Model-Based Systems Engineering in the Design and Development of Firearm Suppressors

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***Abstract*—Firearm suppressors play a critical role in reducing noise, flash, and recoil during firearm discharge. However, the design of suppressor systems presents challenges due to the need for precise optimization of acoustics, material science, and gas flow mechanics. This paper presents an integrated approach to the design and evaluation of firearm suppressors using *Model-Based Systems Engineering (MBSE)* and *Systems Modeling Language (SysML) diagrams*. This study applies hypothesis testing to verify the effectiveness of suppressor designs. By integrating MBSE into the systems engineering process, we ensure that design iterations and analyses are conducted systematically, from conceptualization through testing. The effectiveness of suppressors is measured using sound pressure levels (SPL) and evaluated using paired sample t-test which we focus only on statistical significance of noise reduction. This framework demonstrates how MBSE, SysML, and statistical testing improve the design and validation processes of firearm suppressors.**

Keywords—Model-Based Systems Engineering, Systems Modeling Language, firearm suppressor, Design, T-Test

I. INTRODUCTION

Thailand's defense industry has evolved from basic weapon production to high-tech S-curve sectors such as Automotive, Agricultural Biotechnology, Medical and Wellness Tourism, Smart Electronics, and Aviation and Logistics [1][2][3]. Effective engineering management is crucial for navigating these complex areas, particularly in defense, where systems engineering integrates expertise from various disciplines. For instance, developing missile guidance systems requires proficiency in electronics, control and software engineering while solid propulsion systems depend on knowledge of chemistry and materials science. To manage this complexity, the use of modeling tools, such as symbolic diagrams, serves as a visual aid to represent system behaviors, thereby enhancing both communication and comprehension among collaborators.

In this paper, we propose integrating *Model-Based Systems Engineering (MBSE)* and *Systems Modeling Language (*SysML) into suppressor design to improve analysis and optimization. SysML can visually depict system architecture and behavior, leading to better design outcomes. This paper explores the application of systems engineering in the design of firearm suppressors, which are used for noise reduction, flash suppression, recoil mitigation, and gas management. Firearm suppressor are designed to mitigate the noise, flash, and recoil associated with gunfire. The development of suppressor systems requires interdisciplinary collaboration between mechanical engineers, acousticians, material scientists, and system integrators to optimize their performance while ensuring safety, durability, and regulatory compliance. Traditional design approaches rely on prototype-based iterations, which can be expensive and time-consuming. Traditionally, suppressor development depended on expensive physical prototypes. By incorporating statistical methods such as hypothesis testing, alongside *Model-Based Systems Engineering (MBSE)* and *Systems Modeling Language (SysML),* engineers can streamline the design process, optimize performance, and lower costs. MBSE transitions design efforts from document-based methods to digital models, while SysML provides visual representations of component interactions, improving analysis and efficiency [6][7].

II. SYSTEMS ENGINEERING

Systems engineering is an interdisciplinary field focused on managing complex systems throughout their lifecycle, from design to end-of-life, the process ensures that the resulting products are efficiency, durability, and reliability. The process begins with the design of components to fulfill specific requirements, progressing thereafter to development, manufacturing, and the provision of maintenance [8].

The V-shaped model, originating in software development, outlines the product development cycle, including stages like user requirements gathering, the crafting of system and detailed designs, the manufacture of the product, and its eventual testing and acceptance by the user [4].

To simplify communication and reduce complexity, symbolic language is often used. The principles of systems engineering were conceived to unify diverse engineering disciplines, enabling them to function collaboratively as a unity entity. This integration encompasses several critical engineering domains, including mechanical engineering, which focuses on the structural integrity of the designed equipment, ensuring it can withstand the immense pressures and elevated temperatures generated during firearm discharge, while also selecting appropriate materials that guarantee durability and operational reliability. Furthermore, the contributions of aerodynamic engineering are essential for modeling the flow of hot gases produced upon firing, while acoustical engineering is tasked with analyzing the suppression of sound waves, ensuring their effective reduction, and studying the vibrations that could potentially compromise the equipment's performance and accuracy. Additionally, thermal engineering plays a vital role in assessing heat generation to ensure that the temperatures induced by gunfire do not cause damage to the equipment. Material engineering is equally significant in the selection of suitable materials for production. Thus, it becomes evident that the design and development of such a compact yet complex piece of equipment necessitates a comprehensive understanding across multiple engineering disciplines.

