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MODULAR EXHAUST DESIGN AND MANUFACTURING PROCESS FOR LOW COST LOW VOLUME RAPID BUILD TO ORDER SYSTEMS

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ABSTRACT

Engine exhaust noise is a significant contributor to the overall acoustic signature of military ground vehicles. Reducing this noise without sacrificing engine power and a large amount of space required for a high performing muffler is a costly and challenging task. This paper introduces a method to automate the exhaust system design process and implement modular manufacturing techniques for low volume production runs of 10 to 1000 units. This modular method provides high-performing, customized exhaust systems without the large cost burden and long lead times associated with ground vehicle exhaust system procurement.

INTRODUCTION

Current methods for developing high performing exhaust systems for military ground vehicles require a significant amount of time for optimizing the acoustic elements and result in expensive, low volume manufacturing processes with long lead times. The characteristics of engine exhaust noise make it a high priority when attempting to reduce the overall acoustic signature of a vehicle. Combustion tones and low order harmonics generally dominate the noise levels near the vehicles introducing risk of degraded soldier awareness and communication. Because low frequency combustion tones travel efficiently through the atmosphere, often resulting in unacceptable vehicle detection ranges, there is an increasing priority by the U.S. Armed Forces to reduce noise levels in and around the vehicles while improving their detection range.

This paper introduces an innovative process for designing, optimizing and manufacturing affordable, high performance, passive exhaust systems. We describe a system for using target attenuation or insertion loss curves as inputs to optimize a muffler which drastically reduces development time. This has been accomplished through the development of software that creates a 1-D multi-domain model based on the inputs of desired attenuation, space claim, backpressure and exhaust gas temperature. An overview of this process is shown in Figure 1. The model can be used both to optimize the acoustic elements to meet the performance requirements and to facilitate the creation of a technical data package (TDP) containing the manufacturing specifications for the system. The TDP is inserted into a streamlined manufacturing process that efficiently handles the low volume production runs typical of military ground vehicles. High performance, build-to-order exhaust systems with short lead times can be produced without the high price tag normally associated with a highly customized exhaust system.

Figure 1: The modular muffler process

ACOUSTIC SIGNATURE MANAGEMENT

One of the main contributors to the acoustic signature of ground vehicles is the engine exhaust. Engine combustion emits low-frequency noise at a relatively high level compared to other noise sources. Attenuating the exhaust noise is a challenging task but very important to the health and safety of the vehicle crew.

From a human factors standpoint, vehicle-borne noise could easily reach levels that make it difficult to be near the vehicle for extended periods. Wearing hearing protection is not desirable since this decreases the awareness of crew members to useful sounds coming from the vehicle and surrounding environment. Noises that resonate at certain frequencies could also make crew members uncomfortable and distract them from their mission.

From a safety standpoint the low-frequency exhaust noise has a big impact on vehicle detection range. If left untreated, these noises will result in unacceptable detection ranges, risking the safety of the crew. Improvements in vehicle noise control are critical for safety and maximizing mission effectiveness.

The current state of the art techniques for developing a new exhaust system for small fleets, such as seen in the US Military, are not cost effective. Much time is spent running acoustic and flow analyses on muffler design iterations until the desired performance is attained. Depending on the requirements, this stage could take anywhere from two weeks to two months. The initial cost of the muffler is driven up by the large amount of engineering time spent on analysis. Once the design is completed, the technical data package must then be produced. This requires more engineering time, both to verify that the muffler elements can be manufactured and to create a detailed production package. The result is a new exhaust system that will not have enough volume in production to effectively amortize the upfront costs. Each part is made individually and then hand-assembled and welded. The high cost of a custom exhaust has driven some DoD programs to purchase vehicles with a minimally effective catalog muffler, or no muffler at all. This paper presents a process to allow all types of ground vehicle programs to procure application specific, high performing exhaust systems for an incremental increase in cost. It utilizes a combination of software and modular design concepts to drastically reduce the amount of resources normally used in exhaust system development.

