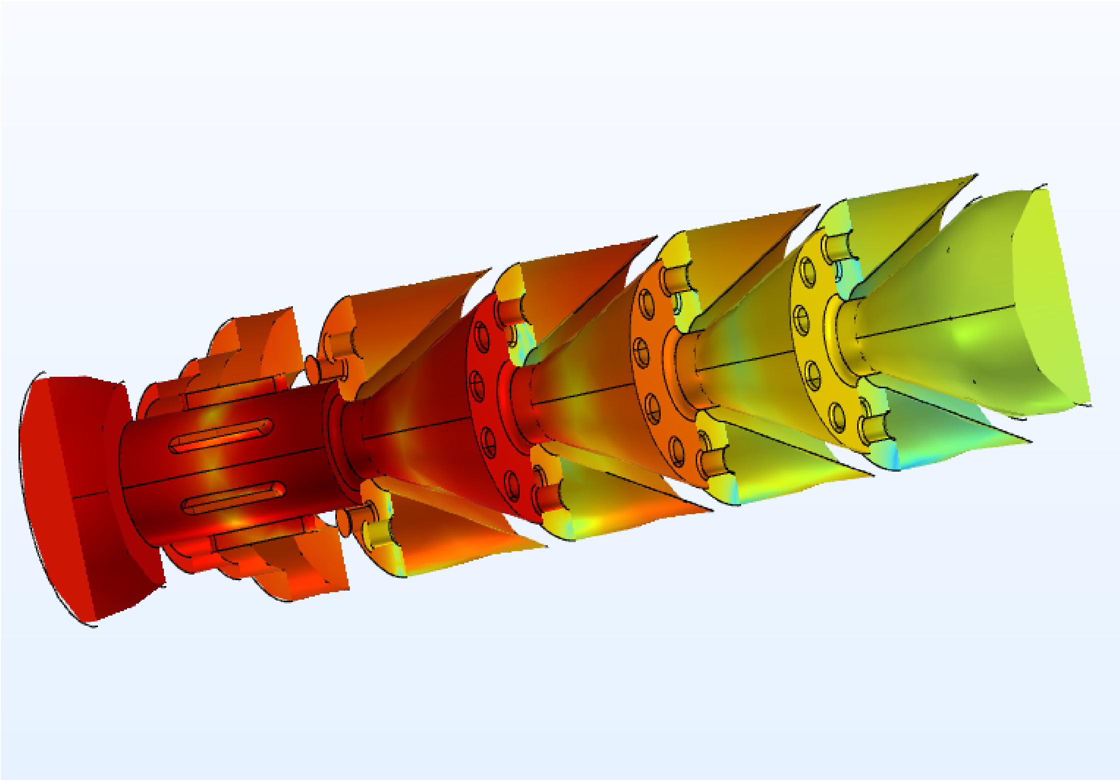

NVH Improvement in D4/D6 Marine Diesel Engines

Design Change Proposals to reduce Noise and Vibrations in the D4 and D6 engines

Master's Thesis in Product Development

Yeshwanth Kirupakaran

DEPARTMENT OF MECHANICS AND MARITIME SCIENCES

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2023
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Master's thesis 2023

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Cover: Decrease in Sound Pressure Level as the exhaust gasses flows through a silencer.

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Abstract

Noise, Vibration and Harshness (NVH) in marine diesel engines has gained recent attention, and many outboard competitors have shown significant improvements in this area. Optimal NVH standards ensure enhanced performance, environmental sustainability, and passenger comfort. This thesis aims to comprehensively investigate the NVH sources, their characteristics, and mitigation strategies in Volvo Penta's D4 and D6 marine diesel engines.

The research methodology adopts a multi-faceted approach, addressing various sources of noise. Through an extensive literature review and the development of a noise source separation algorithm, key factors influencing engine NVH and exhaust noise generation were identified. This is complemented by an in-depth user and stakeholder study, which includes numerous interviews and focus group responses.

The outcome of this research laid the groundwork for proposing effective requirements and functions for NVH reduction. Several concepts were synthesized and compared. The most promising solution is further developed and simulated for acoustics and vibro-acoustics. The implications of these findings are profound, as reducing engine NVH and exhaust noise emissions not only enhances passenger comfort but also complies with strict regulatory requirements regarding noise pollution and emission standards in maritime environments.

Keywords: marine diesel engines, noise, vibration, NVH, exhaust noise, signal processing, computational simulations, passenger comfort, regulatory requirements, environmental sustainability.

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I am indebted to the participants of this study, whose willingness to share their time, knowledge, and experiences has made this research possible. Their insights and perspectives have enriched the findings and have been crucial in achieving the objectives of this thesis.

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To everyone who has contributed, directly or indirectly, to the completion of this master thesis, I offer my heartfelt thanks. Your support, encouragement, and belief in my abilities have been instrumental in making this research a reality.

Yeshwanth Kirupakaran, Gothenburg, June 2023

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

NVH	Noise, Vibration and Harshness
DSP	Digital Signal Processing
EMD	Emperical Mode Decomposition
EEMD	Ensemble Emperical Mode Decomposition
TVFEMD	Time Varying Filter Emperical Mode Decomposition
ICA	Independant Component Analysis
FFT	Fast Fourier Transform
PSD	Power Spectral Density
CRDI	Common Rail Diesel Injection
SPL	Sound Pressure Level
RPS	Rotations per Second
IMF	Intrinsic Mode Functions
IPS	Inboard Propulsion System

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1
Introduction

This chapter begins with an introduction to the company, followed by an exposition of the contextual background of the problem. It then specifies the project's objective, which includes both a problem statement and a mission statement. Subsequent sections delineate the research questions that underpin the literature review. The scope and constraints of the project are also explained. The chapter concludes with a brief summary of the report's contents.

1.1 Volvo Penta AB

Volvo Penta, a subsidiary of Volvo Group, which specializes in the design, manufacturing, and supply of marine and industrial engines. With a strong focus on quality and performance, they provide an extensive range of engines and propulsion systems for diverse applications. [1]
In the marine sector, Volvo Penta offers a comprehensive selection of inboard and outboard engines tailored for both leisure and commercial vessels. Renowned for their exceptional performance, fuel efficiency, and reliability, these marine engines cater to various boat types such as yachts, powerboats, sailboats, and workboats. To enhance the boating experience, Volvo Penta also provides an array of controls, instruments, and accessories. Volvo Penta has spearheaded multiple pioneering advancements within the marine engine sector, such as the introduction of the sterndrive unit, the "Duoprop" with contra-rotating propellers, and the "Forward Drive System". [1]
Volvo Penta maintains a strong commitment to sustainability and actively engages in the development of environmentally friendly solutions. They have been actively involved in pioneering hybrid and electric propulsion systems for marine applications, contributing to the reduction of emissions and the overall ecological impact of the industry.

1.2 Background

Volvo Penta's diesel aquatic drivelines exhibit a greater degree of noise emissions when compared to similar outboard diesel engines produced by competitors, particularly when idling or operating at low speeds. It is also imperative for Volvo Penta to ensure compliance with the upcoming EU regulations governing underwater noise levels. [2]

The purpose of this thesis is to help Volvo Penta identify the reason behind higher noise levels in their current D4 and D6 engines, and to conceptually redesign this engine to be more silent while maintaining performance.

1.3 Aim

The goal of this thesis is to develop technical and feasible solutions for improving perceived Noise, Vibration and Harshness (NVH) for the D4 and D6 engines in physical applications, and present the best solution out of an environmental, economic, and technical perspective. To provide more lucidity, the problem is presented in a comprehensible manner, and a mission statement was formulated as seen below in Table 1.1.

Problem Statement: *How to identify the noise producing parts of the engine, and how to reduce the perceived noise and vibration from these parts of the engine?*

Mission Statement: D4 and D6 Engine Enhancements	
Product Description	• Engine enhancements to the D4 and D6 engines to reduce NVH.
Benefit Proposition	• Lower perceived noise of the engine. • Lower vibrations on the boat making usage more comfortable. • Lower underwater noise as well as exhaust noise.
Key Business Goals	• Compete with outboard engines in terms of NVH. • Increase customer satisfaction. • Raise the standard of marine diesel engines.
Primary Market	• All current and future boat owners. • Boat rental agencies.
Constraints	• Engine cast cannot be changed. • Flammable material cannot be used on the engine.
Stakeholders	• New and Existing Customers • Retailers • Penta Employees • Manufacturing Supply Chain

Table 1.1: Mission Statement for the Product Development Process

1.4 Research Questions

1. What is the difference between sound levels of current Volvo Penta engine and competitors outboards engine?
2. What is the impact of Volvo Penta's Clear Wake technology, and its' feasibility in other engines?
3. How to reduce noise and vibration caused by bubbles formed during idling?
4. The engine has many noise producing parts which needs to be evaluated separately. This includes the oil pump, gears in the engine, high pressure fuel pump, turbine side of the turbocharger, cylinders, belt drives, etc. How much noise is produced by each of these parts, and what frequencies are dominant in them?
5. How to model the engine in an FEA software to simulate vibration and noise produced by the engine. How to perform simulations of the current as well as improved version of the engine.
6. There is no encapsulation for the engine, which is common in the automobile industry. What will be requirements for such an engine encapsulation?
7. At higher speeds, the engine mounts do not provide enough suspension to isolate vibrations from the body of the boat. This is also one of the big differences between inboards and outboards. How to evaluate and fix this problem?

1.5 Scope and Limitations

This improvement study will only focus on the D4 and D6 aquamatic sterndrive engines, although other versions will be looked at for inspiration. The scope of the thesis project was further narrowed after collecting information about the thesis. This will be mentioned in the subsequent chapters.

1.6 Overview of the Report

This report begins by discussing the theory related to this thesis project, and contains relevant information that is pertinent to understanding the problem and its solutions. Subsequently, the methodology employed during the course of this project is detailed, which provides information on all the methods that were used to execute the project. The following chapter focuses on the results obtained from the aforementioned methods, offering an explanation as to why they are relevant and describing how these results have influenced the project's progress. Finally, the conclusion chapter sums up the entire thesis project and provides details about proposed future plans.

1.7 Planning

A project plan was developed with the aid of a Gantt Chart, as illustrated in Figure 1.1. The Gantt Chart provides a visual representation of the project's timeline, detailing the sequence and duration of individual tasks.

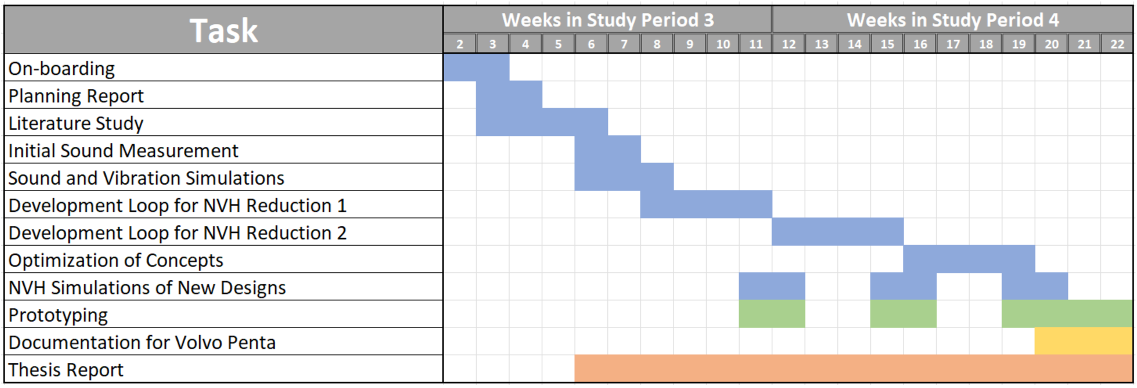

Figure 1.1: Project Timeline

2

Theory

This chapter contains brief theory behind some of the major methods and tools used during the course of this thesis.

2.1 Digital Signal Processing (DSP)

Digital Signal Processing (DSP) is a field that involves the manipulation, analysis, and transformation of digital signals through mathematical algorithms and computational techniques. It focuses on processing signals that have been converted from analog to digital form. DSP finds applications in diverse areas such as audio, video, communications, radar, and medical imaging. [3]

2.1.1 Empirical Mode Decomposition (EMD)

The Empirical Mode Decomposition (EMD) approach is designed to analyze fluctuating and complex data. One of EMD's standout features is that it pulls its foundational elements straight from the data it's examining, allowing for a more flexible analysis. This is different from older techniques that rely on predetermined patterns. EMD's process involves breaking down the data's energy based on its inherent time patterns, moving from the quickest changes to the slower ones. When you combine all these broken-down elements, they align closely with the original data. Each of these elements captures the primary rhythm found in the remaining data. EMD's versatility has made it useful in a range of fields, with its ability to adjust to the data being a major strength. This approach hones in on the specific timing patterns in the data, leading to a tailored analysis. [4]

2.1.2 Ensemble Empirical Mode Decomposition (EEMD)

EEMD is a more advanced extension of the previously mentioned EMD. It was developed to address the issues associated with EMD, which struggles with noise in the data and when the data changes over time.
EEMD has a randomization technique which enhances the robustness of the decomposition process. In this method, the input signal is decomposed multiple times, each time with the addition of a slightly different realization of random noise. By performing this ensemble decomposition, the influence of random fluctuations is averaged out, resulting in more accurate and consistent underlying modes. [5]
The EEMD algorithm follows these steps:

- Random noise is added to the input signal.
- Empirical Mode Decomposition is performed on the noisy signal to obtain Intrinsic Mode Functions (IMFs).
- The above steps are repeated for multiple iterations, with each iteration using a different realization of random noise.
- The IMFs obtained from each iteration are averaged to derive the final IMFs.

By employing EEMD, the decomposition process becomes more robust and less sensitive to noise and data variations. This technique is particularly effective in handling noisy or non-stationary signals, where traditional EMD may yield inconsistent results. The decomposition of a signal using EEMD enables the identification and analysis of distinct frequency components or modes present in the signal. This has widespread applications in fields such as signal processing, time series analysis, and biomedical engineering, where understanding underlying oscillatory patterns is essential for extracting meaningful insights from complex data. [5]

2.1.3 Time-Varying Filter Empirical Mode Decomposition (TVFEMD)

The Time-Varying Filter Empirical Mode Decomposition (TVFEMD) represents a refined version of the EMD, specifically designed to enhance the decomposition of signals that change over time. This is achieved by integrating a time-varying filter, a departure from the conventional EMD that relies on a static filter. The dynamic nature of the filter in TVFEMD allows it to adjust in response to the signal's progression, ensuring a more accurate decomposition that captures the nuances and shifts of the foundational modes.[6]
In the TVFEMD methodology, the signal undergoes a series of iterative processes. During each iteration, the adaptive filter is applied to varying segments of the signal. This systematic approach aids in isolating the Intrinsic Mode Functions (IMFs), which are indicative of specific oscillatory behaviors or time scales present in the signal during certain periods. Consequently, TVFEMD proves effective in dissecting signals characterized by non-stationarity, encompassing those with fluctuating frequencies or amplitude shifts.[6]
Utilizing TVFEMD to dissect a signal that changes over time into its foundational IMFs provides researchers with a deeper understanding of the primary elements influencing the signal's overarching behavior throughout its duration. Such insights are invaluable in domains like signal processing, the study of vibrations, and the monitoring of structural integrity. In these fields, a nuanced grasp of how phenomena change over time is pivotal for a comprehensive understanding of system behaviors.[6]

2.1.4 Independent Component Analysis (ICA)

Independent Component Analysis (ICA) stands as a prominent method in signal processing, designed to disassemble combined signals back into their original, separate components. This can be likened to deducing individual ingredients from a blended dish.

When dealing with signals, ICA is employed to unravel a collection of overlapping signals that have been recorded at the same time. Imagine several musical instruments playing together; ICA aims to identify and isolate each instrument's unique sound from this collective noise. This separation hinges on the premise that the original sound sources are not correlated with one another, much like identifying distinct fruits within a mixed fruit bowl. [7]
To achieve this separation, specific filters are identified. When applied to the combined signals, these filters facilitate the extraction of the individual components. At the heart of ICA is the notion that the individual components have distinct statistical characteristics, setting them apart from the combined signals. Harnessing these statistical differences, ICA effectively isolates the original sources from their amalgamated form. [7]
The versatility of ICA is evident in its myriad applications, spanning from audio and image processing to intricate data analysis. It proves invaluable in situations where various sources overlap, and the challenge lies in pinpointing and retrieving the original, uncorrelated components. This process paves the way for a deeper exploration and comprehension of the foundational data.

