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REFINEMENT OF EXHAUST SYSTEM NOISE FROM LARGE DIESEL ENGINES USING ONE DIMENSIONAL (1D) SIMULATION

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Abstract

The airborne noise levels for large capacity diesel engines must meet legislative requirements as a minimum and may have additional constraints on level and spectral content. Exhaust system testing and development for this class of engine is generally limited to confirmation testing due to limited availability of test facilities, high cost of test hardware and testing, limited physical access, and low production volumes. Large diesel engines differ significantly from those used for automotive applications in regard to gas flow characteristics, exhaust system design, and operational modes. This study evaluates the applicability of an automotive industry one dimensional (1D) simulation software suite (Ricardo WAVE™) to the refinement of large diesel engine exhaust system performance and describes the modelling approach used. The Defence Science and Technology Group (DSTG) has developed a computer based capability for modelling the acoustic response and flow performance of exhaust systems and exhaust system components representative of large diesel engines. This capability can be used for exhaust system components, complete exhaust systems, and full engine installations. A virtual transmission loss test bench approach was employed to reduce simulation run times compared to that of complete engine installations. The modelling was conducted in order of increasing complexity where simple models were validated before progressing to more complex models. Published research and data were used for validation. The modelling capability described in this study permits assessment and development of exhaust systems, with or without engine source data, at lower cost. Savings are achieved through a reduction in test samples and physical testing.

1. Introduction

Large capacity diesel engines are used in marine, rail, and off-highway applications as propulsion engines, with generators for electrical power generation, and in diesel electric propulsion. The airborne noise levels must meet legislative requirements as a minimum and must in some applications meet additional constraints on level and spectral content. Experimental verification and development of system performance is time consuming, expensive and requires dedicated test facilities [1, 2]. This has driven the emergence of mathematical modelling, including software simulation, which is quicker, cheaper, and more flexible with respect to test parameters and test configurations. Exhaust and intake system modelling and optimization are well-researched areas with respect to automotive industry applications [3-11]. The software used in this research program is an automotive one-dimensional (1D) engine and gas dynamics simulation software package called Ricardo WAVE™.

Mufflers for large diesel engines are large, expensive to manufacture and difficult to manoeuvre with limited availability of on-engine test facilities. To illustrate the size of these components and to show the difference to automotive components, the exhaust silencer for a particular 1.5 MW marine diesel application is two metres in length and weighs 400 kilograms. In addition, the subject diesel engines differ significantly from those used for automotive applications in the following areas: higher gas flow volumes, larger amplitude exhaust / cylinder blow down pulses, lower engine speeds, constant speed operation for diesel generators, and exhausting under water in some applications. Tests on such large diesel engines are rare except for confirmation testing, due to the limited physical access, low production volumes, cost of operation, safety considerations and very limited availability.

2. One Dimensional Modelling

2.1 Ricardo Wave™ Software

The Defence Science and Technology Group (DSTG) has a licence for the Ricardo one-dimensional (1D) engine and gas dynamics simulation software suite - WAVE™. This software is used by the Power and Energy Systems Group of Maritime Division (MD) for the prediction and optimisation of diesel generator performance under maritime operating conditions. It can be used to model general and complex compressible fluid networks with flow in terms of finite volume elements, which include constant area or tapered pipes / ducts, junctions of multiple ducts, orifices, and termination points such as infinite plenums, anechoic boundaries and special machinery elements such as engine cylinders, turbochargers, superchargers and pumps. Simulations are conducted by the code solver performing the calculations needed to simulate the engine operation including power output, gas flows, and emissions. A typical engine simulation model is shown in Figure 1.