1-D MODELING

1-D acoustic and flow modeling will form the basis for designing and optimizing the muffler. SIDLAB, a commercially available, 1-dimensional acoustic and flow software design tool will be used to create and analyze a series of two-port elements that make up the muffler. A graphic of a simple model is shown in Figure 2. It consists of a helmholtz resonator with a length of straight pipe on each side and open end conditions on the inlet and outlet.

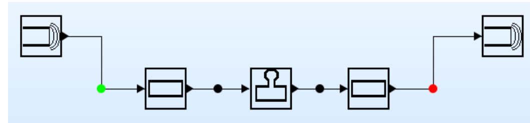

Figure 2: Simple 1-D muffler circuit.

The different end conditions are defined by the following one-port elements;

- open end
- constant impedance
- reflection free
- IC engine impedance
- user defined impedance.

The muffler elements supported by SIDLAB and that work well in IC engine exhaust systems include;

- Helmholtz resonator
- Quarter wave resonator
- Expansion chamber
- Perforated duct
- Lined duct
- Orifice
- Diffuser
- Area expansion
- Area contraction

The model has three options for noise sources; constant pressure, IC engine source strength, and a user-defined source characterized by a frequency dependant pressure.

Once the graphical model is developed, a system of equations can be derived and solved. To build the equations, two state variables are chosen to represent the pressure and mass velocity in the system, respectively. For each element in the graphical model, a 2x2 transfer matrix can be defined. This matrix describes the linear transformation of these state variables across the element. This can be shown as:

$$\begin{bmatrix} p_r \\ v_r \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} * \begin{bmatrix} p_{r-1} \\ v_{r-1} \end{bmatrix}$$

where r represents the element in the element number in the chain.

In models with multiple elements strung end to end, the resulting system of equations can be simplified by finding one transfer matrix which represents the linear transformation across the entire system. It is evident from the equation above that the system matrix can be found for elements in series by multiplying across each transfer matrix.

At this point various performance results such as transmission loss, insertion loss, noise reduction and backpressure can be calculated.

The main advantage of 1-D modeling in this case is that elements can be reconfigured and altered and new results can be realized in a very short amount of time. Combining this method with the modular exhaust optimization and manufacturing techniques has been shown to reduce development time from weeks to days or possibly hours.

MUFFLER OPTIMIZATION OVERVIEW

Software has been developed to support the rapid design of a high performance exhaust system using global optimization techniques. A user starts the optimization process by entering a target insertion loss or transmission loss curve along with their engine exhaust characteristics and the cross-sectional shape of the muffler space claim. This is followed by choosing a muffler configuration such as two-chamber or three-chamber and the initial, desired acoustic elements. This step also starts the automatic generation of a parameterized 3-D manufacturing model, using the SolidWorks CAD package, to be used for generating the TDP. An example 3-D model generated by the modular software is shown in Figure 3. Next the parameters of the system are defined. Typical parameters consist of muffler width and height, chamber length, pipe diameters and pipe thickness.

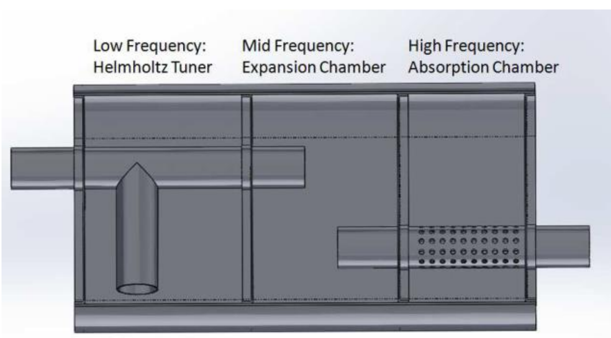

Figure 3: 3-D manufacturing model created with modular parameters.

Once the elements have been defined the software automatically creates and runs a 1-D model representing the initial design of the full muffler. The initial results will be compared with the target TL or IL curve. Next, an optimization algorithm is used to tune the parameters to reduce the error between the results and the target. In a matter of minutes the element parameters can be adjusted and new results calculated. As the elements are updated, the manufacturing model is automatically re-built in real time with the latest parameter definitions. This is useful for visualizing the muffler on the vehicle and also for verifying the manufacturability.