2.1.5 RobustICA

RobustICA, or Robust Independent Component Analysis, stands as a method designed to disentangle combined signals, revealing their foundational independent elements. It's a tool of choice in diverse domains like signal processing, brain studies, and image interpretation. At its heart, RobustICA seeks to pinpoint independent elements that account for the observed intermingled signals. Throughout its operation, the technique iteratively isolates these signals, all the while reducing the impact of any disruptive noise or anomalies. [8]
The journey starts with an initial guess of the independent elements. This guess is methodically honed until it aligns closely with the true sources. With every cycle, the method amplifies the non-Gaussianity of the isolated signals, a metric indicative of their statistical independence. To counteract the effects of noise or anomalies, RobustICA integrates a resilience metric, ensuring results aren't skewed by a single anomalous data point. This adaptability equips the method to manage a broad spectrum of signal varieties. [8]
RobustICA's endgame is to unveil independent elements that mirror the foundational sources from the initial combined signal. Its utility is evident across sectors, from voice recognition and image interpretation to financial data scrutiny. The technique shines especially in contexts riddled with pronounced noise or data anomalies, situations where conventional ICA methods might falter. [8]

2.1.6 Fast Fourier Transform (FFT)

The Fast Fourier Transform (FFT) is a fundamental algorithm in signal processing, designed to efficiently convert a signal from its time domain to the frequency domain. This transformation allows for the identification of the distinct frequencies that constitute a given signal, along with their respective amplitudes. By segmenting the time-domain signal into smaller portions and analyzing each individually, the FFT provides a comprehensive depiction of a signal's frequency content. Its application is pivotal in various fields, from audio spectrum analysis to telecommunications, enabling the extraction of intricate details and patterns within complex data sets. [9]

2.2 Marine Engine

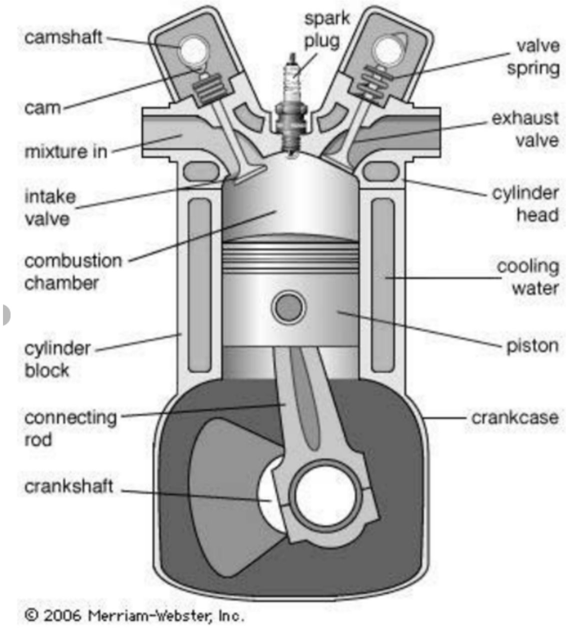

Figure 2.1: Cross Section of an Engine Piston, taken from Merriam-Webster

Marine diesel engines are specialized internal combustion mechanisms tailored for powering nautical vessels. Their functionality hinges on a series of critical phases that transform fuel energy into mechanical force. A general piston design is shown in Figure 2.1, where the different ports and parts of the piston are seen. Delving into the mechanics of a marine diesel engine:

- Air Intake: The cycle commences with the piston descending, generating a vacuum in the cylinder. This action pulls in fresh air via the intake valves, filling the combustion chamber.
- Air Compression: The piston's upward trajectory compresses the entrapped air, elevating its temperature and setting the stage for efficient combustion. Diesel engines, with their high compression ratios, optimize fuel burn.
- Fuel Injection: Approaching the culmination of the compression phase, fuel is meticulously sprayed into the cylinder. The atomization of the fuel ensures its thorough amalgamation with the compressed air, with the engine's injection system dictating the timing and volume of fuel delivery.
- Combustion and Power Generation: The elevated temperature and pressure conditions within the cylinder spontaneously ignite the fuel. The ensuing com-

bustion propels the piston downward, translating the energy from the ignited gases into mechanical force.

- Exhaust Release: Post the power generation, the piston's upward motion expels the combustion residues via the exhaust valves, which are then channeled out through the engine's exhaust infrastructure.
- Cycle Continuation: This four-phase sequence—intake, compression, combustion, and exhaust—is perpetually reiterated, ensuring uninterrupted power production. Each turn of the engine's crankshaft signifies a full cycle for every cylinder.

The linear motion of the pistons, resulting from this process, is relayed to the crankshaft. This apparatus then morphs the pistons' to-and-fro movement into a rotational one. This rotation is subsequently relayed to a propulsion mechanism, a propeller in this case, producing the necessary thrust to navigate the vessel through aquatic terrains.

Typically, marine diesel engines utilize heavy fuel oil, necessitating meticulous filtration, heating, and combustion regulation. To counteract overheating, cooling systems, utilizing either seawater or freshwater, are integrated. Additionally, lubrication mechanisms are in place to minimize friction between mobile components, ensuring the engine's longevity.

2.2.1 Vibration Order

Engine vibration order denotes the relationship between the frequency of vibrations and the engine's rotational speed. This metric is pivotal for discerning and categorizing distinct vibration trends stemming from diverse engine components. To elucidate; engines, during their operation, harness the combustion process to produce rotational movement. This movement, in turn, can instigate vibrations across various engine elements, including but not limited to the crankshaft, pistons, and connecting rods.

Typically, the vibration order is articulated as a factor of the engine's speed of rotation. A first-order vibration mirrors the engine's rotational frequency. To illustrate, an engine functioning at 600 RPM would exhibit a first-order vibration frequency of 600 cycles per minute or 10 Hz. Subsequent vibration orders manifest at frequencies that are integral multiples of the engine's speed. For instance, in an engine operating at 600 RPM, a second-order vibration would resonate at 1200 CPM or 20 Hz, while a third-order vibration would resonate at 1800 CPM or 30 Hz.

By scrutinizing an engine's vibration order spectrum, specific vibration frequencies and their associated orders can be understood. Grasping vibration orders is imperative for the effective diagnosis and mitigation of engine-related challenges. Through a detailed frequency and order analysis, the origins of disruptive vibrations can be traced, and corrective actions can be implemented, whether that entails realigning components, substituting degraded parts, or undertaking comprehensive maintenance. Such proactive measures ensure optimal performance of the engine and diminished NVH.

2.2.2 ClearWake Technology

In the latest line of IPS drives at Volvo Penta, when operating at lower speeds or when idling, Clear Wake system activates. It redirects the exhaust directly to the air instead of causing underwater bubbles. This results in lower bubbling noise and lower vibrations caused by bubbles hitting the hull of the boat.[10]
This makes the water surrounding the boat less disturbing, and helps maintain calm waters during docking as well. This is activated automatically when the engine reaches below a certain RPM, and remains activated till the engine RPM goes beyond this threshold. Once the engine RPM has crossed this threshold, the bypass valve closes and the gasses are redirected to the underwater exhaust, which keeps noise levels low.[10]

3
Methods

This chapter introduces the methods used in this thesis project, and gives a brief description of how each method was used in context of this thesis.

3.1 Literature Study

To answer the research questions stated in Section 1.4, a comprehensive and concise literature study was conducted. This included studying how the engine works, points of interest in the engine, functionality of the major parts of the engine, material flow in and out of the engine, and previous studies and experiments conducted on the engine. All of this was made available by Volvo Penta, and field experts at the company were contacted to get specific reports and data for certain key areas of concern. Some research papers were reviewed to find correlation between the problem at Penta and other engine manufacturers. This was carried out with the information search which is explained in Section 3.2.1.

3.2 Customer Needs Study

The Customer needs study was conducted to identify elements of the product that motivates a customer to buy or use the engine. This study provided valuable insight about what specific feature is important to the customer base, which is called critical needs of the customers. This information would be beneficial for the company to make decisions about what changes are needed in the engine to better satisfy the customers' expectations. A happy customer base could increase the demand for the product, which would increase the revenue generated by the product, which leads to further investment by the company to innovate the product. Furthermore, a good customer needs study could reveal latent needs of customers, which are difficult to find by studying the engine.
The details of the customers needs study has been explained in detail in the following sub-sections.

3.2.1 Information Search

As described by Denscombe,

"An information search aims to arrive at a conclusion about the state of knowledge on a topic based on a rigorous and unbiased overview of all the research that has been undertaken on that topic." [11]

In other words, information search is conducted to educate oneself about unknown technologies and methods that may be relevant to answer the research questions and to complete the thesis. This process must be systematic, rigorous and repeatable so that the collected information could be studied and reviewed by anyone interested in the project.[11]

Two kinds of information sources were used to gather data: [12]

- Primary Information Source - Information that was gathered primarily by the author. This includes data gathered from interviews, study visits, questionnaires, focus groups, and operating the product.
- Secondary Information Source - Information gathered by reading reports, articles, journals, websites, and research papers. This information was gathered by people not involved in this project, yet could prove useful for the completion of the project.

3.2.2 Qualitative Methods

Methods for collecting qualitative data serve as research tools designed to acquire non-quantitative or subjective information. These methods aim to offer a deep understanding, capture diverse viewpoints, and investigate complex issues. The following outlines prevalent techniques for qualitative data collection:

- **Conversational Interviews:** In the realm of qualitative inquiry, interviews consist of guided dialogues between the investigator and the study subjects. These can be categorized as structured, semi-structured, or open-ended. While structured interviews rely on a fixed set of queries, semi-structured ones blend these with spontaneous discussions, and open-ended interviews are more free-form. Interviews are instrumental in probing into the participants' beliefs, lived experiences, and viewpoints. In this project, interviews were conducted with employees of Volvo Penta working closely with the D4 and D6 engines, engineers who test these engines, the sales team at Volvo Penta, a shopowner that sells these engines in boats, and boat owners. In total, there were two formal interviews with product development engineers, and conversational questions were raised to over ten engineers at different roles inside Volvo Group. Other than this, a couple of informal interviews were conducted with test engineers at Volvo Penta.
- **Focus Groups:** These consist of a small assembly of individuals (typically between 6-10) who deliberate on a designated subject. A trained facilitator steers the conversation, prompting participants to divulge their thoughts, past experiences, and ideas. The strength of focus groups lies in the richness of data obtained through collective interaction and shared perspectives. Fellow classmates and boat owners were reached out to for conducting focus group discussions. There were attendees at the first focus group discussion, and four participants during the second time.

- **Field Observations:** This approach involves the methodical watching and recording of actions, interpersonal dynamics, and occurrences in their authentic environments. Researchers may opt for either active engagement in the setting being observed, known as participant observation, or a detached role, termed non-participant observation. These observations yield crucial insights into societal interactions, cultural norms, and behavioral trends. The working of the engine was observed, both during test rig runs and real use in boats.
- **Content Examination:** This entails the scrutiny of textual, visual, or multimedia materials, such as official documents, images, videos, or historical archives. The aim is to understand historical backdrops, institutional procedures, cultural relics, or narrative structures. This method can function independently or complement other qualitative strategies. Previous tests and research done on the D4 and D6 engines were studied, comparison videos were viewed online, and the engine manual was examined thoroughly.
- **In-Depth Case Analysis:** This involves comprehensive scrutiny of particular subjects, groups, institutions, or scenarios. Data is amassed from diverse avenues, including but not limited to interviews, field observations, and content examination, to offer a holistic understanding of the subject matter. Case studies facilitate the exhaustive investigation of intricate issues within their actual settings.
- **Exploratory Surveys:** Although surveys are generally linked with quantitative studies, they can also feature open-ended queries to amass qualitative information. These questions permit respondents to articulate detailed answers, thereby allowing researchers to garner rich, qualitative insights in addition to numerical data.

Qualitative data collection techniques provide a layered, contextual, and intricate comprehension of human experiences, conduct, and social intricacies. Often, researchers utilize a blend of these methods to cross-verify data, thereby bolstering the reliability and authenticity of their conclusions.

By using qualitative data collection methods, all the customers, users and stakeholders were identified by conducting interviews with field experts, customer relations department at Penta, customers, and users of the engine. The users were split into six categories:

- Primary User: These are users who directly interact with the product and experience all the features and problems first hand.
- Secondary User: These users own the product, and use the product to provide a service. If any problem exists, they usually get this information from one of their customers using the product.
- Tertiary User: Users who maintain the functionality of the product instead of using it directly are called tertiary users.
- Lead User: A lead user is a person who is highly knowledgeable about the working of the product and uses the product frequently. These kind of users are very important to customer studies as they can give clear and concise statements about issues with the product and can also suggest possible solutions to these problems.
- Extreme User: There are people who use the product in the harshest way

possible, or use the product in dire conditions where the product has the lowest tolerance.

- Typical User: People who use the product as it was designed to be used are called typical users.

3.2.3 Quantitative Methods

Quantitative methods serve as organized instruments for collecting data in numerical form. These methodologies enable the measurement of various aspects, which are then transformed into numbers for subsequent mathematical analysis. The ensuing techniques are employed:

- **Conducting Surveys:** Questionnaires are distributed among groups of individuals, featuring questions with multiple-choice options or open-ended responses. This process occurs through online platforms, telephone interactions, or written surveys. Its purpose is to gain insights into people's thoughts, emotions, and actions. Surveys were sent out to several departments of Volvo Penta, and boat owners.
- **Insights from Controlled Experiments:** Controlled scenarios are designed to observe how changes influence outcomes. Individuals might experience different conditions, allowing researchers to compare their reactions. This practice is common in fields like psychology, medicine, and social sciences.
- **Using Pre-existing Data:** Existing datasets collected by other parties are examined to unveil fresh perspectives or validate prior discoveries. Such data sources encompass surveys, reports, and organizational records.
- **Identifying Patterns through Data Mining:** Computer algorithms are employed to unveil concealed patterns within extensive datasets. This method finds utility in domains like marketing, finance, and healthcare, aiding in informed decision-making. Noise and temperature data from the D4 and D6 engines was studied and represented in several graphs for easy understanding.

These methods yield precise numerical results, permitting the application of mathematical analysis and facilitating discussions about large participant groups. Often, these techniques are combined with alternative research approaches to achieve a comprehensive understanding.

3.3 Pre-Development Study

To understand the different noise sources in the engine, an algorithm was developed to separate the noise sources in the engine. The algorithm uses the statistical analysis concepts of TVFEMD and RobustICA to mathematically find component sources from a mixed signal. The signal is supplied as a .wav audio file, and the algorithm iteratively separates all the main noise sources. The code was developed in python and can be found in Appendix A.

3.4 Product Development Methodology

Out of the four types of Product Development projects that are mentioned by Ulrich et al. [13], this thesis can be categorized as an "incremental improvements to existing products" project. This section will explain the methodology used during the product development cycle following the guidelines stated in Ulrich et al. [13]. The customized process flow for this project is shown in Figure 3.1.

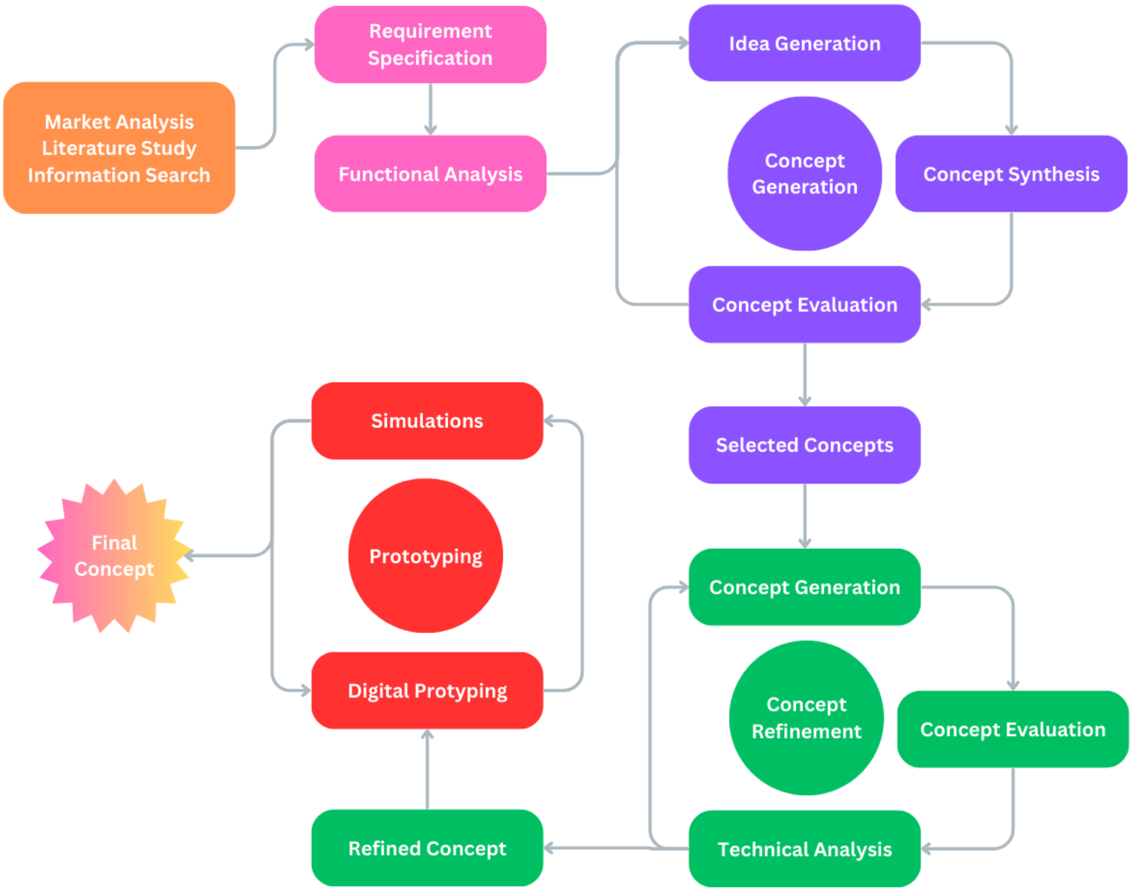

Figure 3.1: Process Flow Diagram

3.4.1 Requirement Specification

The requirements specification plays two crucial roles in product development:

1. Guiding the solution generation process: It provides a clear direction and framework for developing solutions. By outlining the specific requirements and objectives that the product needs to fulfill, it helps steer the development process towards meeting those goals. This ensures that the solutions generated are aligned with the desired outcome. [14]

2. Providing normative information for evaluation: The requirements specification serves as a benchmark against which the developed product can be evaluated. It

defines the normative criteria and standards that the product must meet in order to be deemed successful. By referring to the requirements specification during evaluation, the product can be objectively assessed to determine if it fulfills the specified requirements. [14]

3.4.2 Functional Analysis

In a broad sense, functional decomposition and analysis refer to the process of breaking down and examining a system based on its purpose or intended functionality. It involves identifying and analyzing the functions that a system should perform or is expected to perform.
This approach starts with identifying the main function of the system and then systematically decomposing it into sub-functions. Each function is typically described using a two-word combination consisting of a verb and a noun, capturing the action and the object of that action. [15]

3.4.3 Idea Generation

The working of idea generation within the domain of product development revolves around the systematic cultivation of imaginative and innovative concepts, aimed at propelling the inception of novel products or the improvement of pre-existing ones. Idea generation encompasses the thorough exploration of a diverse spectrum of notions, theories, and potentialities, facilitated through an array of techniques and approaches. The primary objective is to foster divergent thinking, stimulate unconventional viewpoints, and unearth unique insights. This progression derives its impetus from inherent creativity, inquisitiveness, and an all-encompassing comprehension of customer requisites and prevalent market trends.
Various tools and methodologies were used throughout the idea generation process. These encompass brainstorming sessions, the creation of concept maps, prototyping, market scrutiny, customer consultations, trend evaluation, and technological surveying. Such methodologies serve as catalysts for creativity, facilitate collaborative endeavors, and yield a substantial repository of ideas, which can subsequently be subjected to evaluation and refinement.
It is imperative to acknowledge that not all ideas conceived during this process will prove practicable or viable. Nevertheless, the core objective of idea generation is to amass a diversified pool of possibilities from which the most promising concepts can be culled for subsequent maturation. These selected concepts will undergo meticulous scrutiny, refinement, and empirical testing to assess their feasibility and potential for successful realization. [13]

3.4.4 Concept Synthesis

Concept synthesis constitutes a vital element of the product development procedure, wherein a variety of ideas and components are harmonized to forge a coherent and feasible product concept. This phase builds upon the notions generated in the

brainstorming stage, molding them into concrete concepts that can be honed and advanced.
Concept synthesis involves the refinement and integration of the most promising ideas into a comprehensive product concept that harmonizes with market demands and business goals.An integral part of concept synthesis revolves around crafting a kind of synergy that sets the product apart from existing solutions in the market. The synthesized concept aims to present distinctive and captivating attributes or advantages that cater to user requirements and align with the overarching product strategy.
The output of concept synthesis is a clearly defined and polished product concept, which assumes the role of a guiding roadmap for subsequent developmental phases. This concept shapes detailed design, engineering, prototyping, and testing endeavors, creating a trajectory for further enhancement and execution.

3.4.5 Concept Evaluation

Concept evaluation is a process that examines and studies the potential of product ideas formed during the stages of idea generation and concept synthesis. It's about thoughtfully analyzing if these concepts could work and be successful in the market, helping to decide which ones are worth developing further.
This process includes these important steps:

- **Setting Evaluation Standards:** Defining clear criteria and measurements that match the project's goals and what's wanted in the end. These standards can include things like how possible the idea is technically, how much people want it, how it stands out from competitors, how financially practical it is, and how well it fits with the company's big plans.
- **Picking the Best Ideas:** Going through the ideas that were created and picking out the ones that fit the criteria. Each idea gets looked at carefully to see what's good about it, what's not so good, and what could be a problem. Ideas that don't match the criteria or have big problems might not be considered anymore.
- **Giving Scores and Rankings:** Giving scores or rankings to the ideas that are left, using the criteria from earlier. This scoring helps to compare the ideas and decide which ones should be developed more. The scoring makes it easier to fairly compare different ideas.
- **Checking if Ideas Are Feasible:** Checking if the ideas that were chosen can actually work. This means looking at whether they can be made, how much they might cost, what resources are needed, and if there are any technical or legal obstacles. The aim is to figure out if these ideas can really happen with the resources available.
- **Making a Choice:** Based on the evaluations, the people making decisions can pick the most promising ideas to move forward. They look at how much the market might like the idea, if it's technically doable, if there are enough resources, and if it fits with the company's plans. The goal is to choose ideas that have the best chance of success and fit with what the company wants to do.

For this thesis project, three different kinds of matrices were used for idea evaluation:

- **Elimination Matrix:** This matrix uses very general functions, and each concept is checked by these functions. If the concept passes all the functions, then it moves on to the next step, else it is eliminated.
- **Pugh Matrix:** One concept is chosen as datum at random, and each concept is checked against this datum in all the evaluation criteria. If a specific concept performs better than the datum, a '+' is placed in its cell, and if the product performs worse, a '-' is placed. Net value of each concept is calculated, and the top 50% move to the next step.
- **Kesselring Matrix:** Weights are assigned to each criterion, and the concepts are rated on a scale of 1 to 10, 10 being ideal. The best scoring concepts proceed to further steps.

3.4.6 Concept Refinement

Concept refinement is a stage where the chosen product concept is improved and made better through a repeating process. The goal is to make the concept clearer, more doable, and more likely to succeed in the market. This is done by looking at it closely, making changes based on feedback, and evaluating it.
This process has a few important steps:

- **Iterative Modifications:** The concept is changed and tweaked based on what was found during the analysis. This might mean altering how it looks, what it does, its features, or how it's described. Changing things helps use new ideas and make the concept fit what customers want, what's happening in the market, and what the company wants to achieve.
- **Prototyping:** Making models or samples of the improved concept to see how it looks and works, and how people might use it. Trying out models helps find any problems with the design, how easy it is to use, or anything else that needs fixing. The feedback from testing these models guides changes to the concept, making it closer to something that can really work for users.
- **Feasibility Assessment:** Looking again at whether the improved concept can actually be done. This means thinking about whether it's technically possible to make, if the company has the resources, and if it makes financial sense. This step makes sure that the improved concept can really be turned into a real product.
- **Decision Making:** After going through the process of refining the concept, informed choices are made about how good the improved concept is for the market. This might mean deciding to keep working on it, putting more resources into it, or maybe thinking about other ideas. These choices are based on whether the improved concept can really work and be successful.

4
Results

In this chapter, the empirical findings of the research has been explored, building upon the methods detailed in the previous chapter. Each result is presented systematically, ensuring clarity and coherence for the reader. These findings provide answers to the research questions, and also set the stage for the subsequent discussion chapter. By contextualizing these results within the broader scope of the study, a comprehensive understanding of the implications and significance of the research is offered.

4.1 Literature Study

This section has findings from the literature study that was conducted to answer the research questions stated in Section 1.4. The literature review has been divided into three categories for clarity. It begins with a study of the engine, followed by an exploration of current systems addressing the NVH issue, and concludes with methods to isolate noise sources within the engine.

4.1.1 Engine Study

For this thesis project, two engine lines were selected:

- Volvo Penta D4: An in-line four-cylinder marine diesel engine.
- Volvo Penta D6: An in-line six-cylinder marine diesel engine.

Both engine lines are known for their high performance, low emissions, and compact designs. The engines feature a Common Rail Diesel Injection (CRDI) system and are equipped with a turbocharger for enhanced speed, as well as a supercharger for rapid acceleration.

The D4 engine has two power strokes for each rotation of the crankshaft, leading to 2nd order vibrations. In contrast, the D6 engine's pistons fire three times for each rotation of the crankshaft, resulting in 3rd order vibrations.
The arrangement of pistons and their firing order are designed such that the forces involved in the motion of a pair of pistons cancel each other out. However, the pistons accelerate and decelerate at different rates, leaving some residual forces that do not cancel out. These forces are responsible for 2nd order vibrations in the D4 engine and 3rd order vibrations in the D6 engine. Some noise and vibration is also caused by the fuel entering the piston at very high pressures (> 2000 bar).

The top and rear sides of the engine are mostly flat, which amplifies the noise, similar to how a drum works.

Material Flow Diagrams
The airflow dynamics within the engine has been visualized in Figure 4.1.

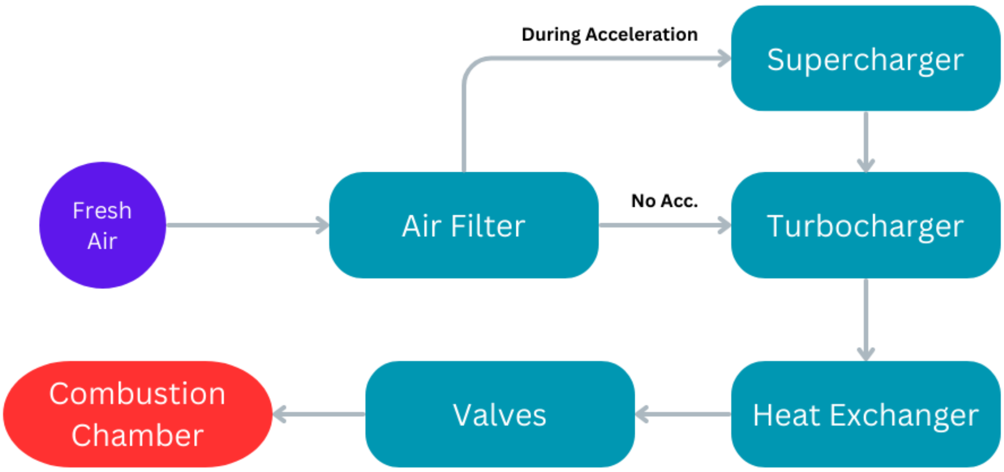

Figure 4.1: Air Flow through the Engine

After combustion with air, the exhaust gasses make their way through the engine as shown in Figure 4.2.

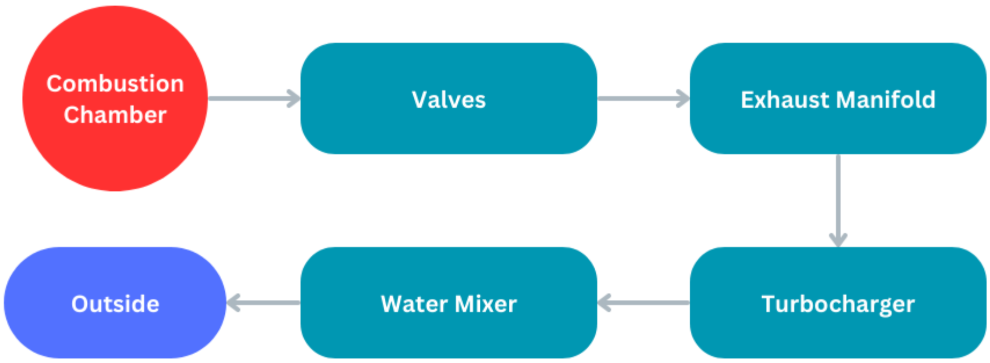

Figure 4.2: Exhaust Flow through the Engine

Sea water is used as a coolant in the heat exchanger, and is sent back into the ocean with the exhaust gasses as seen in Figure 4.3.

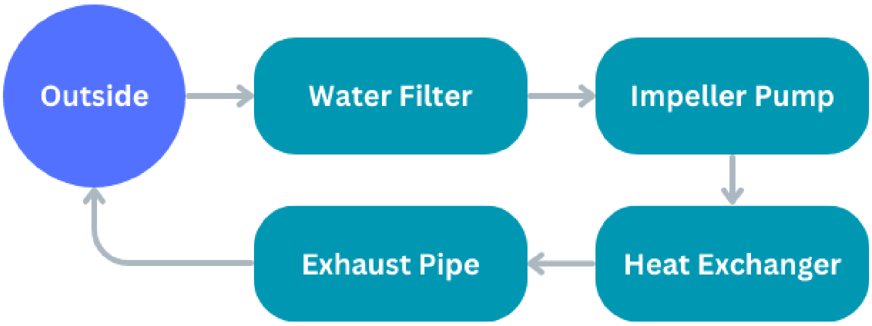

Figure 4.3: Water Flow through the Engine

4.1.2 Existing Improvements

In the context of the problem, Volvo Penta has implemented several measures to ensure low NVH levels in their engines. These include:

- **Underwater Exhaust** - The water serves as a muffler, significantly reducing exhaust noise.
- **IPS Drive System** - The IPS drive features an exhaust rerouting system that directs the exhaust through an upward-facing pipe. This pipe is engaged only when the boat operates at low speeds or is idling.
- **Engine Balancing** - The engine design is optimized to ensure that most of the excess forces produced by the engine's moving parts are neutralized.
- **Engine Mounts** - Volvo Penta uses robust rubber mounts for its engines, which dampen high-amplitude vibrations produced by the engine.
- **Engine Room Insulation** - Given that the engines are of the inboard aquamatic type, they are housed within an engine room. This compartment can be sealed and equipped with acoustic lining to minimize noise levels.

4.1.3 Noise Source Separation

To address Research Question 4 from Section 1.4, an online search was carried out to identify methodologies and research papers that focus on isolating individual noise sources from a composite noise signal. The search highlighted a DSP methodology named EMD [4]. Subsequent searches related to EMD unveiled more advanced and reliable derivatives of EMD, including EEMD [5] and TVFEMD [6]. Additionally, an algorithm named RobustICA [8] was identified, which refines the separated noise signals to ensure they are entirely independent of one another. The principles and workings of these algorithms were detailed in Chapter 2.

4.2 Customer Needs Study

This section showcases the detailed outcomes from the investigation focused on understanding customer requirements. Valuable insights into consumer desires, anticipations, and main concerns have been obtained. These insights pave the way for the requirement specification and also offer a solid basis for the entire product development process. These results were obtained by implementing the methods mentioned in Section 3.2

4.2.1 Customer Analysis

To identify the various customers, stakeholders, and users of the Volvo Penta D4 and D6 engines, an interview was set up with members of the Volvo Penta sales team. This interview proved instrumental in recognizing the different types of customers and users. Interviews were also held with the management staff at Volvo Penta to understand the stakeholders and ascertain their requirements.

The list of customers, stakeholders and users can be seen in Figure 4.4.

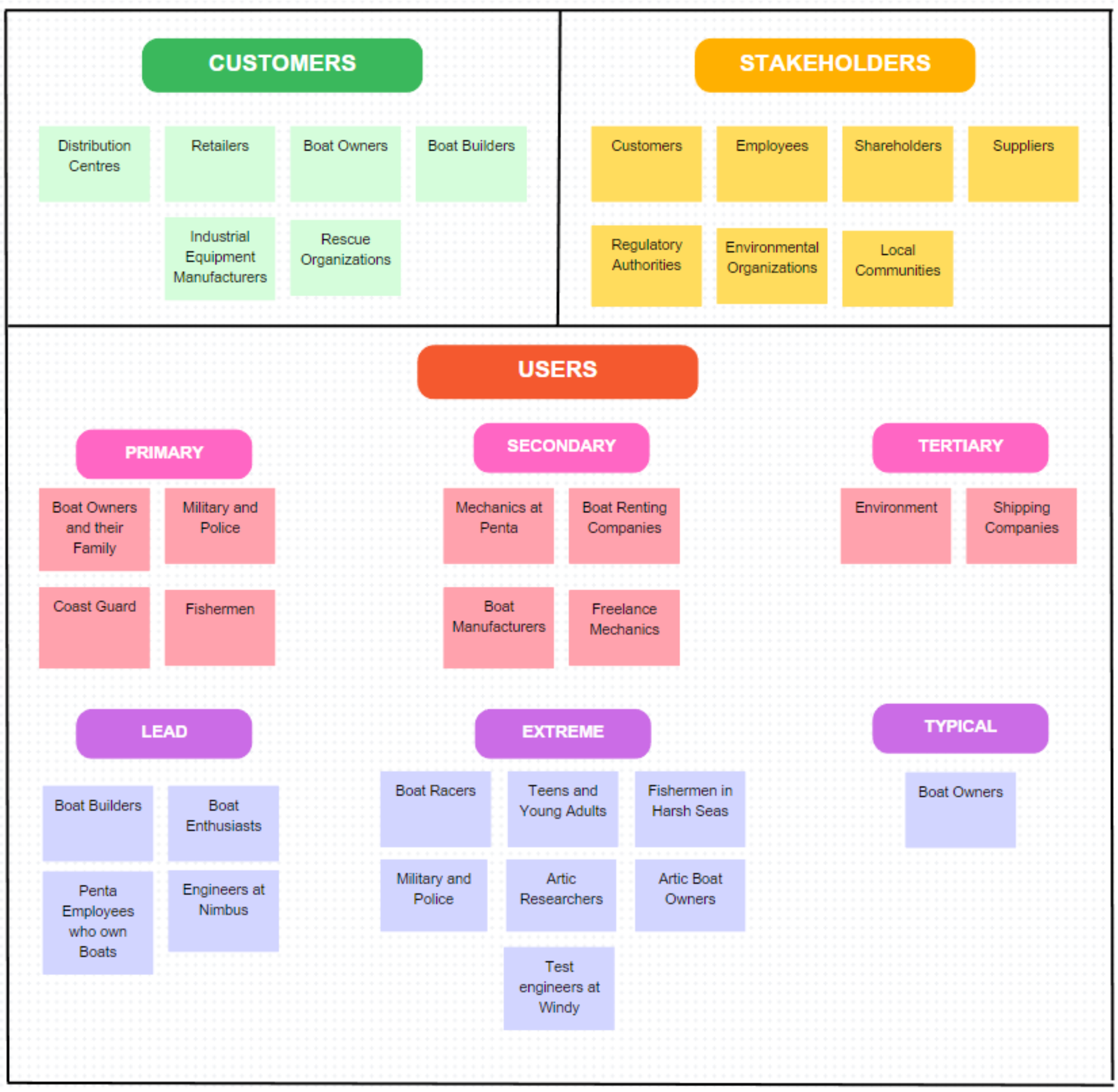

Figure 4.4: Different Customers, Stakeholders, and Users of the D4 and D6 Engines

4.2.2 Customer and Stakeholder Needs

After identifying the customers, users, and stakeholders, efforts were made to gather their specific requirements. This comprehensive elicitation was achieved through a multi-pronged approach: conducting interviews, organizing focus group discussions, administering surveys, making direct observations, and experiencing the engine's operation firsthand.