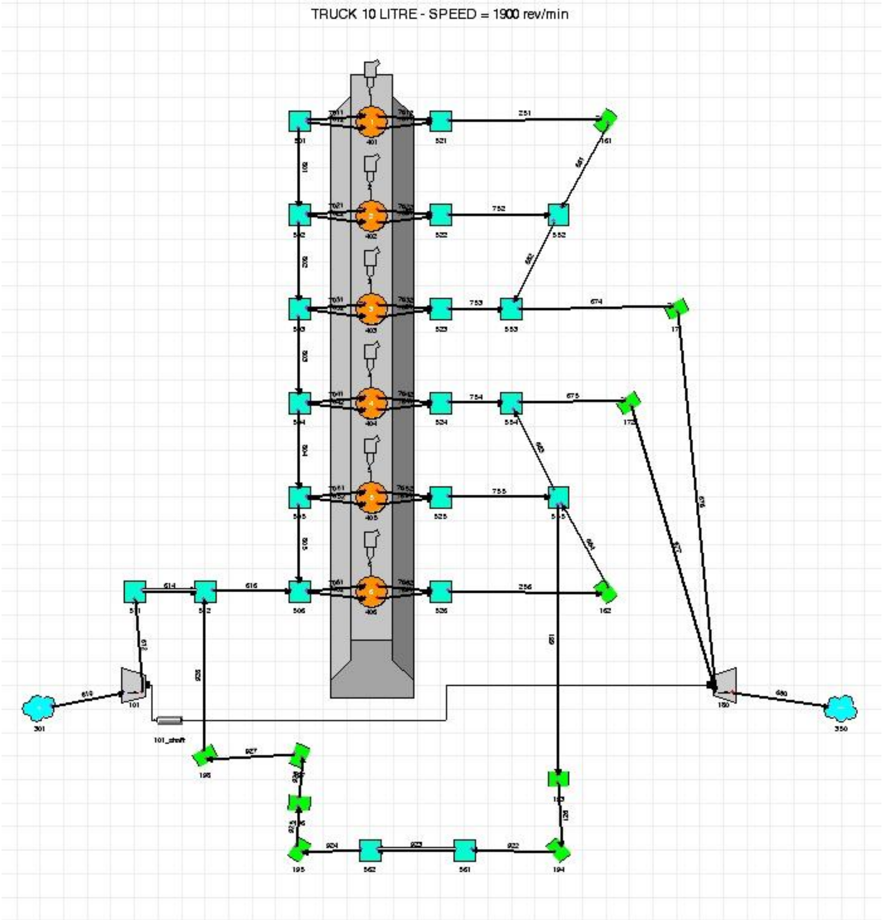

Figure 1. Schematic of Wave™ model of six cylinder turbo-charged diesel engine[10]

2.2 Modelling Methodology

The software models gas flow systems by breaking down the physical layout into 1D elements. Figure 2 shows a 1D model with three elements to represent an expansion chamber muffler. These elements are further subdivided by WAVE™ into 1D sub-volumes as shown in Figure 3 to give the user specified physical and frequency resolution. The 1D elements have longitudinal dimensions that are at least ten times the transverse dimensions and are used on the assumption that there are no lateral modes. Using 1D elements compared to three-dimensional (3D) elements markedly reduces the element complexity and number of elements which in turn greatly reduces solution run times. WAVE™ can model more complex systems by meshing with multiple 1D elements (see Figure 4) to give a quasi-3D model. As lateral modes within a 1D duct are not considered, the effective frequency range and mesh size must take into account the duct's characteristic (lateral) frequency [12] – approximately 1 kHz for a 300 mm diameter circular duct. Note that these multiple 1D elements are only connected in the longitudinal direction and not in the transverse direction as 3D elements would be.

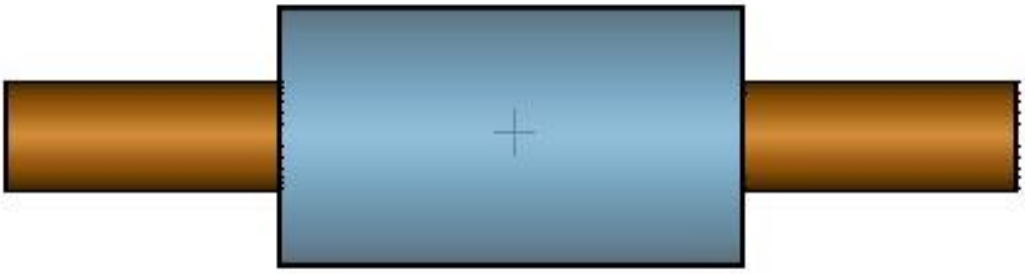

Figure 2. Simple 1D expansion chamber muffler model (3 elements)