III. Background and Literature Review

A. Firearm Suppressor

Suppressors are devices attached to the muzzle of firearms to reduce the noise and muzzle flash produced when a firearm is discharged. Key components include the baffle stack, expansion chambers, and the outer tube, all of which work together to slow down and cool the high-pressure gases that follow the bullet. The efficiency of a suppressor depends on the design of its internal structure, the choice of materials, and the compatibility with different types of ammunition. Suppressors are widely used in military, law enforcement, and civilian shooting sports [9]. They reduce the sound of gunfire to levels that protect hearing and reduce noise pollution. Despite these benefits, suppressors are subject to strict regulations in many countries.

The design of suppressors has been studied in many ways. The study of the importance of suppressors in hearing protection and reducing sound pressure levels during shooting is explained, considering factors such as weight, mobility, and stability. In addition, the article proposes a suppressor that combines the properties of a suppressor and a muzzle brake to reduce noise [11]. The study of the noise associated with rifle shooting and assesses the effectiveness of the suppressor and considers the risk of hearing damage and studies the sound attenuation properties using LES (Large Eddy Simulation) in fluid dynamics calculations [12]. The study of gunshot sound and shooter position estimation is explored, summarizing various phenomena related to gunshot sounds. The study highlights that under controlled conditions, the speed of sound in air increases with temperature, and that the operation of suppressors is influenced by environmental factors such as temperature, humidity, and wind. These factors can affect the efficiency of suppressors in real-world conditions, further emphasizing the complexity of their design and use [13].

B. Model-Based Systems Engineering (MBSE)

MBSE represents a paradigm shift in systems engineering, emphasizing the use of digital models to design and validate complex systems. It enables the integration of various engineering disciplines, improves communication among teams, and supports lifecycle management by ensuring that every phase of the system's development can be traced back to the original requirements.

MBSE eliminates the reliance on traditional document-based processes, allowing teams to simulate, analyze, and verify system designs through digital twins. This approach is particularly effective for systems like firearm suppressors, where acoustic, thermal, and material considerations intersect.

C. Systems Modeling Language (SysML)

SysML is a graphical modeling language designed to support systems engineering. It provides a standardized way to represent *system architecture*, *behavior*, *requirements*, and *parametric relationships*. SysML's wide variety of diagram types, such as *Block Definition Diagrams (BDD), Internal Block Diagrams (IBD),* and *Parametric Diagrams*, make it a powerful tool for visualizing the structure and functionality of complex systems like firearm suppressors [5].

D. SysML language structure

The systems engineering process is different from the manufacturing process that focuses on repetitive activities to produce quality products with less time and cost. However, the systems engineering process is to find problems to solve or classify the causes of problems or issues with high impact. The problem of work complexity can be solved by using a diagram that describes how to work. The UML language has been developed to help describe the relationship of various parts of engineering work, and rather adapted to *System Modeling Language* or *SysML* [5].

The language was developed by Object Management Group to be used as an industry standard for use in systems engineering. This language that helps to describe specific characteristics, design, and verification that cover the steps of systems engineering work from before starting the system or product development to system termination. *SysML* language can be used to describe the system requirements model by considering the behavior, structure and parameter values Parametric. It includes diagrams essential for systems engineering tasks i.e., *Behavior Diagram*, *Requirement Diagram*, and *Structure Diagram* [5][6][7].

IV. Simulation in Firearm suppressor

Suppressors are critical components in firearm systems, engineered to reduce the acoustic signature of a shot by minimizing the noise produced during firing. The effectiveness of a suppressor largely depends on its internal design, specifically the arrangement of baffles, which redirect and dissipate the flow of high-pressure gases to reduce sound. Traditionally, suppressor design has relied on iterative prototyping and empirical methods [12][13][14].

In this section a more systematic approach by incorporating *Model-Based Systems Engineering (MBSE)* into the design process, ensuring that key factors like noise reduction, durability, and ergonomics are considered together from the beginning.