The statements and feedback collected from these diverse methods were then meticulously analyzed. They were categorized using the KJ method, a structured technique for grouping similar ideas and deriving overarching themes. This method is an organization technique to sort all of the open points into different categories to get a better understanding of the collected data [16]. The outcomes of this methodological categorization can be viewed in Figure 4.5 and Figure 4.6.

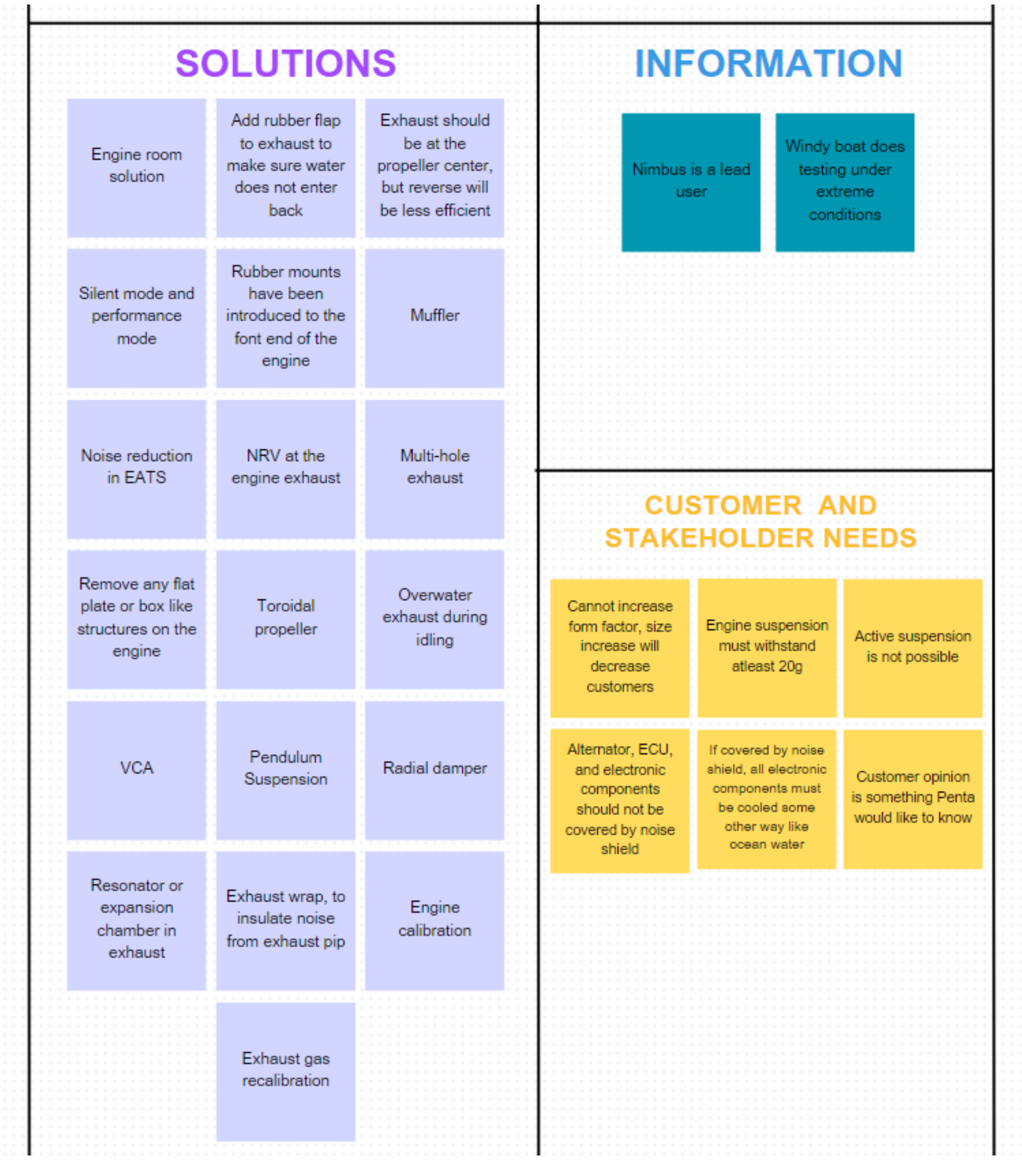

Figure 4.5: Results after Performing KJ Analysis

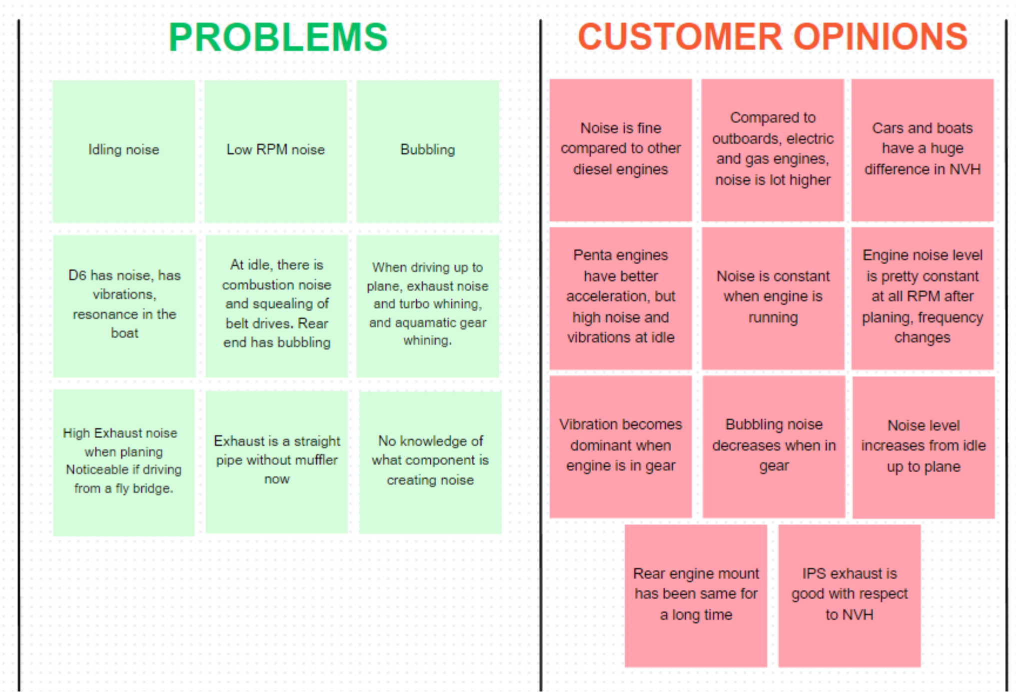

Figure 4.6: Results after Performing KJ Analysis (continued)

The collected statements were refined and translated into specific customer needs. These articulated needs with their corresponding prompts and statements are comprehensively presented in Table 4.1.

Question	Statement	Interpreted Need
Impression	Lot of noise, vibrations and resonance.	The engine can be less noisy and vibration free.
Comparison	Performance is better, but idle noise is higher.	Noise during idling can be reduced.
Type of noise	At idle and at lower speeds, bubbling noise and combustion noise can be heard.	When idling, bubbling noise can be reduced.
Type of noise	At lower speeds, At idle and at lower speeds, bubbling noise and combustion noise can be heard.	Engine combustion noise can be suppressed or reduced.
Type of noise	At higher speeds, the exhaust comes out of the water and is very noisy. I cannot have a conversation with people on the fly bridge.	Exhaust noise can be reduced.

Table 4.1: Statements made by Customers and its' Corresponding Interpreted Need

The captured needs were labelled to classify the nature of the need as seen in Table 4.2.

- **Explicit Needs:** These are the needs that customers can easily articulate or express directly. They are clear, straightforward, and often come up during direct interactions or surveys.
- **Implicit Needs:** These are the needs that are not directly stated but are understood or implied. They might not be voiced by the customer, but they are expected and are often considered basic standards in a product or service.
- **Latent Needs:** These are the needs that customers themselves might not be aware of until they see or experience a solution. They are hidden desires or unexpressed needs that can be uncovered through in-depth research, observation, or innovative thinking.

	Customer and User Needs
**	Reduced noise at lower speeds
**	Reduced noise during idling
**	Reduced bubbling noise at idle
*	Reduced noise and vibrations during operation
!	Reduced exhaust noise
!	Have multiple operation modes
	*** - Implicit Needs*
	** - Explicit Needs*
	! - Latent Needs

Table 4.2: Categorized Compilation of Customer and User Needs

Some of the stakeholders' needs can be translated as constraints the product development process. These restrictions have been pointed out in Table 4.3.

Stakeholder Restrictions
§ Cannot increase engine form factor, it will reduce customer base
§ Engine suspension must withstand 20g force
§ Alternator, ECU and other electronic components need to be cooled
§ Either don't cover the electronic components or cool them some other way
§ Customer opinion on current condition of engines
§ Comply with future EU regulations

Table 4.3: Compilation of Stakeholder Needs

The interpreted needs were also sorted using the Kano Model to be able to prioritize the needs. It also helps to understand how customers perceive features and which features could lead to increased satisfaction. The model classifies customer preferences into three main categories [17] -

- **Basic Needs:** These are the essential features or attributes that customers expect. If these needs are not met, customers will be extremely dissatisfied.

However, merely meeting these needs doesn't particularly enhance overall customer satisfaction; it's just the minimum requirement. This is represented in the color red and commonly known as "Must Have's"

- **Performance Needs:** These are the attributes that customers explicitly desire and are often the primary considerations in a purchase decision. Improving performance needs can lead to increased satisfaction, while failing to meet them can lead to dissatisfaction. This is represented in the color yellow and commonly known as "1D Needs"
- **Excitement Needs:** These are unexpected features or attributes that, when present, can significantly increase customer satisfaction. However, their absence doesn't necessarily lead to dissatisfaction since customers don't expect them in the first place. This is represented in the color green and commonly known as "Delighters"

The Kano model for the captured needs is illustrated in Figure 4.7.

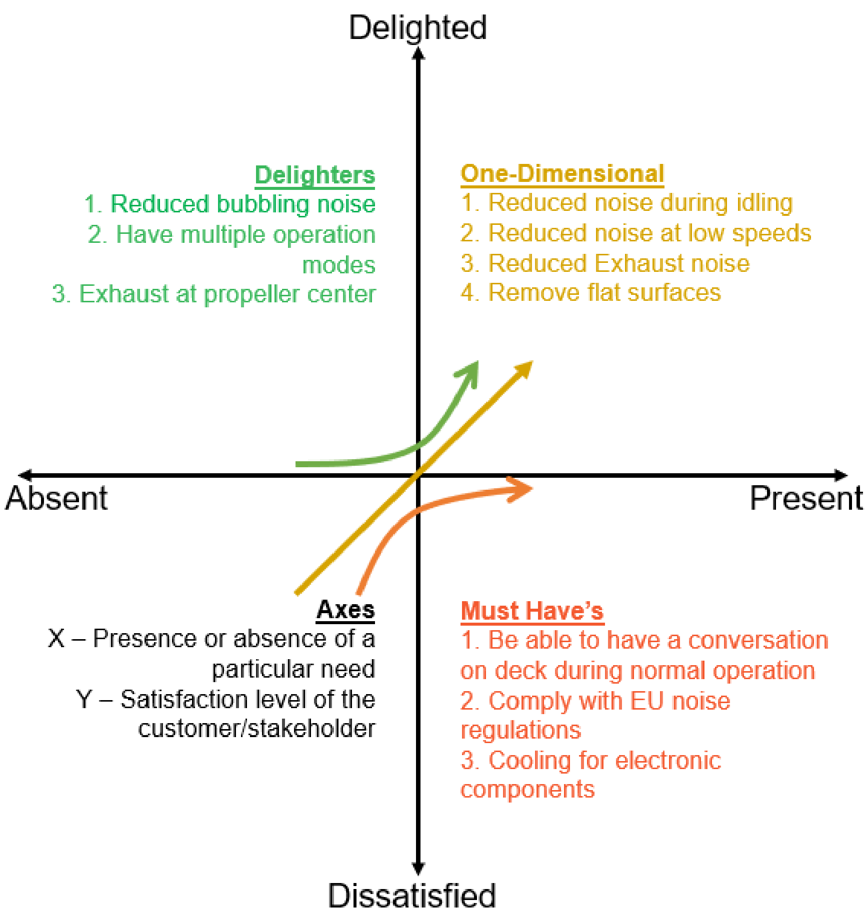

Figure 4.7: Kano Model of the Customer and Stakeholder Needs

4.2.3 Technology Analysis

Marine diesel engines have historically been known for their significant levels of noise, vibration, and harshness (NVH). However, due to technological advancements and a growing focus on passenger comfort and environmental concerns, there has been a noticeable shift towards reducing NVH in these engines.
Here are the ways in which this reduction is being achieved currently:

- **Acoustic Insulation:** In modern times, marine engines are often placed within specially designed compartments equipped with advanced acoustic insulation materials. These materials absorb sound waves, which significantly decreases the noise that reaches passenger and crew areas.
- **Engine Mounts:** Advanced systems for mounting engines have been developed to isolate vibrations from the engine's structure. These mounts, typically made from materials like high-damping rubber or other composites, absorb and disperse vibrational energy, preventing it from being transferred to the ship's framework.
- **Exhaust Muffler:** Engine mufflers, integral components of exhaust systems, are designed to alleviate noise produced during engine operations. These devices work in two main ways: through reflective muffling, where sound waves are directed back into themselves, causing cancellation through destructive interference; and through absorptive muffling, where sound energy is converted into heat as it passes through sound-absorbing materials.
- **Engine Design Optimization:** Contemporary marine diesel engines are constructed with NVH reduction in mind. This includes optimizing combustion processes, refining piston and crankshaft designs, and ensuring smoother operation across various loads and speeds.
- **Active Noise Cancellation:** Drawing inspiration from technologies used in the automotive and aerospace sectors, some marine engines now integrate active noise cancellation systems. These systems employ microphones to capture engine noise and then generate sound waves that are out of phase, effectively counteracting the unwanted noise.
- **Vibration Analysis and Balancing:** State-of-the-art diagnostic tools enable real-time analysis of vibrations. By comprehending vibration patterns, engineers can make adjustments to ensure that the engine operates in a balanced state, thus minimizing vibrations.

4.2.4 Patent Analysis

The front of NVH reduction in marine diesel engines has seen a surge in technological advancements, and this is reflected in the patent landscape. Below is a brief analysis of patents related to the aforementioned technologies:

1. **Acoustic Insulation:** Patents in this area focus on innovative materials and designs that offer superior sound absorption. Some patents detail multi-layered insulation systems, combining materials of different densities to optimize noise reduction.
2. **Engine Mounts:** The patent landscape reveals designs that incorporate hydraulic or pneumatic elements in engine mounts, allowing for dynamic adjust-

ments based on engine load and speed. There are also patents on self-adjusting mounts that respond in real-time to engine vibrations.

3. **Exhaust Muffler:** Engine mufflers, pivotal in noise reduction for vehicles, have seen a surge in patent activity over recent years. The patent landscape reveals a focus on innovative internal structures that optimize sound wave reflection and absorption, while ensuring minimal backpressure on the engine. Advanced materials that withstand high temperatures and resist corrosion are increasingly patented, alongside integrated systems that combine noise control with emission reduction. Additionally, there's a growing interest in Active Noise Control (ANC) technologies within mufflers, with major automotive companies from the U.S., Japan, and Europe leading the patent filings. This suggests a global push towards more efficient and environmentally-friendly muffler technologies.
4. **Engine Design Optimizations:** A plethora of patents exist around optimizing various engine components, from combustion chamber designs to innovative piston shapes. These patents aim to achieve smoother engine operation, reduced friction, and minimized noise generation.
5. **Active Noise Cancellation:** The patent landscape in this area is vast, with innovations ranging from advanced algorithms for real-time noise detection and cancellation to integration methods that seamlessly incorporate noise-canceling systems within the engine or vessel structure.
6. **Vibration Analysis and Balancing:** Patents in this domain focus on diagnostic tools and software that can provide real-time feedback on engine vibrations. Some patented systems also offer automated balancing solutions, adjusting engine parameters on-the-fly to minimize vibrations.