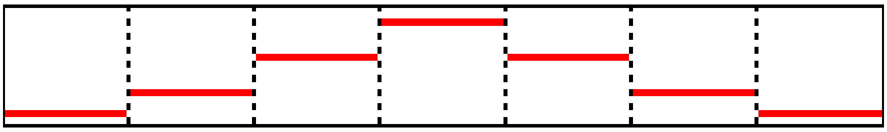

Figure 3. Subdivision of 1D duct to improve frequency response [10]

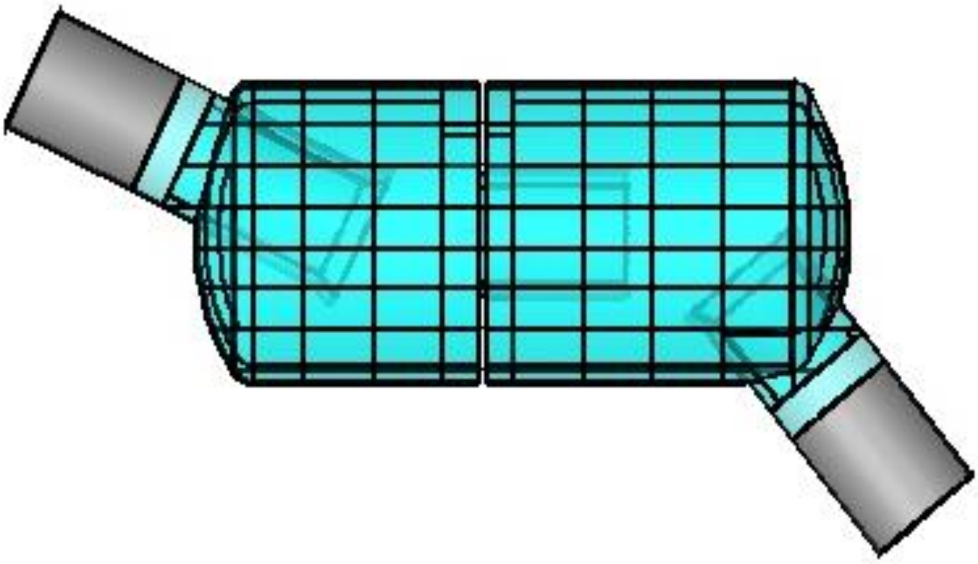

Figure 4. Complex meshed 1D muffler model

2.3 Governing Equations

In the "Fluid Control Volume" shown in Figure 5, the duct is one dimensional in that the gas flow parameters vary only in the longitudinal direction and with time. The flow of gas is assumed to be non-linear, one-dimensional, inviscid, compressible, and unsteady, and the governing equations are conservation of mass, momentum, and energy.