The design of suppressors involves creating a cup-shaped device with internal components that layer and channel the expansion of gases produced during combustion. When a firearm is discharged, the explosion of gunpowder propels the bullet forward, releasing a burst of high-pressure gases. These gases, upon escaping the barrel, compress the surrounding air and create a pressure wave—what we recognize as the sound of a gunshot. A suppressor works by slowing down the expansion of these gases, thereby reducing the intensity of the pressure wave and thus the sound [11][12][13].

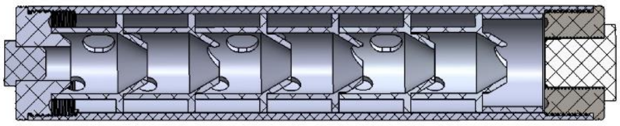

Fig. 1. Illustrate the internal parts of a baffle type firearm suppressor

To optimize suppressor performance, Computational Fluid Dynamics (CFD) plays a pivotal role. CFD simulations provide insights into how gases move within the suppressor, highlighting pressure levels and acoustic properties that are crucial for fine-tuning the internal design as illustrate in the Figure 1. The engineers can enhance the effectiveness of a suppressor by changing the arrangement of the baffles and evaluating how well the suppressor can release or dissipate heat [11].

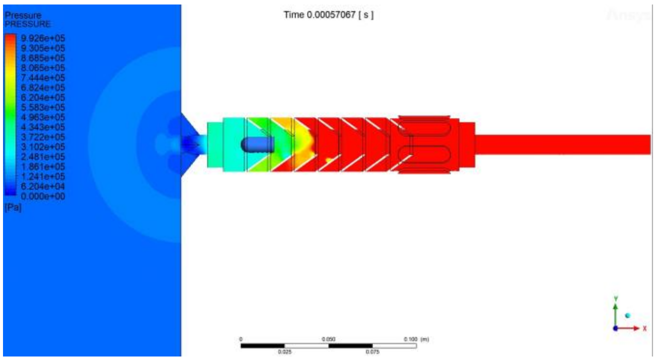

Fig. 2. Illustrate the simulation of pressure of firearm suppressor

V. CASE STUDY: MODELING AND SIMULATING A FIREARM SUPPRESSOR

Suppressors, also known as silencers, are essential components of firearm systems, designed to reduce gunfire noise and enhance operational safety [13]. Traditionally, suppressor design has relied on empirical methods like trial and error, requiring designers to test multiple prototypes to optimize performance. However, this approach is often time-consuming, costly, and inefficient. With advancements in engineering methods, the integration of *Model-Based Systems Engineering (MBSE)* provides a more efficient and systematic approach to suppressor design. MBSE uses models to manage the complexity of engineering systems, ensuring that all design elements are considered from the start [10].In systems engineering and *Systems Modeling Language (SysML),* the Use cases are essential for defining requirements, Modeling behavior, and ensuring traceability in SysML, contributing to successful engineering outcomes as they define functional requirements and enhance communication among stakeholders [8][10].

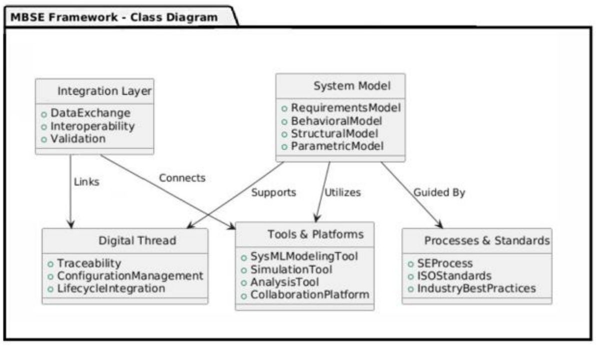

Fig. 3. Illustrate the MBSE Framework as the class diagrams

In accordance with systems engineering principles, it is crucial in the initial stage to understand the specific characteristics of the equipment to be designed. This involves determining the required level of noise reduction, the structure of the equipment, and its components. Additionally, it is important to consider other necessary requirements from relevant stakeholders, such as the weight and length needed for practical use.