MUFFLER OPTIMIZATION ALGORITHM

There are several different methods for implementing the optimization algorithm that need to be evaluated. The choice of algorithm depends mainly on the size and complexity of the domain of system parameters. Options include large parametric studies, simple slope climbing algorithms, hybrids of these, or more complicated global optimization techniques such as genetic algorithms or simulated annealing.

In these muffler designs, the domain of potential system parameters is relatively small compared to the processing power of a modern CPU. Several assumptions can be made which significantly limit the number of possible solutions. An example is the fact that only fixed pipe sizes for elements will be used according to what inventory is readily available. Another example is that there is a practical limit to the number of chambers that can be fit inside a muffler. Another observation which aids in the optimization process is that the complexity of the domain space is low. For example, changing the length of the neck on a Helmholtz element mainly affects the tuned frequency of the element. Likewise, many of the parameters in the system are expected to affect only aspects of the system TL or IL in a simple continuous fashion. These assumptions make it probable that a large parametric study encompassing the entire design space or simple hill climbing algorithms will be sufficient for tuning the system.

In the case that these simple algorithms do not produce favorable results independently, they can be combined into a simple hybrid algorithm. The algorithm would first do a rough survey of the solution domain by using parameter intervals set to limit the overall runtime of the survey. Next, a hill climb algorithm or a finer parametric algorithm could be implemented to search near the best point found in the initial survey. This process could be repeated until an adequate solution is identified.

A final option is to use a more complicated global optimization algorithm for tuning the system. These algorithms are generally provided in software packages for tuning black box systems, and require only the range of potential inputs and a fitness function. Each of these algorithms can be evaluated quickly because they are very similar in how they will be integrated into the software.

GENERATING THE TECHNICAL DATA PACKAGE (TDP)

Once the desired muffler performance is obtained a TDP is required to define how the muffler will be built. This will include part drawings, assembly drawings and 2-D layouts for CNC cutting of sheet metal parts. The manufacturing model will facilitate the creation of drawings such that the TDP will closely follow the completion of the muffler optimization. Minimal engineering time will be needed to finalize the TDP for manufacturing. This will mostly involve verification that each part and assembly supports the modular manufacturing techniques and ensuring there is enough detail to produce the parts. Near future developments will add automatic generation of CNC code and necessary information for material planning.

MANUFACTURING TECHNIQUES

Current manufacturing processes for low volume, custom designed systems do not support fast lead times at an affordable price. The modular muffler design process will limit the complexity of the exhaust system so that special tooling and fixtures will not be needed for production. The restriction of the design space will also ensure that the design will address durability requirements as demanded in a typical muffler installation environment. Limitations determined in the design stage drive the manufacturing model to a shape and configuration that can be produced with simple manufacturing techniques. A streamlined process that integrates certain manufacturing processes will make short lead times possible for build-to-order exhaust systems. These manufacturing processes will include;

- CNC cutting
- CNC machining
- Stamping
- CNC roll forming
- Resistance roll welding
- Tracked seam welding

The level of automation used will depend on the production volumes encountered and the variations of muffler configurations that must be accommodated. Figure 4 shows a CNC roller forming a muffler shell. CNC machines are ideal for low volume production because they combine some automation with the ability to rapidly switch from one program to another with no tooling changes and minimal setup time.

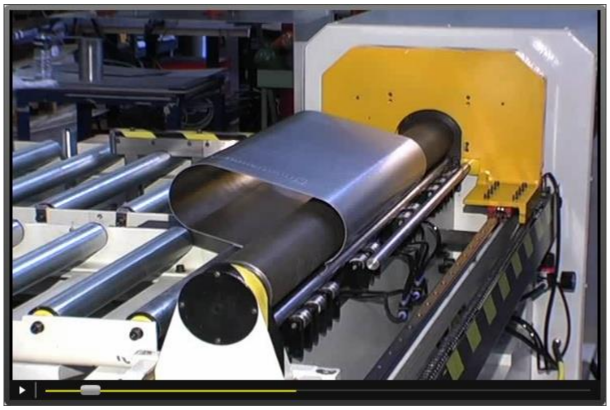

Figure 4: CNC roll forming a muffler shell.