4.2.5 Competitor Analysis

1. Yanmar Marine International: Yanmar's 4LHA series and 6LY series are direct competitors to Volvo Penta's D4 and D6 engines. Yanmar is renowned for its reliable and durable marine diesel engines. Their compact design, fuel efficiency, and global service network make them a preferred choice for many boaters. Some users have reported challenges in sourcing spare parts in specific regions.
2. Mercury Marine: Mercury's SeaPro series, particularly models, are competitors in the smaller engine range. Mercury offers a wide range of outboard engines, known for their performance and innovative features. Their engines are lightweight and come with advanced technology integrations.
3. Cummins Inc.: Cummins QSB5.9 and QSB6.7 are in the same range as Volvo Penta's D4 and D6 engines. Cummins is a global leader in power solutions and offers marine engines with robust performance and durability. Their global presence ensures easy availability of parts and service. Their primary focus is on larger engines, which might make their smaller engine range less diverse.
4. Caterpillar Marine: Caterpillar's C4.4 and C6.6 marine engines compete with the D4 and D6. Caterpillar is known for its high-performance marine engines and has a strong reputation for durability and reliability. They also have a

vast global dealer network. Caterpillar's marine engines are often perceived as being on the pricier side, which might deter some potential customers.

5. MAN Marine: MAN's D0834 and D0836 are competitors to the D4 and D6 engines. MAN engines are known for their advanced engineering and efficient fuel consumption. They also offer a good balance between performance and emissions. MAN's service network might not be as extensive as some of its competitors, leading to potential delays in service or parts availability in certain regions.

4.2.6 Benchmarking

After talking to company executives and conducting an online research study in the noise levels of engines manufactured by competitors, the following results were obtained. All sound levels are approximate and are corresponding to the noise produced during full load operation. [18]
In the low power range, which is comparable to the 175 hp D4 engine manufactured by Volvo Penta, it is seen in Figure 4.8 that the D4 engine has a competitive noise emission when compared to other inboards. Although, there is a 4 dB-A difference in noise level when comparing with outboard engines.

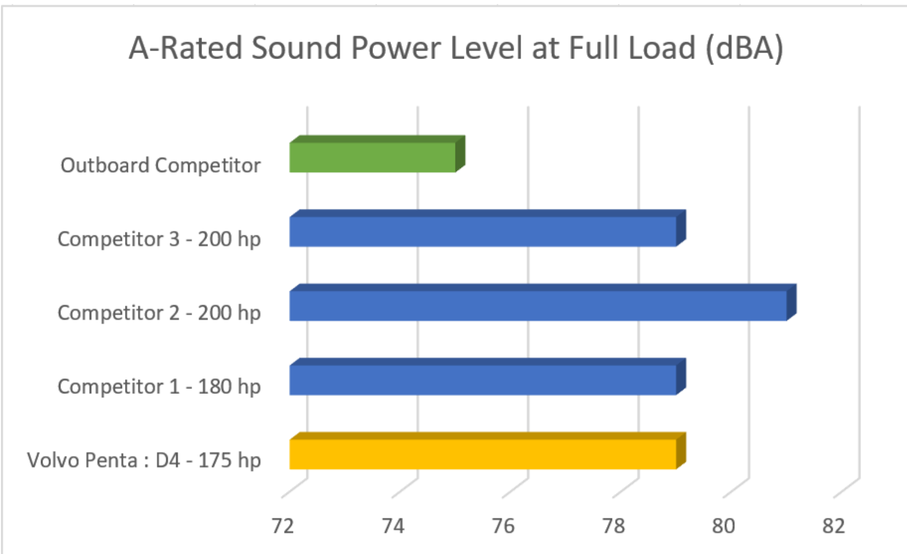

Figure 4.8: Noise Comparison in the 175 hp Power Range

Similarly, in the medium to high power range which is comparable to Volvo Penta's 400 hp D6 engine, it is leading the inboard market in noise levels. However, there is 4 dB-A difference in comparison to outboard engines as seen in Figure 4.9.

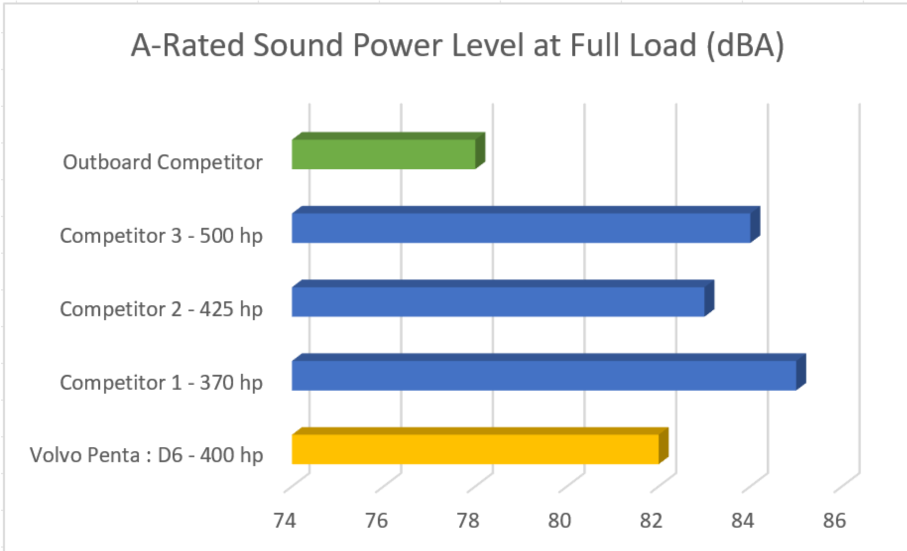

Figure 4.9: Noise Comparison in the 400 hp Power Range

4.3 Pre-Development Study

The noise source separation algorithm, TVFEMD, was applied to the noise signal produced by an idling D4 engine. The results in the time domain can be seen in Figure 4.10. The input signal is depicted in red, whereas the component signals are displayed in green. The green signals represent noise produced by different parts of the engine, and if added back up, it will recreate the input signal (red). It's important to note that the amplitude of each individual signal has been adjusted to ensure all waves are visible on a single graph, hence they have unequal amplitudes.

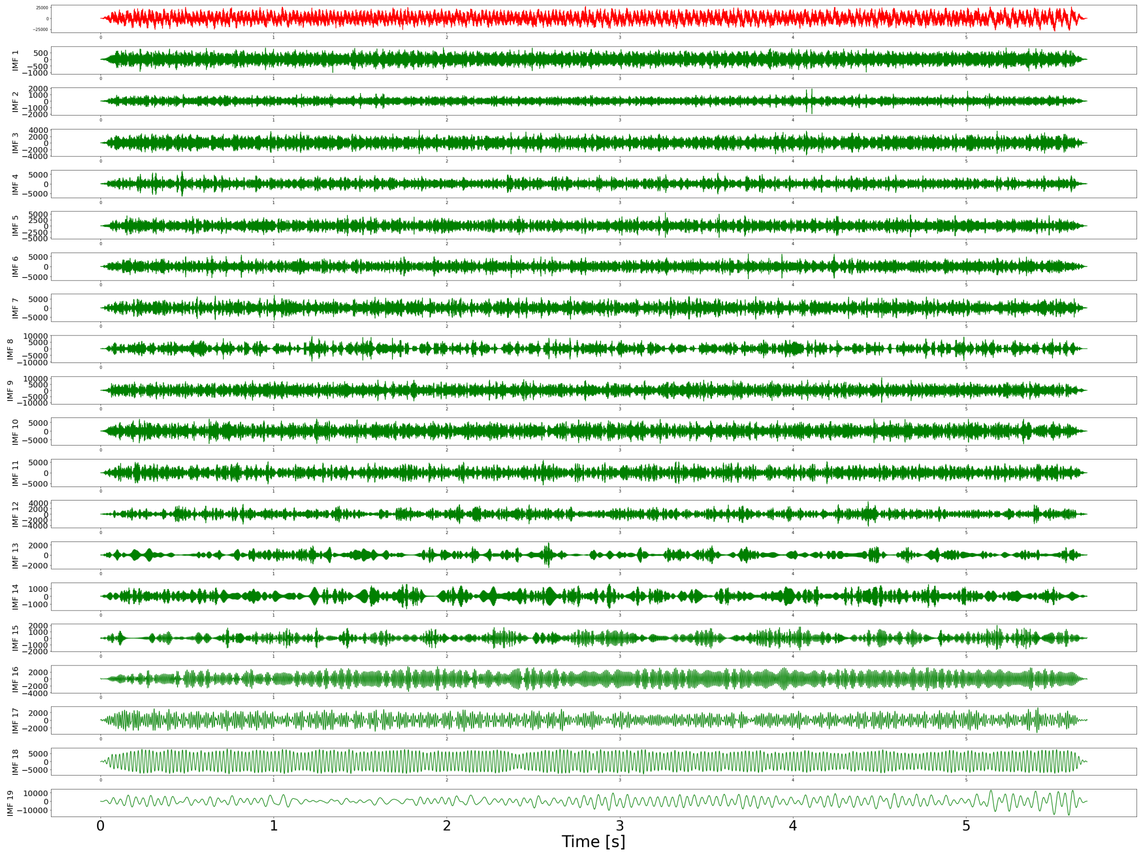

Figure 4.10: TVFEMD results from idling sound data in time domain

The signals were transformed into the frequency domain using FFT, and all the resulting signals are presented in Appendix B. All the graphs maintain consistent amplitude, facilitating easier identification of the more prominent signals. It can be deduced that most of the signals at higher frequencies exhibited very low excitations compared to those at lower frequencies. The prominent noise signals in the frequency domain are illustrated in Figure 4.11.

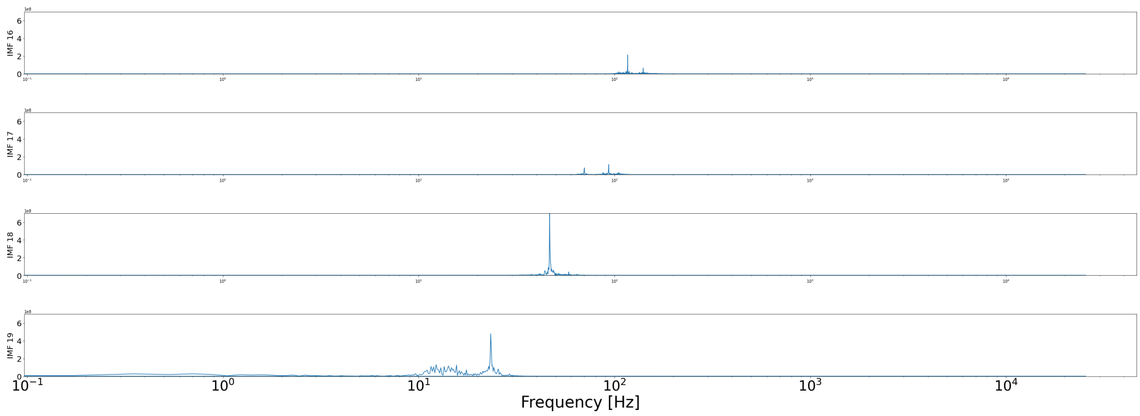

Figure 4.11: TVFEMD results from idling sound data in time domain

The peaks in Figure 4.11 (from bottom) are observed at frequencies of 23.33 Hz, 46.67 Hz, 93.51 Hz, and 140.18 Hz. It's established that an idling D4 engine operates at 700 RPM, which translates to 11.67 RPS or 11.67 Hz. This suggests that the dominant noise source is twice the engine speed, often referred to as the 2nd order vibration. As outlined in Section 4.1.1, it's recognized that the 2nd order vibrations in the D4 engine result from piston firing. The primary noise sources have been verified to be the engine firing and its 2nd harmonic, which produces the noise at 46.67 Hz.

The last signal, which is named as IMF 19 in Figures 4.10 and 4.11 seemed to have a lot of unresolved components, and was hence disassembled using the TVFEMD algorithm again. The results can be seen in Figure 4.12 and Appendix Figure B.2.

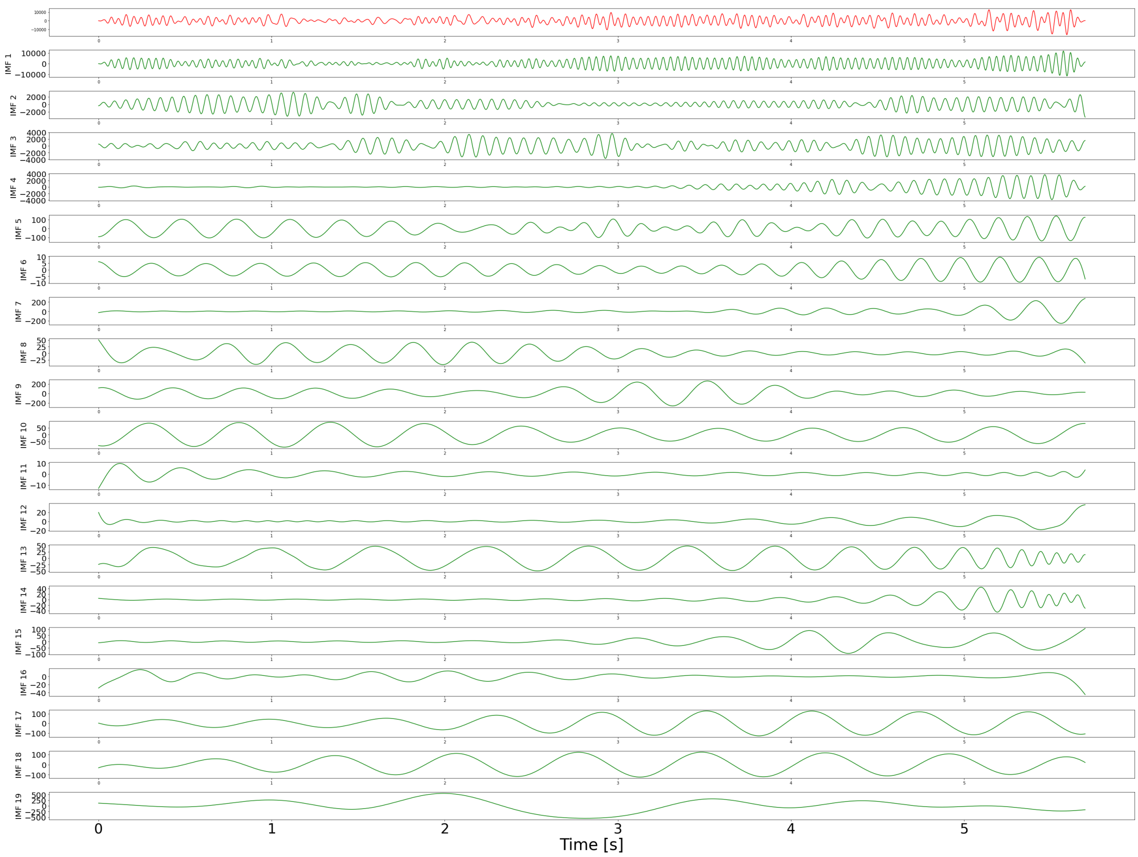

Figure 4.12: TVFEMD results from low frequency idling sound data in time domain

The scope of the thesis project was limited to identifying noise sources. However, an employee at Volvo Penta highlighted that these signals might be valuable for creation of future simulation deck files. As a result, additional effort was made in extracting independent noise signals from the provided mixed signal.
The noise signals from the first iteration of TVFEMD served as input for the RobustICA algorithm. The outcomes from the independence process of the noise signals are illustrated in Figure 4.13 and Figure 4.14.