The MBSE framework, the suppressor design is based on a structure divided into several chambers called baffles, which store air pressure at specific intervals to reduce the noise generated by the pressure from gun powder combustion. The design process involves breaking down the suppressor into its individual components. The baffle type suppressor typically comprises several key elements that functions together to reduce the noise generated when a firearm is discharged, as shown in the *Structure diagram.*

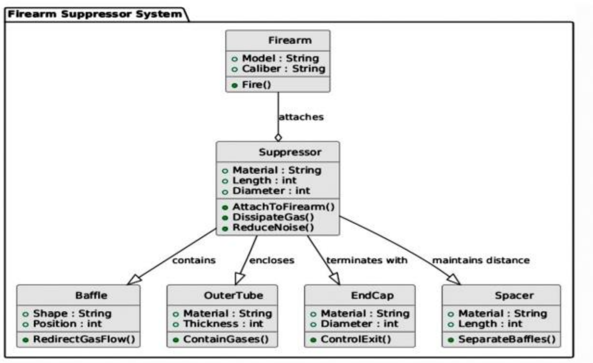

Fig. 4. Illustrate the *Structure diagram* of firearm suppressor

MBSE can be applied to suppressor design, outlining the size, space, configuration, steps involved, and the results obtained, and how diagrammatic models aid in this process.

A. System Requirements and Specifications

The initial step in suppressor design involves defining the system requirements and specifications, and MBSE provides a structured framework for this task. MBSE employs tools like *SysML (Systems Modeling Language)* to capture the critical parameters that a suppressor must meet. These requirements include noise reduction targets, material durability, heat dissipation, weight, and ergonomics. For example, noise reduction may involve achieving decibel (dB) levels well below a specific threshold, while ensuring the suppressor is lightweight enough for practical use in the field.

Through *Requirements Diagrams*, engineers can visually outline these goals, ensuring that the suppressor's design meets all necessary criteria. By capturing these requirements early in the process, MBSE ensures that they guide all subsequent design decisions, reducing the risk of overlooking critical factors [5][6]. This clear definition of requirements leads to a more targeted and efficient design process, ensuring that the final suppressor meets both performance and operational needs.

B. Functional Analysis and Decomposition

Once the requirements are defined, the next step is to break down the suppressor's functions into manageable components. MBSE uses *Functional Block Diagrams (FBDs)* to analyze the system's functions and the interactions between subsystems. In suppressor design, this involves decomposing the system into key functions such as gas redirection, noise attenuation, and heat management as illustrate the *Functional Block Diagrams (FBDs).*

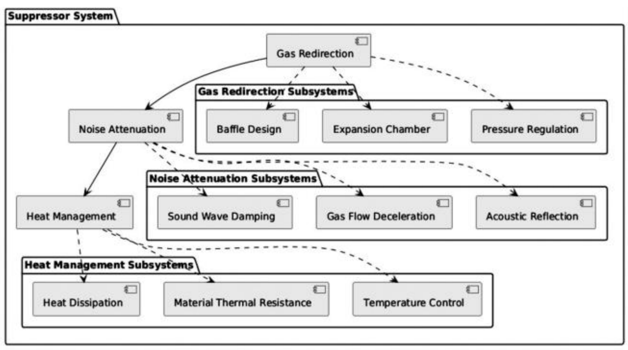

Fig. 5. Illustrate the *Functional Block Diagrams (FBDs)* of firearm suppressor

Each subsystem plays a vital role in suppressor performance. For instance, the baffle stack's primary function is to slow down and redirect the gases generated by gunpowder combustion, reducing the pressure wave that creates noise. The heat management subsystem ensures that the materials can withstand the high temperatures generated by repeated use.

MBSE's functional analysis ensures that each of these functions is optimized, and by breaking them down, engineers can focus on improving the interaction between components. For example, altering the baffle design to optimize gas redirection can improve noise suppression without increasing the suppressor's weight. This detailed functional decomposition helps pinpoint design trade-offs and allows for precise modifications, leading to a more effective overall design.