A simple stamping process has been developed for production of muffler end caps and baffles. A stamped end cap is shown in Figure 5. The tooling is very inexpensive and consistently produces accurate parts. Another advantage of this type of stamping is that baffles of any shape and configuration can be accommodated. The simplified process ensures that changeover between different production runs is fast and simple.

Figure 5: Stamped muffler end cap.

Regardless of the run sizes, the lead times will be short and tightly managed.

MODULAR EXHAUST APPLICATIONS

The modular exhaust design and manufacturing process has the potential to improve performance, cost, logistics, and lead times across a wide range of applications. Recent success in the development of a high performance muffler for the power sports industry has demonstrated that the design process is cost effective in meeting desired performance requirements. Figure 6 depicts a UTV muffler that was developed using the modular process.

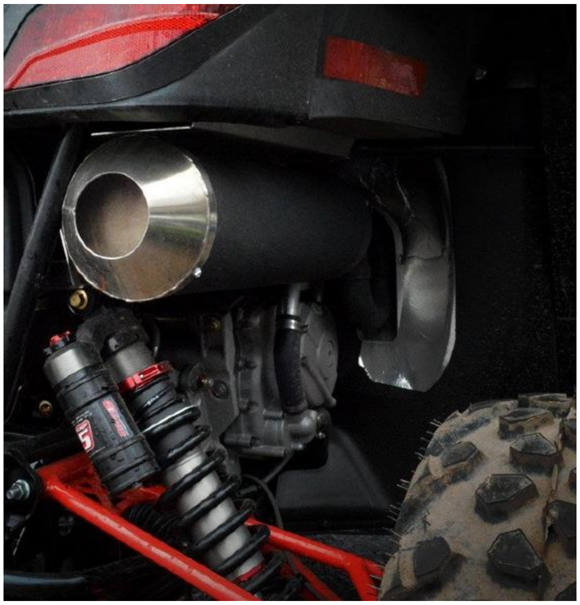

Figure 6: After-market UTV muffler developed with the modular process.

Near term efforts to demonstrate the modular process are planned for several military ground vehicles. Reaching beyond the military ground vehicle market, the technology can be extended to other industries such as naval defense, off-highway and other industries where custom designed mufflers are desired at low quantities.

EXHAUST SYSTEM COST ANALYSIS

The current processes for developing a custom exhaust system are time consuming and labor intensive. Several weeks can be spent designing, analyzing and optimizing a muffler in order to meet the basic performance and space claim requirements for ground vehicles. The resulting design will usually lead to a complex shape that is meant to maximize usage of the exhaust system space claim. This requires a custom fixture and tooling for production which adds cost and increases lead times.

The modular software will shorten the design and optimization stage from weeks to near negligible time. It will also provide a final design that is straightforward to manufacture. No special tooling or complex fixtures will be required since the shape and configuration are restricted during the design stage to what the streamlined manufacturing process can support. The transition from design to manufacturing will be fast due to the TDP being generated automatically in the software. The target volumes for the modular exhaust production process are between 10 and 1000 mufflers. The baseline pricing for a mid-size muffler will be in the $500 range for a quantity of 100 units. A comparable, custom muffler built with conventional manufacturing processes would cost upwards of $2,000. The price will vary with muffler size and performance characteristics required by the customer. The manufacturing process will also reduce the lead times normally associated with custom exhaust systems. Build-to-order mufflers will relieve customers of having to manage a large inventory since new production can be set up and running in a very short time.

CONCLUSIONS

This paper has shown how advancements in acoustic modeling software, 3-D CAD software and manufacturing technology can be combined to form a new state of the art process for exhaust system development. Engine exhaust noise has long been a difficult problem area when trying to manage acoustic signatures of ground vehicles. The process presented has shown how we can fill the need to greatly reduce the cost and logistical footprint of customized exhaust system procurement for military ground vehicles without sacrificing engine power or performance. Future enhancements for this technology will be a robust optimization algorithm and advanced manufacturing techniques that will allow for faster lead times and higher quantities for build to order exhaust systems.

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