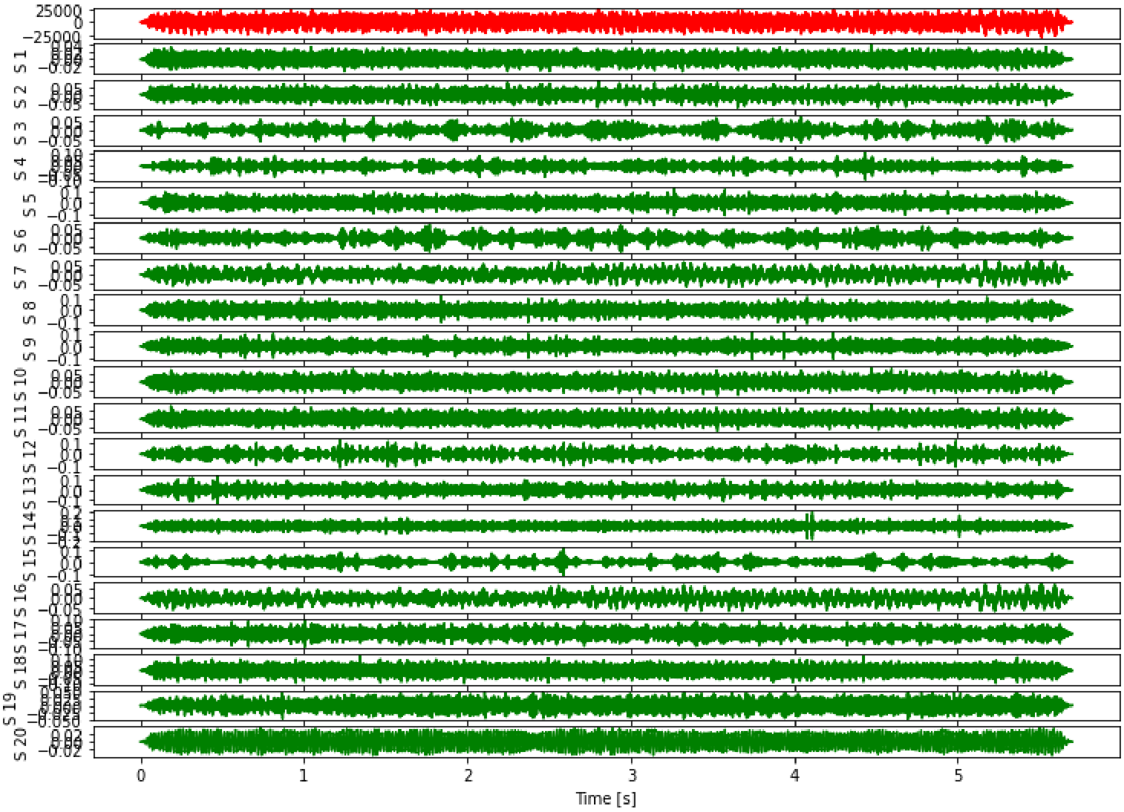

Figure 4.13: RobustICA results from idling sound data in time domain

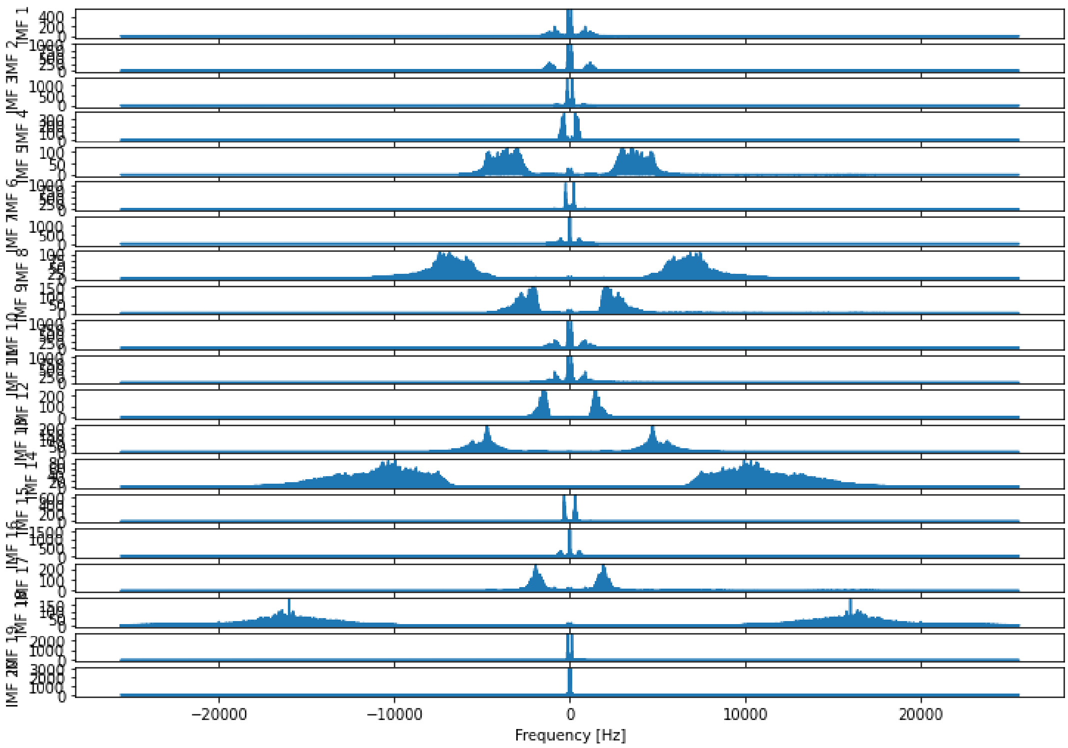

Figure 4.14: |RobustICA results from idling sound data in frequency domain

4.4 Product Development Cycle

The results presented in this section are based on the methodology outlined in Section 3.4.

4.4.1 Requirement Specification

The information collected from the customer needs study served as the foundational framework for this document. This document has been consistently updated to incorporate new insights and information. Table 4.4 presents a comprehensive list of requirements essential for enhancing the development process. Meanwhile, Table 4.5 enumerates a set of desires. While these desires might not be mandatory, they play a crucial role in elevating customer satisfaction and should be given due consideration.

Requirements

No.	Type	Statement	Verification
R1	Main	During planing, perceived exhaust noise shall be lower than current generation	Testing/ Simulation
R2	Internal	During normal operation, the improvements for the engine shall not reduce performance of the engine	Testing/ Simulation
R3	Internal	The form factor of the design shall be smaller than the current exhaust pipe	Testing/ Simulation
R4	Internal	The design shall fit into the current exhaust pipe	Testing/ Simulation
R5	Internal	The design shall not increase back pressure	Testing/ Simulation
R6	Internal	The design shall be able to withstand high temperatures	Testing/ Simulation
R7	Internal	The design shall withstand high pressure	Testing/ Simulation
R8	Internal	The design shall withstand corrosive elements found in the exhaust	Testing/ Simulation
R9	Internal	The design shall be easy to install and remove	Testing/ Simulation
R10	Internal	The design shall reduce the size of bubbles in the exhaust	Testing/ Simulation

Table 4.4: List of Requirements

Desires

No.	Type	Statement	Verification
D1	User	During idling, the exhaust shall not produce excessive bubbling	Testing/ Simulation
D2	User	The new engine parts shall be easy to install	Testing/ Simulation
D3	User	The new engine parts shall have the ability to be sold separately as standalone upgrades	Testing/ Simulation
D4	User	The new components shall not infringe on any existing patents	Testing/ Simulation

Table 4.5: List of Desires

4.4.2 Functional Analysis

A list of functions were derived from the requirement specification, and were analyzed using a function means tree, which can be seen in Figure 4.15. The primary function is at the top and represented by the jade trapezium, while the sub-functions are denoted by the sap green trapeziums. The means to achieve these functions are illustrated using violet rectangles.

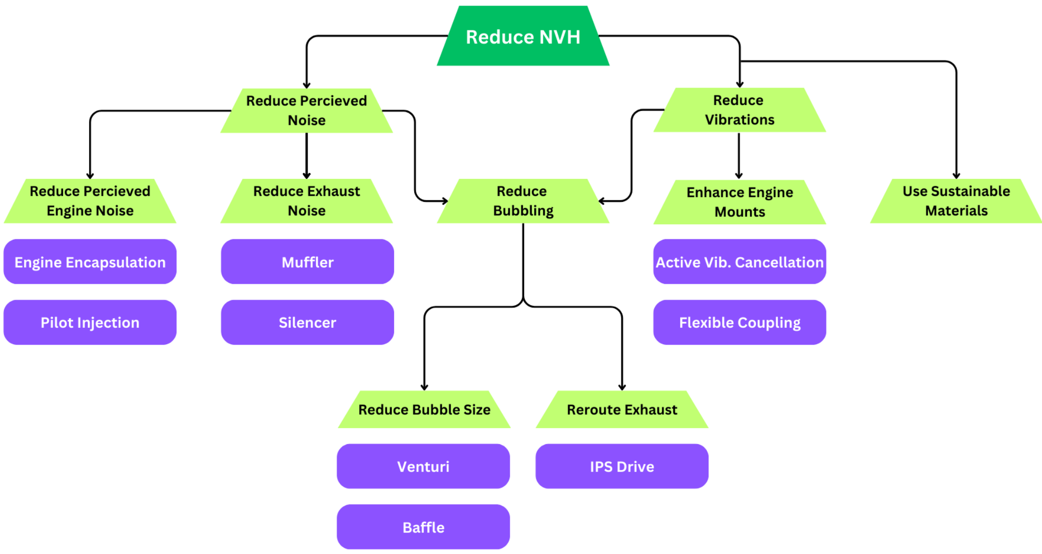

Figure 4.15: Function Means Tree

4.4.3 Idea Generation

The process of generating ideas was facilitated through various brainstorming techniques, as detailed in Section 3.4. Additionally, insights from interviews and focus group discussions contributed to a richer and more diverse set of ideas. This expansive collection of concepts and suggestions is illustrated in Figure 4.16.

FUNCTIONS	IDEAS				
	1	2	3	4	5
Reduce Percieved Engine Noise	Engine Encapsulation	Pilot Injection	Sound Proofing Engine Room	Active Noise Control	
Reduce Exhaust Noise	Muffler	Deep Underwater Exhuast	Accoustic Insulation	Redesign Exhaust System	Hull Insulation
Reduce Bubble Size	Bubble Diffuser	Multiple Outlets	Additonal Water in Exhaust	Venturi	Baffle
Reroute Exhaust	IPS Drive	Manual Reroute			
Enchance Engine Mounts	VCA	Active Vibration Damping	Hydrasulic	Pneumatic	

Figure 4.16: Idea Matrix

4.4.4 Concept Synthesis

Drawing from the list of ideas presented in the preceding section, certain concepts were deliberately omitted to streamline the scope of the thesis project. In Figure 4.17, the ideas that were set aside are depicted in shades of red, while the ideas that were retained for further exploration are highlighted in shades of green.

FUNCTIONS	IDEAS				
	1	2	3	4	5
Reduce Percieved Engine Noise	Engine Encapsulation	Pilot Injection	Sound Proofing Engine Room	Active Noise Control	
Reduce Exhaust Noise	Muffler	Deep Underwater Exhuast	Accoustic Insulation	Redesign Exhaust System	Hull Insulation
Reduce Bubble Size	Bubble Diffuser	Multiple Outlets	Additonal Water in Exhaust	Venturi	Baffle
Reroute Exhaust	IPS Drive	Manual Reroute			
Enchance Engine Mounts	VCA	Active Vibration Damping	Hydrasulic	Pneumatic	

Figure 4.17: Morphological Matrix for Concept Synthesis

From the three categories mentioned above, there is a possibility to come up with 100 different combination of concepts. Some concepts go beyond the scope of this thesis project, and hence were not considered for the next stage in the product development process. This includes ideas for the first function like, pilot injection, sound proofing engine room, and active noise cancellation. These ideas were kept in the morphological matrix as it could be probed into in the future.

4.4.5 Concept Evaluation

The accepted concepts were put in an elimination matrix as seen in Figure 4.18. The concept names are derived from the idea numbers assigned to them in Figure 4.16, the first digit corresponds to idea number for the first function, second digit corresponds to idea number in second function, and third number corresponds to idea number in the third function.

Evaluation Matrix for NVH Reduction								Criteria Fullfillment	
								(+) : Yes	
								(-) : No	
								(?) : More Evaluation Needed	
								Decision	
								(+) : Yes	
								(-) : No	
Solution Alternative	Solves main problem	Fulfills all demands	Compatible	Safe	Reasonable cost	Reasonable packaging	Enough Information	Comment	Decision
111	+	+	+	+	+	+	+		+
112	+	+	+	+	+	+	+		+
113	+	+	-					Need more water from pumps	-
114	+	+	+	+	+	+	+		+
115	+	+	+	+	+	+	+		+
121	+	+	+	+	-			Not realizable	-
122	+	+	+	+	-				-
123	+	+	-					Need more water from pumps	-
124	+	+	+	+	-			Not realizable	-
125	+	+	+	+	-				-
131	+	+	+	+	+	+	+		+
132	+	+	+	+	+	+	+		+
133	+	+	-					Not realizable	-
134	+	+	+	+	+	+	+		+
135	+	+	+	+	+	+	+		+
141	+	+	+	+	+	+	+		+
142	+	+	+	+	+	+	+		+
143	+	+	-					Need more water from pumps	-
145	+	+	+	+	+	+	+		+
146	+	+	+	+	+	+	+		+
151	+	+	-					Not manufactured by Penta	-
152	+	+	-						-
153	+	+	-						-
154	+	+	-						-
155	+	+	-						-

Figure 4.18: Elimination Matrix

The remaining concepts, after the application of the elimination matrix, were evaluated using a Pugh Matrix. Concept 132 was arbitrarily selected as the datum, against which other concepts were compared based on various criteria. If a concept outperformed the datum, it was denoted with a "+"; if it was on par with the datum, it received a "0"; and if it was inferior, it was marked with a "-". The sum of the +'s and -'s provided a net score for each concept. Concepts with a score of 0 or higher were advanced to the subsequent stage. The Pugh Matrix is shown in Figure 4.19.

Pugh for NVH Reduction												
Criteria	Alternatives											
	111	112	114	115	131	132	134	135	141	142	144	145
Noise Reduction	+	+	+	+	+		-	0	0	0	0	0
Vibration Reduction	+	+	+	+	+	D	-	0	0	0	0	0
Back Pressure	-	0	-	0	-	A	-	-	+	+	+	+
Engine Performance	0	0	-	0	-	T	-	0	+	+	+	+
Cost	+	+	+	+	0	U	0	0	-	-	-	-
Ease of Assembly	+	+	+	+	0	M	0	0	-	-	-	-
Complexity	-	-	-	-	0		0	0	-	-	-	-
Total (+)	4	4	4	4	2	0	0	0	2	2	2	2
Total (-)	2	1	3	1	2	0	4	1	3	3	3	3
Net Value	2	3	1	3	0	0	-4	-1	-1	-1	-1	-1

Figure 4.19: Pugh Matrix

The concepts that persisted were further scrutinized using a Kesselring Matrix to refine the selection. Each criterion was assigned a specific weight (w), and every concept was evaluated on a scale from 1 to 10 against these criteria. The score derived for each concept was then multiplied by the weight of the respective criterion, resulting in a value denoted as 't'. The cumulative 't' values for each concept were then compared against an ideal benchmark. The evaluation scale for each concept ranged from 1 to 100, with 100 being the optimal score. Based on these scores, the concepts were ranked, facilitating the identification of the best concepts. This is shown in Figure 4.20. Concept 115, 111, and concept 131 had the first three ranks respectively. These concepts for chosen for further development and refinement.

Kesselring Matrix for NVH Reduction															
Criteria	w	Ideal		Alternatives											
				111		112		114		115		131		132	
		s	t	s	t	s	t	s	t	s	t	s	t	s	t
Noise Reduction	0.3	10	3	9	2.7	8	2.4	8	2.4	9	2.7	7	2.1	7	2.1
Vibration Reduction	0.3	10	3	10	3	7	2.1	8	2.4	9	2.7	10	3	7	2.1
Back Pressure	0.15	10	1.5	5	0.75	7	1.05	2	0.3	8	1.2	7	1.05	8	1.2
Engine Performance	0.1	10	1	7	0.7	8	0.8	2	0.2	8	0.8	8	0.8	9	0.9
Cost	0.05	10	0.5	6	0.3	6	0.3	6	0.3	6	0.3	4	0.2	4	0.2
Ease of Assembly	0.05	10	0.5	10	0.5	10	0.5	10	0.5	10	0.5	5	0.25	5	0.25
Complexity	0.05	10	0.5	5	0.25	5	0.25	5	0.25	5	0.25	8	0.4	8	0.4
T = Σ t			10		8.2		7.4		6.35		8.45		7.8		7.15
S = T/Tideal			100		82		74		63.5		84.5		78		71.5
Rank		NA		2		4		6		1		3		5	

Figure 4.20: Kesselring Matrix

4.4.6 Concept Refinement

After the key ideas were selected, they underwent further iteration by progressing through the product development cycle once again. This led to the development of ideas that incorporated multiple features for a single function. The majority of this process involved creating digital prototypes and assessing the concept's functionality through acoustic simulations. The outcomes of the refinement phase are detailed in the following sections.

4.5 Prototyping

For this thesis project, digital prototyping was deemed the most efficient use of limited time. The initial digital prototypes were created using Fusion360. This choice was made because Fusion360 is a simpler tool, and there was no need for precision modeling at that stage.
The final prototype, however, was developed using PTC Creo, as Volvo Penta employs PTC Creo for most of its design work. Furthermore, PTC Creo facilitates easier design iterations and features a robust tree structure, allowing others to modify the design if necessary.