C. Component Design and Interaction

One of the critical challenges in suppressor design is optimizing the baffle stack—the internal structure responsible for controlling the flow of gases. MBSE uses *Internal Block Diagrams (IBDs)* to model the relationships between components, helping engineers visualize how each baffle interacts with the gas flow and how changes in one component affect others as illustrate in Figure 6.

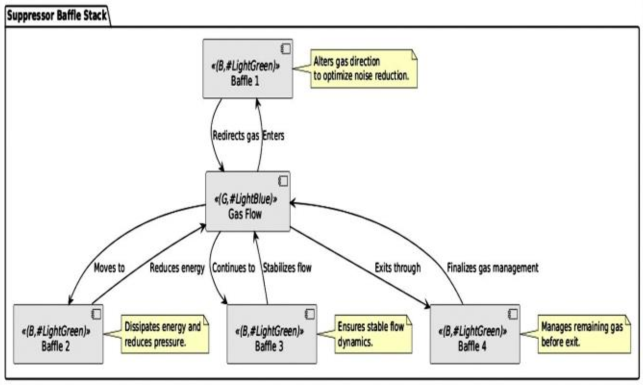

Fig. 6. Illustrate the *Internal Block Diagrams (IBDs* of firearm suppressor

At this stage, Computational Fluid Dynamics (CFD) simulations are incorporated into MBSE models to evaluate the flow of gases within the suppressor. Analyzing gas movement, pressure distribution, and heat dissipation throughout the baffle stack allows engineers to optimize the internal geometry of the suppressor for improved noise attenuation. For instance, simulations enable the examination of various baffle designs, materials, and configurations to identify the most effective arrangement for noise reduction, while simultaneously ensuring the device's durability under diverse firing conditions.

Parametric Diagrams are used to specify and analyze constraints and performance characteristics of systems or system components. These diagrams focus on defining mathematical or logical relationships between system parameters, enabling the verification and optimization of design requirements, performance, and behavior [5].

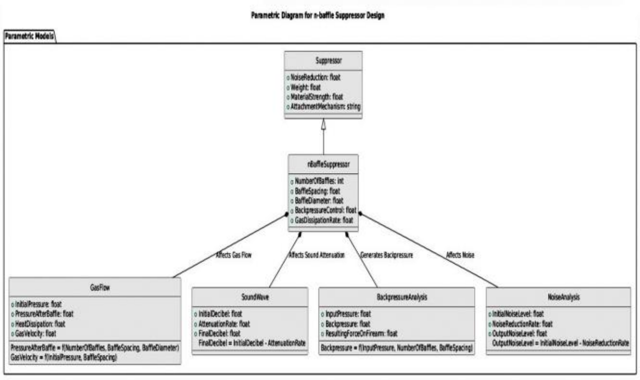

Fig. 7. *Parametric diagrams* of firearm suppressor

Parametric Diagrams are integral to model-based systems engineering (MBSE), as they provide a clear and structured way to represent the functional performance of systems within the context of engineering requirements [5][6].

VI. Hypothesis Testing of Firearm Suppressors

Designing firearm suppressors constitutes a highly intricate engineering challenge, necessitating meticulous attention to various factors, including noise reduction, durability, thermal management, and recoil control. To develop efficient and effective suppressors, designers use hypothesis testing, a statistical method that helps validate design modifications and the assessment of their impact on system performance. Hypothesis testing serves as a pivotal tool in the engineering design process, as it empowers engineers to make data-driven decisions, ensuring that modifications to baffle configurations are not only scientifically valid but also practically beneficial. This approach is indispensable within the engineering framework, as it ensures that decisions are grounded in empirical evidence, thereby guaranteeing that the alterations to the suppressor's internal arrangement enhance both performance and functionality.

A. Experimental Design for Suppressor Testing

To proof that there are statistically significant differences between the means of different groups or conditions. The suppressor has been adjusted to configure the baffles in two different forms for testing and comparison. A statistical hypothesis test is conducted to determine whether the design meets the objectives. To test the effectiveness of different suppressor designs, we measure the sound pressure level (SPL) emitted by the firearm in both suppressed and unsuppressed states. The two different configuration suppressor are tested under controlled conditions.

