8.3	-24.8
48	85.7	82.5	78.9	76.5	86.1	89.4	86.1	82.2	76.9	81	76.9	73.2	76.7	75.5	73.3	69.3	66.9	62.8	56.6	46.7	40.3	24.6	0.3	-34.4
48.5	84.3	84.3	80.4	75.7	86.5	89.7	88.6	85.6	77.4	81.8	76.7	78	76.8	74.3	72.8	69.6	67.2	62.5	55.6	45.8	39.1	22.7	-2.7	-39
49	85.3	86.6	81.3	74.6	85.3	88.8	88.7	86.2	75.8	80.6	75.3	76.3	74.4	73	72.1	69.7	66.9	61.7	54.4	44.6	37.6	20.4	-6.1	-44.1
49.5	84.6	86	81.7	74.8	83.5	86.1	86.7	84	75.7	78.8	75.1	74.6	71.6	71.2	69.9	67.2	64.3	58.3	50.5	38.8	31.5	13.6	-14.2	-53.8
50	84.9	84.5	82.5	74.4	81.9	85.7	87.3	83.7	77.5	78.5	78.1	73.9	72.2	71.7	69.6	65	62.6	57.1	50.3	38.1	30.5	11.8	-17.2	-58.5
50.5	83.7	84.3	81.7	73.2	79.3	83.6	86.7	84	77.2	76.7	78.5	73.8	72.3	71.4	70.2	65.8	62.6	57.5	50.5	37.9	29.9	10.4	-19.7	-62.8
51	80.3	81.1	79.7	73.7	76.4	80.3	83.5	81	75.1	73.3	76.4	72.2	71.4	69.7	67.9	65.8	62	55.9	48.1	35	26.7	6.4	-24.9	-69.8
51.5	80.3	78.9	78.3	74.1	74.8	78	80.8	79	73.5	70.1	73.6	68.6	69.3	68.6	66.2	64.4	60.6	54.4	46.2	32.5	24	2.9	-29.7	-76.3
52	77.9	78.5	77.5	73.4	73.9	77.5	80.5	77.5	72.2	66.6	70.9	65.3	66.6	64.7	63.1	60.7	56.6	51.5	43	28.8	19.9	-2	-35.8	-84.1
52.5	77.7	76.2	76.5	71.3	71.6	77	79.6	77.6	74.2	66.2	72.3	69.7	72.7	67.9	65.8	63.2	60.2	53.6	45.5	30.8	21.6	-1.1	-36.1	-86.2
53	80.4	76.7	75.4	70.6	68.9	75.4	77.7	77.7	74.5	66.3	72.3	70.4	73.2	69.4	67	64.2	60.9	54.4	45.9	30.6	21.1	-2.4	-38.6	-90.5