Below are the digital prototypes, which were created on Fusion360, for various bubble-reducing mechanisms:

Venturi Type Bubble Reducer: This bubble reducer accelerates the fluid velocity as it flows through the pipe, increasing the mixing of gases with the water in the exhaust system. The reduced cross-sectional area also aids in diminishing the size of the bubbles. The prototype for this can be seen in Figure 4.21

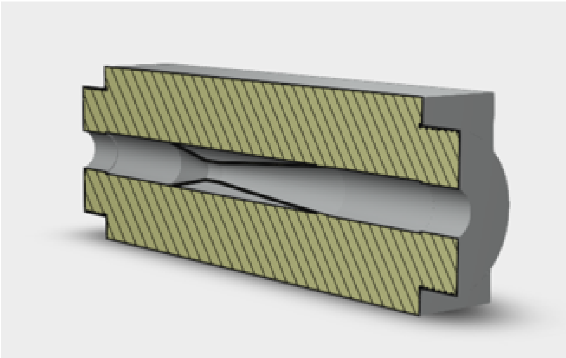

Figure 4.21: Venturi type Bubble Reducer with Baffles

Baffle type Bubble Reducer with Noise Absorption: This kind of design was inspired by pistol silencers, which utilize the flexible material in baffles to act as noise absorbents. The baffles also act as a mixing chamber for the gasses to dissolve in the water, which causes fewer air bubbles in the exhaust.

Venturi Type Bubble Reducer with Baffles: This design is akin to the previous concept but includes the addition of baffles in the venturi. These openings further fragment the bubbles into smaller pockets of air. A concept of this can is illustrated in Figure 4.22

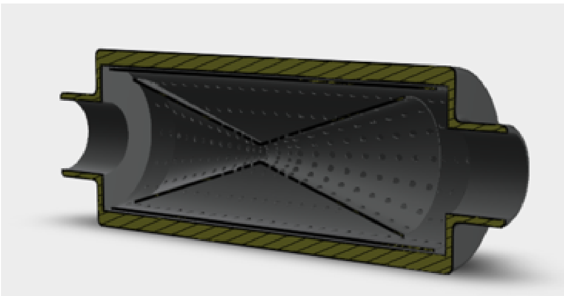

Figure 4.22: Venturi type Bubble Reducer

A prototype of Concept 131 is illustrated in Figure 4.23. The component depicted in green is an absorptive layer designed to absorb low-frequency noises. The expansion chamber induces interference among sound waves. Consequently, some noise reduction occurs due to the standing waves generated by this interference, predominantly with higher-frequency waves. The exit is equipped with a diffuser, akin to those found on water taps.

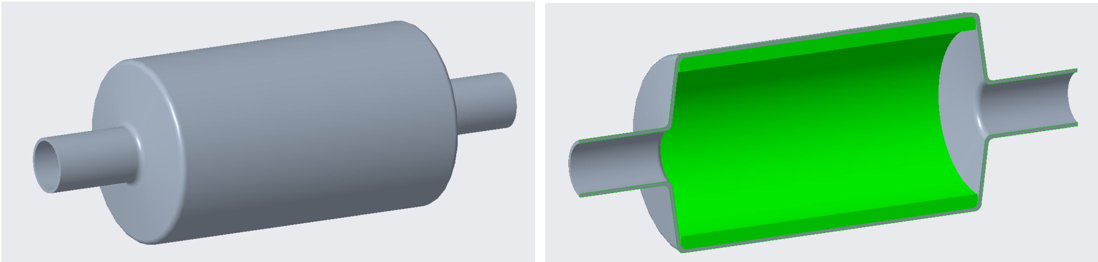

Figure 4.23: Expansion Muffler

The subsequent prototype was developed by merging the ideas from Concept 111 and Concept 115, as depicted in Figure 4.24. This design incorporates a Helmholtz resonator to mitigate high-frequency noise, a technique commonly employed in automobile mufflers. The perforations effectively curbed low-frequency noises far better than other concepts. However, its bulky dimensions and the increased back pressure led to the concept's dismissal.

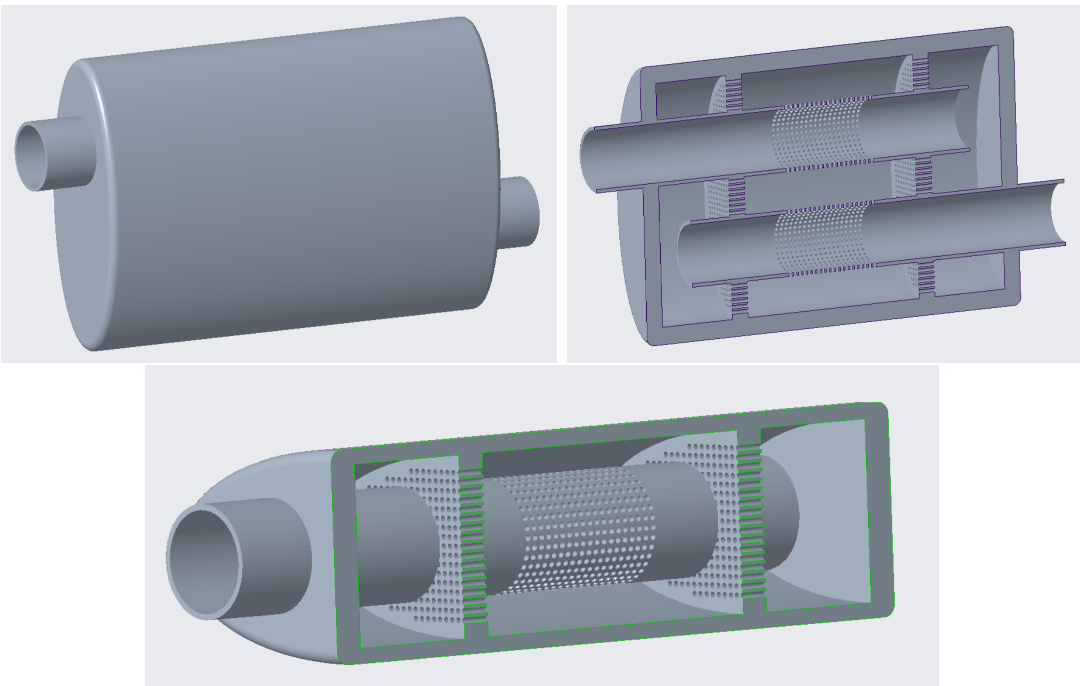

Figure 4.24: Baffle Muffler with Perforates

Concept 115, which ranked first in the concept evaluation stage, was the primary focus during prototyping. An early model of this concept is depicted in Figure 4.25.

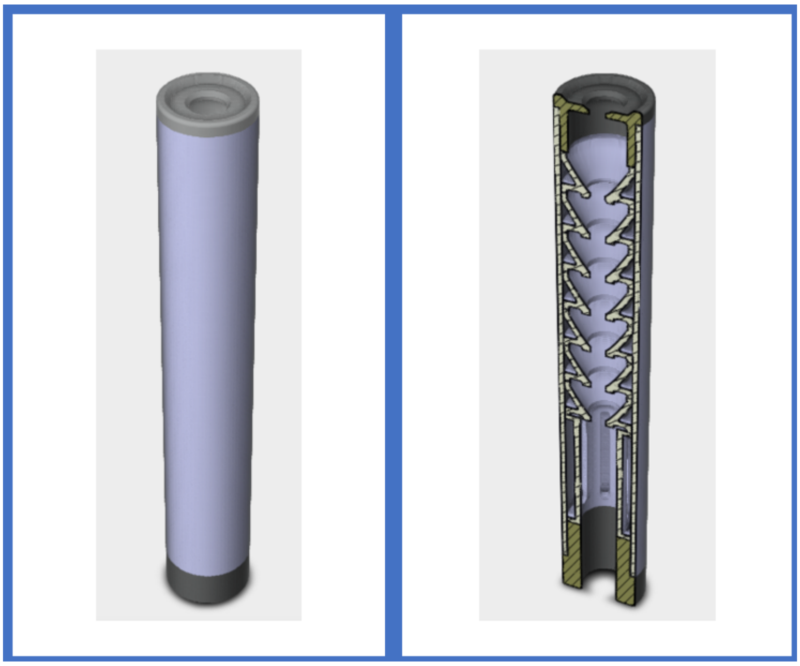

Figure 4.25: Muffler with Baffle type Bubble reducer

This concept underwent further refinement through acoustic and acoustic-shell simulations to ensure the product operated within the required frequency range. The final concept is illustrated in Figure 4.26 and its' components are shown in Figure 4.27.

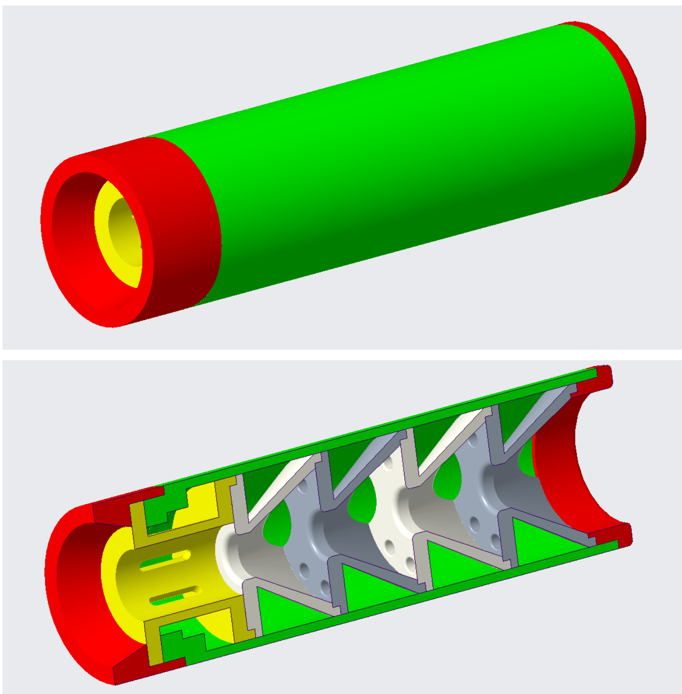

Figure 4.26: Final Concept

The bottom part, depicted in red, has a tolerance fit with the cover, shown in green. The slider, illustrated in yellow, is made of a flexible material and also maintains a tolerance fit with both the cover and the bottom. The top of the slider features a male groove, while the bottom of the cup, displayed in white, and grey, has a corresponding female groove. Additionally, the top of each cup incorporates a male groove pattern to accommodate multiple cups as required. Finally, the top section, also depicted in red, screws into the cover.

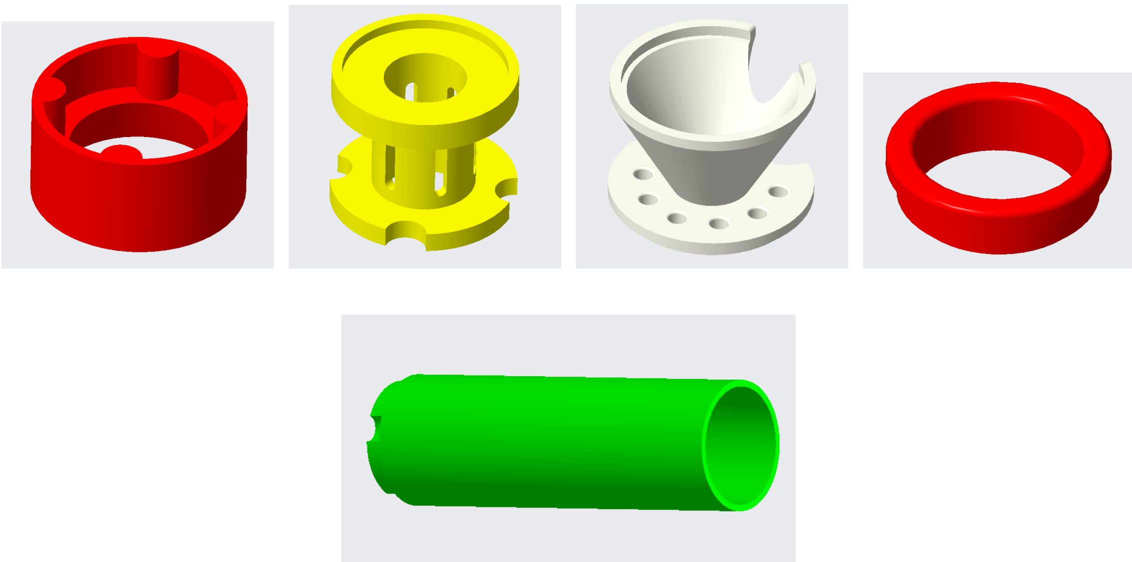

Figure 4.27: Final Concept Components

4.6 Simulations

Acoustic simulations were conducted on selected concepts using an FEM tool named COMSOL 6.1. These simulations were instrumental in pinpointing optimal solutions and iteratively adjusting design dimensions as required.

The simulation is not influenced by the sound pressure level at the inlet but solely by the shape of the concept. The phenomena of interference and standing waves lead to a gradual reduction in the sound pressure level, as illustrated in Figure 4.28. The simulation demonstrates the reduction in SPL as the sound waves propagate through the muffler. This is due to formation of standing waves (sound waves cancelling each other out) when sound reflects back from the outer surface of the body. Since this simulation only took into account the acoustic nature of the muffler, sound absorption by the muffler is not measured.

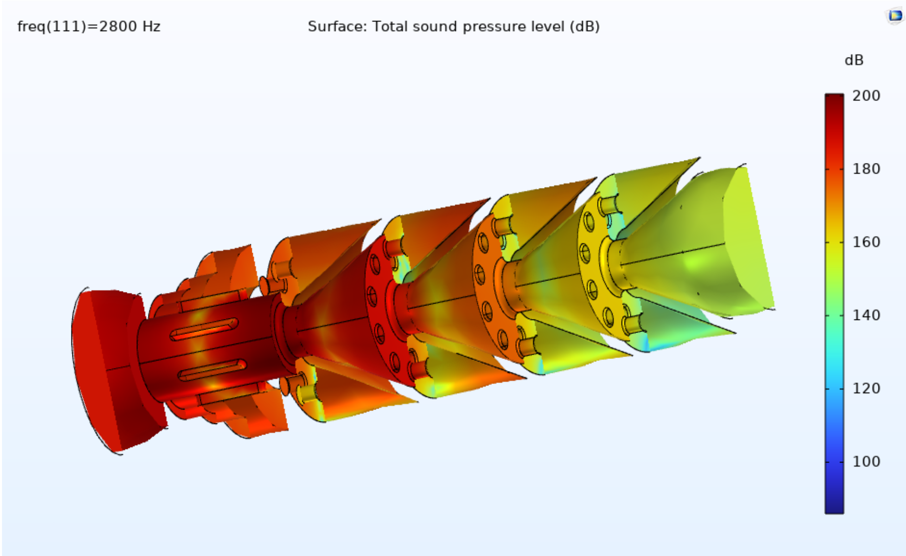

Figure 4.28: Sound Pressure Level after Acoustic Simulations

For the acoustic simulation, transmission loss for the entire muffler was also measured, and the results were plotted in both continuous and 1/3 octave bands for clarity. This result will provide an account of the frequencies at which the muffler is working best. The higher the transmission loss at a certain frequency, the better the muffler is at reducing noise at that frequency. As evident in Figure 4.29, the muffler effectively reduces noise at higher frequencies. However, this simulation does not take into account the absorptive properties of the muffler, and hence there is not much transmission loss at lower frequencies.

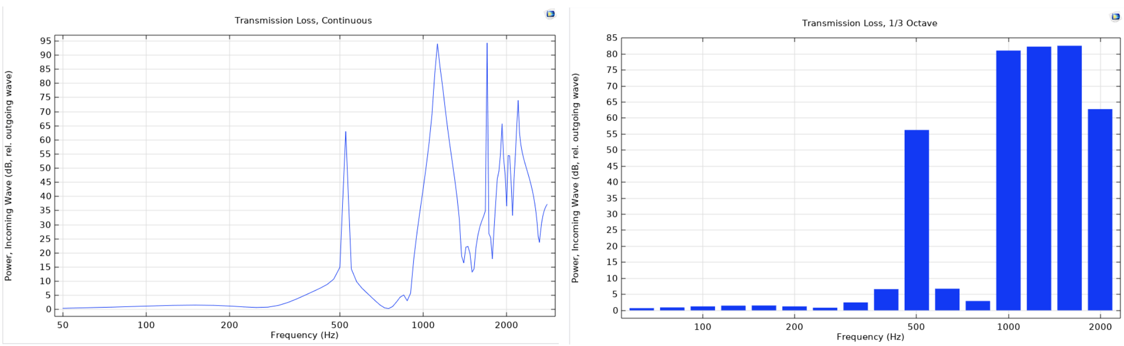

Figure 4.29: Transmission Loss from Acoustic Simulation

Engines are known to produce loud noise at lower frequencies. To determine the transmission loss at these frequencies, absorption must be simulated.
Due to computational power limitations, the intricate design of the muffler could not be directly simulated for absorption. A simplified model, devoid of numerous small ridges and holes, was developed to simulate the acoustic-shell interaction. The outcomes are depicted in Figure 4.30.

These simulations take into account both of the noise reduction phenomenon of mufflers -

1. Noise absorption by the surface material of the muffler.
2. Noise cancellation by reflection from the surface of the muffle.

The simulation reveals a drop in SPL at the end of the muffler and transmission loss at lower frequencies, which was the primary objective.