Fig. 8. The configuration of sound intensity measurement in the field

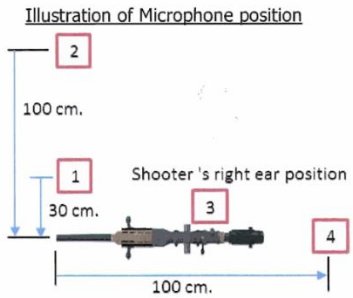

Fig. 9. The microphone configuration for measurement

Average dB Comparison

Mic Number	No Sup (dB)	Type 1 sup (dB)	Type 2 sup (dB)
Mic 1	156.6	139.9	141.3
Mic 2	156.5	131.7	132.9
Mic 3	156.6	133.1	134.2
Mic 4	152.6	125.9	128.0

Fig. 10. Measurement data according to the configuration of microphone

The SPL is recorded using a calibrated sound level meter placed at a standard distance from the firearm, and the results are averaged from 32 shots for each condition. The configuration of sound intensity measurement as in Figure 8 and 9 and the results of sound level at a shooter right ear position in decibels (dB) are presented in the table (Figure 10). In order to interpret the results obtained from the design and testing phases, we use statistical hypothesis testing as a tool to assess whether the performance of the designed device meets the specified criteria. The two sample t-test is applied as the data exhibits a normal distribution.

B. Hypothesis Testing

Considering that two distinct types of suppressors were tested. To compare the measured values effectively, a paired sample t-test is a statistical method used to evaluate if there are significant differences across the means of two groups [17][18][19]. In general, a gunshot produces a noise level of around 156.6 dB, which is higher than the military safety limit of 140 decibels to prevent hearing damage [15][16]. Therefore, the suppressor must be designed to reduce the noise by at least 16.6 decibels, or about 10.60 percent. This reduction serves as the baseline assumption for hypothesis testing to evaluate the suppressor's performance at 90% confident level.

Null Hypothesis (H_0): The mean noise reduction of the suppressor is less than or equal to 10%

$$H_0: \mu \leq 10\% \quad (1)$$

Alternative Hypothesis (H_1): The mean noise reduction of the suppressor is greater than 10%

$$H_1: \mu > 10\% \quad (2)$$

From these measurements, we calculated the percentage reduction in noise levels for each suppressor as follows:

- Type 1 Suppressor: 15.00 % reduction
- Type 2 Suppressor: 14.30 % reduction

Clearly, all suppressors achieved a noise reduction exceeding 10%, with the Type 1 suppressor demonstrating the highest reduction of 15.00%. A paired-sample t-test comparing the unsuppressed firearm to the firearm with the Type 1 suppressor revealed a highly significant p-value (4.49×10^{-50}), leading to the rejection of the null hypothesis (H_0). This provides strong evidence that the mean noise reduction achieved by the Type 1 suppressor exceeds 10%. Similarly, hypothesis testing for the Type 2 suppressor yielded a highly significant p-value (5.67×10^{-41}), further supporting the conclusion that its mean noise reduction also surpasses 10%.

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CONCLUSION

Symbolic diagrams play a crucial role in engineering management by simplifying the representation and comprehension of complex systems. The progression from early *Entity-Relationship (ER) diagrams* to advanced modeling languages such as *SysML* reflects the significant advancements in developing tools that meet the needs of contemporary engineering. The use of these symbolic languages allows engineers to manage and communicate intricate system designs more effectively, thereby enhancing project efficiency and outcomes.

This paper explores the application of *Model-Based Systems Engineering (MBSE)* and *SysML* in the design and analysis of firearm suppressors. By employing SysML's structural and behavioral diagrams, we can create detailed models of suppressor components and their interactions. Furthermore, the application of the paired sample t-test provides a rigorous method for evaluating the performance of suppressor designs. Integrating MBSE with statistical analysis ensures that the suppressor design is both optimized and validated through a data-driven approach, forming a comprehensive framework for suppressor development.

The visualization and simulation of the suppressor's structure, behavior, and interactions with external systems enable engineers to develop more effective and efficient suppressors while meeting key performance requirements. This system-based methodology not only enhances the technical design process but also promotes seamless collaboration among multidisciplinary teams, resulting in more robust and innovative solutions in suppressor technology.

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