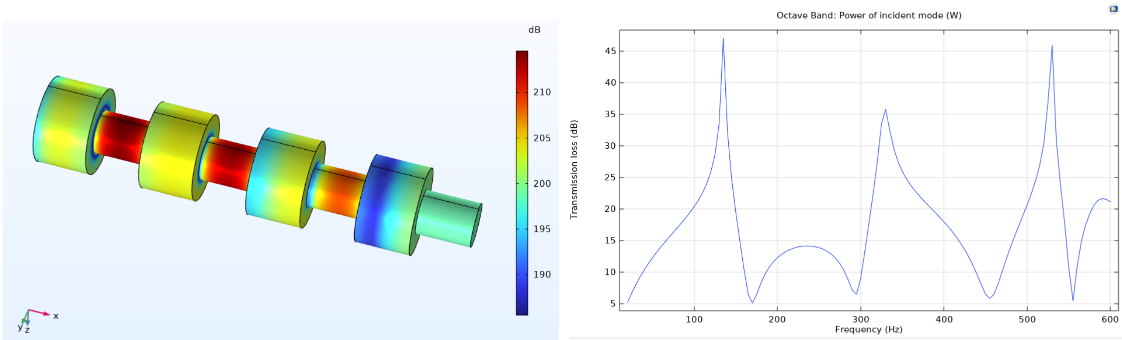

Figure 4.30: Sound Pressure Levels and Transmission Loss from Acoustic-Shell Simulation

5
Conclusion and Recommendations

5.1 Conclusion

Throughout the course of this thesis project, several findings and implications emerged:

- **Deep Understanding of the Engine and the Problem:** Causes of the NVH problem were identified. These include loud piston firing noises and their harmonics, exhaust noise when the boat is above plane, vibrations caused by excessive bubbling at idle, and vibrations when on full load.
- **Customer, User, and Stakeholder Needs:** Customers and users preferred a boat ride that is smoother and less noisy over engine performance. An optimal solution would be the ability to switch between silent mode and power mode.
- **Benchmarks:** While Volvo Penta leads the industry in terms of low NVH levels compared to other inboard engines, its performance is different when compared to outboard engines. Even though outboard engines are less powerful, there is a 4 to 6 dB-A difference between the two, which is significant.
- **Noise Sources:** The noise source-separating algorithm successfully separated noise sources within the engine and resolved them into component waves. The primary noise source from the engine was identified as being due to piston firing and its harmonics.
- **Product Concept:** Numerous concepts and ideas were generated and evaluated. The most promising of these were digitally prototyped. Concept 115 received extensive attention and development.
- **Simulations:** Acoustic and acoustic-shell simulations were executed on the models. The results from the acoustic simulations indicated significant transmission loss at higher frequencies. In contrast, the results from the acoustic-shell simulations showed promising noise reduction potential at lower frequencies. A trend was observed: reducing the size of holes and perforates shifted the transmission loss graph to lower frequencies. An optimal size was determined to ensure minimal back pressure.

5.2 Recommendations

The following recommendations are provided to Volvo Penta for potential further development of this solution:

- Consider the implementation of active noise and vibration cancellation. While the development of this mechatronic system might be costly, it has the potential to reduce noise and vibration to almost negligible levels.
- Introduce the capability to switch between performance mode and silent mode.
- Utilize the noise signals from the noise source-separating algorithm to conduct precise simulations. Employing a sound camera can assist in correlating noise signals with their respective sources. This methodology can be further refined for use in an active noise cancellation system.
- Undertake a complete redesign of the exhaust system to integrate a larger, more efficient muffler. An increase in the diameter of the muffler can exponentially amplify transmission loss.
- For simulations, use more powerful computers to run acoustic-shell simulations on the final concept, rather than relying on a simplified model, to yield more accurate results.
- Implement the encapsulation optimization method discussed earlier and design an encapsulation for the engine. Relevant material information should be sourced from Volvo GTT.

Bibliography

[1] Volvo Penta Homepage. [Online]. Available: https://www.volvopenta.com/

[2] "Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008," *Official Journal of the European Union*.

[3] Digital Signal Processing. [Online]. Available: https://en.wikipedia.org/wiki/Digital_signal_processing

[4] A.-O. Boudraa and J.-C. Cexus, "EMD-based signal filtering," *IEEE Transactions on Instrumentation and Measurement*, vol. 56, no. 6, pp. 2196–2202, 2007.

[5] Z. Wu and N. E. Huang, "Ensemble empirical mode decomposition: a noise-assisted data analysis method," *https://doi.org/10.1142/S1793536909000047*, 2009.

[6] H. Li, Z. Li, and W. Mo, "A time varying filter approach for empirical mode decomposition," *Signal Processing*, vol. 138, pp. 146–158, 2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0165168417301135

[7] J. V. Stone, "Independent component analysis: an introduction," *Trends in Cognitive Sciences*, vol. 6, no. 2, pp. 59–64, 2002. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1364661300018131

[8] F. Bi, L. Li, J. Zhang, and T. Ma, "Source identification of gasoline engine noise based on continuous wavelet transform and EEMD–RobustICA," *Applied Acoustics*, vol. 100, pp. 34–42, 2015.

[9] Fast Fourier Transform. [Online]. Available: https://en.wikipedia.org/wiki/Fast_Fourier_transform

[10] Clear Wake Exhaust. [Online]. Available: https://www.volvopenta.com/marine/accessories/clear-wake-exhaust/

[11] M. Denscombe, *The good research guide : for small scale research projects*. Maidenhead : Open University Press, 2014.

[12] J. Malmqvist, "Product planning – needs and opportunities (PPU085) lecture 4: Information search and analysis," 2021.

[13] K. Ulrich, S. Eppinger, and M. C. Yang, *Product Design and Development*. McGraw Hill, 2020.

[14] N. F. M. Roozenburg and J. Eekels, *Product Design: Fundamentals and Methods*. Wiley, 1995.

[15] L. Almefelt, F. Berglund, P. Nilsson, and J. Malmqvist, "Requirement management in practice: Findings from an empirical study in the automotive industry," *Research in Engineering Design*, vol. 17, pp. 113–134, 12 2006.

[16] R. Scupin, "The KJ method: A technique for analyzing data derived from japanese ethnology," *Human Organization*, vol. 56, pp. 233–237, 1997.

[17] N. Kano, N. Seraku, F. Takahashi, and S. Tsuji, "Attractive quality and must-be quality," *The Journal of the Japanese Society for Quality Control*, vol. 14, pp. 39–44, 1984.

[18] Boat Engine Comparison. [Online]. Available: https://www.boatingmag.com/boat-engine-comparison/

A

Appendix 1

```
"""
Created on Tue Feb 21 14:12:57 2023

@author: Yeshwanth K P
"""
# Required pip installations: SciPy, PyEMD, RobustICA,
PyTVFEMD

from pytvfemd import tvfemd
from scipy import signal
import numpy as np
import pylab as plt
from scipy.fft import fft, fftfreq
from robustica import RobustICA
from matplotlib import cm
from scipy.io import wavfile


# %% Define signal (Change this to the new signal
from D2A converter)

fs,S = wavfile.read('.\Idle Data\PTA85_
D4HybridEngineRoom_C15 Engine_room.wav')
S = S.astype(np.float64)

N = len(S)
duration = N/fs
t = np.linspace(0,duration,len(S))
# t = np.linspace(0, 10, 1000)
# tn = t.shape[0]

# sin = lambda x,p: np.cos(2*np.pi*x*t+p*np.pi*t**2)
# S = sin(33,50) + sin(56,50)+sin(94,50)
```

```
# %% Execute TVF-EMD on S to seperate noise sources
eIMFs = tvfemd(S)
eIMFs = np.transpose(eIMFs)
nIMFs = eIMFs.shape[0]

# %% Plot results of TVF-EMD
plt.figure(figsize=(12,9))
plt.subplot(nIMFs+1, 1, 1)
plt.plot(t, S, 'r')
for n in range(nIMFs):
    plt.subplot(nIMFs+1, 1, n+2)
    plt.plot(t, eIMFs[n], 'g')
    plt.ylabel("IMF %i" %(n+1))
    plt.locator_params(axis='y', nbins=5)
plt.xlabel("Time [s]")
plt.tight_layout()
#plt.savefig('tvfemd_time', dpi=120)
plt.show()

# %% FFT after seperation of noise sources to determine
dominant freq band
yf = dict()
xf = dict()
for n in range(nIMFs):
    yf[n] = fft(eIMFs[n])
    xf[n] = fftfreq(N, 1/fs) #N is number of samples which
    is N = duration*sample_rate
   #xf[n] = np.linspace(20,20000,tn) #this must be removed
plt.figure(figsize=(12,9))
for n in range(nIMFs):
    plt.subplot(nIMFs+1, 1, n+1)
    plt.plot(xf[n], np.abs(yf[n]))
    plt.ylabel("IMF %i" %(n+1))
    plt.locator_params(axis='y', nbins=5)
plt.xlabel("Frequency [Hz]")
plt.tight_layout()
#plt.savefig('tvfemd_freq', dpi=120)
plt.show()

# %% RobustICA to make each source independent of the other
eIMFs = np.transpose(eIMFs)
rica = RobustICA(n_components=nIMFs+1)
Snew, A = rica.fit_transform(eIMFs)
eIMFs = np.transpose(eIMFs)
Snew = np.transpose(Snew)
nSnew = Snew.shape[0]
```

```
# %% Plot results of RobustICA
plt.figure(figsize=(12,9))
plt.subplot(nIMFs+1, 1, 1)
plt.plot(t, S, 'r')

for n in range(nSnew):
    plt.subplot(nSnew+1, 1, n+2)
    plt.plot(t, Snew[n], 'g')
    plt.ylabel("S %i" %(n+1))
    plt.locator_params(axis='y', nbins=5)
plt.xlabel("Time [s]")
plt.tight_layout()
#plt.savefig('tvfemd_RobustICA_time', dpi=120)
plt.show()

# %% FFT after isolation of noise sources to determine
dominant freq band
yf = dict()
xf = dict()
for n in range(nSnew):
    yf[n] = fft(Snew[n])
    xf[n] = fftfreq(N, 1/fs) #N is number of samples which
    is N = duration*sample_rate
    #xf[n] = np.linspace(20,20000,tn) #this must be removed
plt.figure(figsize=(12,9))
for n in range(nSnew):
    plt.subplot(nSnew+1, 1, n+1)
    plt.plot(xf[n], np.abs(yf[n]))
    plt.ylabel("IMF %i" %(n+1))
    plt.locator_params(axis='y', nbins=5)
plt.xlabel("Frequency [Hz]")
plt.tight_layout()
#plt.savefig('tvfemd_RobustICA_freq', dpi=120)
plt.show()

# %% Other Plots
widths = np.arange(1, 21)
cwtmatr = signal.cwt(S, signal.ricker, widths)
cwtmatr_yflip = np.flipud(cwtmatr)
plt.imshow(cwtmatr_yflip, extent=[0, 20000 , 0, 200],
cmap='plasma', aspect='auto',
           vmax=abs(cwtmatr).max(), vmin=-abs(cwtmatr).max())
plt.colorbar()
plt.show()
```

```
psd_freq, psd_pow = signal.periodogram(S,4e4)
plt.semilogy(psd_freq, psd_pow)
#plt.ylim([1e-7, 1e2])
plt.xlabel('Frequency [Hz]')
plt.ylabel('PSD [V**2/Hz]')
plt.show()

psd_freq, psd_pow = signal.welch(S,4e4)
plt.semilogy(psd_freq, psd_pow)
#plt.ylim([1e-7, 1e2])
plt.xlabel('Frequency [Hz]')
plt.ylabel('PSD [V**2/Hz]')
plt.show()

spec_freq, spec_t, spec_pow = signal.spectrogram(S,1)
plt.pcolormesh(spec_t, spec_freq, spec_pow,
shading='gouraud')
plt.ylabel('Frequency [Hz]')
plt.xlabel('Time [sec]')
plt.colorbar()
plt.show()

fig = plt.figure()
ax = plt.axes(projection='3d')
ax.plot_surface(1e4*spec_freq[:, None], spec_t[None, :]/100,
10.0*np.log10(spec_pow), cmap=cm.plasma)
ax.set_xlabel('Frequencies (Hz)')
ax.set_ylabel('Time (s)')
plt.show()



# %% Checking whether the functions add up to the given input
NormS = S/abs(np.min(S))
RICA_S = Snew[0]
for n in range(1,nSnew):
    RICA_S = RICA_S + Snew[n]
Noise = S - RICA_S*10000
multipli_fctor1 = S/RICA_S
# All values should be either NAN or 1

TVF_S = eIMFs[0]
for n in range(1,nIMFs):
    TVF_S = TVF_S + eIMFs[n]

multipli_factor2 = S/TVF_S
```

```
# All values should be either NAN or 1


# %% Finding Dominant Frequency

dom_freq = np.linspace(0,0,nIMFs)
for n in range(nIMFs):
    yf[n] = fft(eIMFs[n])
    xf[n] = fftfreq(N, 1/fs)
    #N is number of samples which is N = duration*sample_rate
    a = yf[n]
    i = np.unravel_index(a.argmax(), a.shape)
    dom_freq[n] = abs(xf[n][i])
```

B

Appendix 2

The unabridged results from TVFEMD in frequency domain can be seen below. These graphs show the excitation of different unknown components of the engine in the frequency domain. Each graph is for an IMF, which is what the algorithm separates the noise signals into. The x-axis of the graph is a logarithmic scale of frequency, while the y-axis depicts the amplitude of frequency in dB. It can be seen that the excitation at higher frequencies are very low. The sources with high amplitudes have been cropped and shown in Figure 4.11.

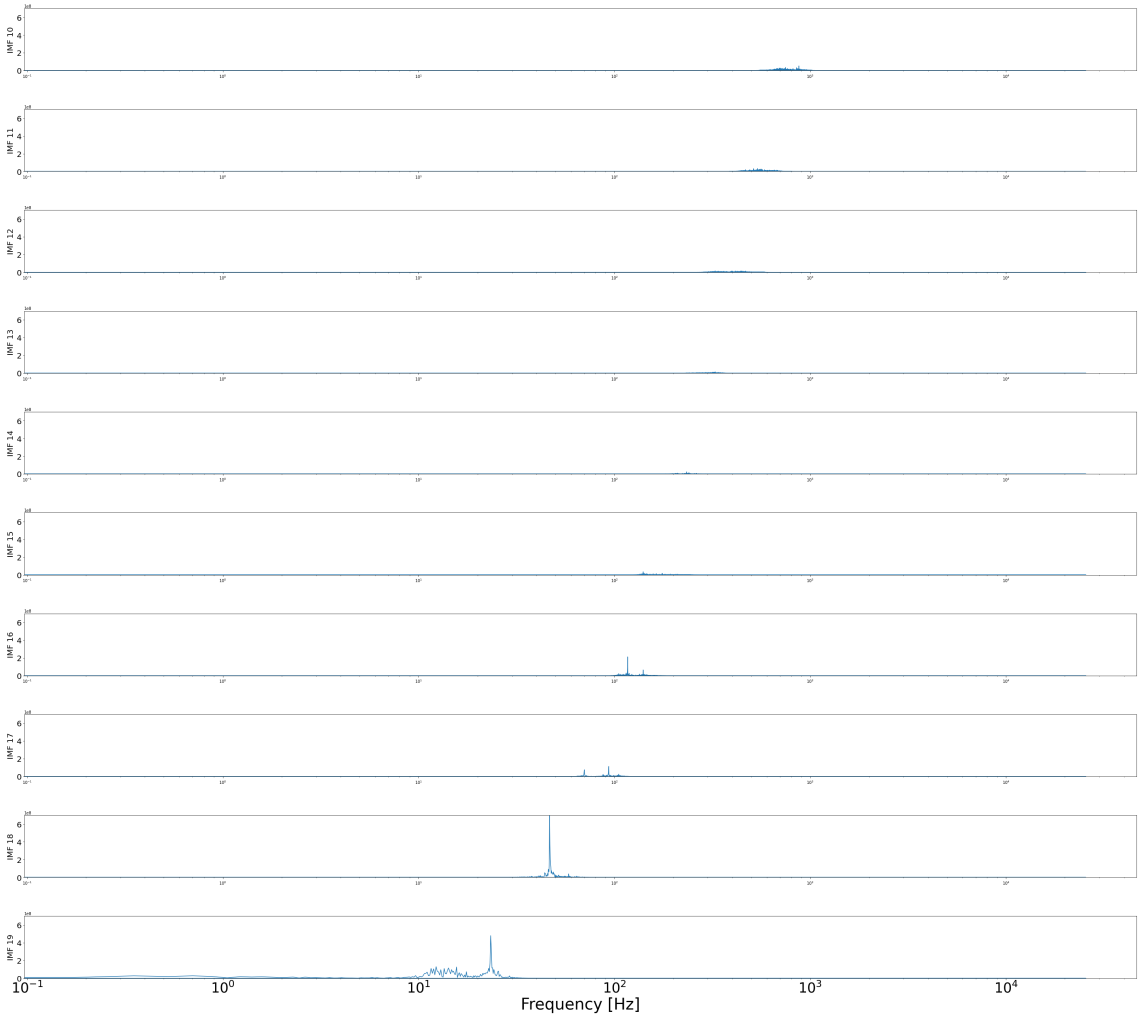

Figure B.1: Complete TVFEMD results from idling sound data in frequency domain

The unabridged results of applying the TVFEMD algorithm on the low frequency signal to further resolve it into component sources in frequency domain.

Figure B.2: TVFEMD results from low frequency idling sound data in time domain

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