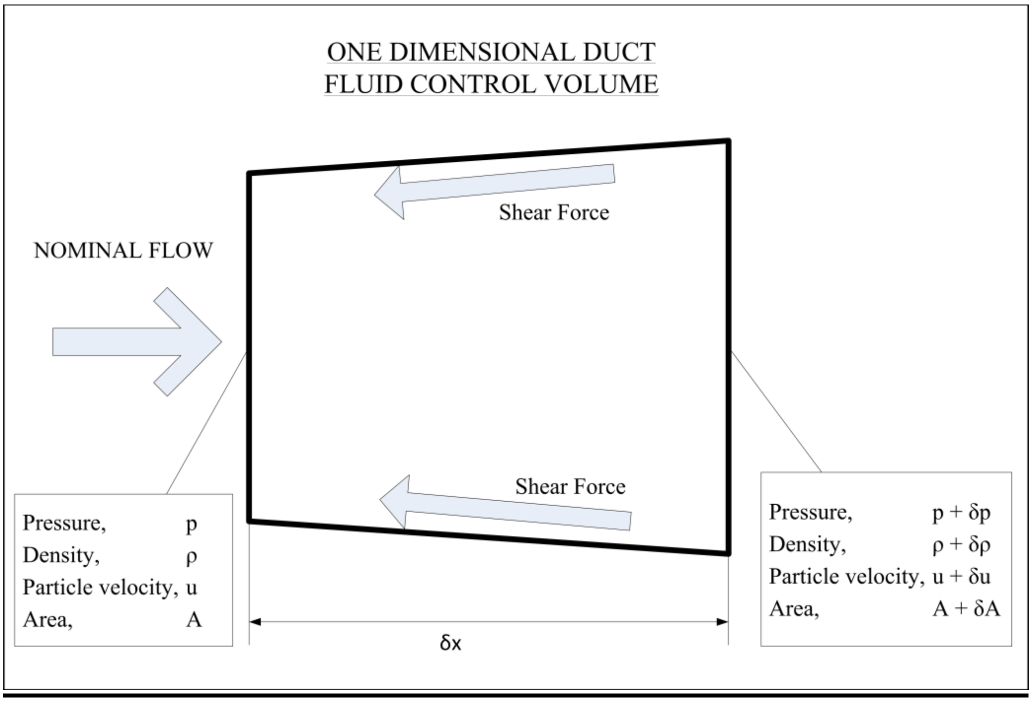

Figure 5. Duct 1D fluid control volume (after [13, 14])

The details of the flow as calculated in the flow network are obtained as a solution of quasi-one dimensional compressible flow equations and are then written in a finite difference form for each of these volumes. A staggered mesh system is used, with equations of mass and energy solved for each volume and the momentum equation solved for each boundary between volumes. The solution of the governing equations is obtained by the application of a finite difference technique, utilizing the finite-volume approach, to the discretization of the partial differential equations. The time-differencing is based on the explicit technique, with the Courant condition determining the time step [10].

2.4 Measurement of Acoustic Performance

The sound pressure level at any point in the exhaust system is the instantaneous combination of multiple forward travelling and backward travelling waves. The sound pressure level at a point as measured by a microphone or pressure transducer is accordingly dependent upon the systems both downstream and upstream of the measurement point. This has implications when measuring and characterising the acoustic performance of single elements and subsystems.

The three common ways of characterising and measuring the acoustic performance of exhaust system components such as a muffler are level difference (noise reduction), insertion loss, and transmission loss [5]. For the purposes of muffler modelling and development, transmission loss is the preferred parameter to characterise the exhaust component due to its independence from the surrounding exhaust systems and source. Transmission loss is defined as the difference in sound power level between the incident wave entering, and the transmitted wave exiting the component. It is purely attributable to the exhaust component of interest and is theoretically independent of the upstream and downstream systems. The Chung-Blaser [15, 16] experimental technique can be used to evaluate the transmission loss and uses two pressure transducers on either side of the test component to measure the upstream and downstream sound pressure levels and post processing to separate the forward and backward travelling waves – see Figure 6.

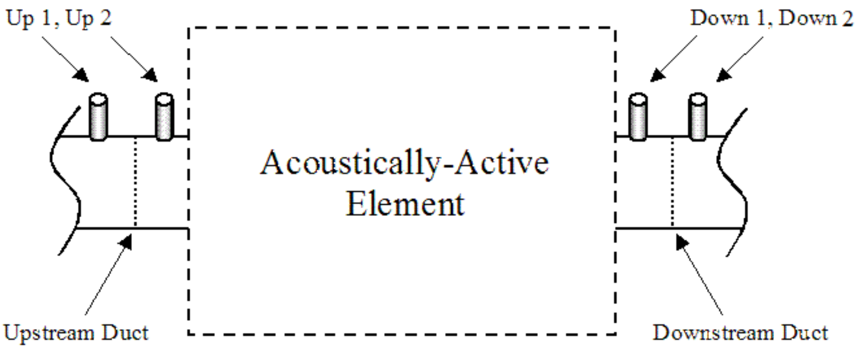

Figure 6. Four microphone arrangement for wave decomposition post processing [10]

2.5 Acoustic Modelling in WAVE™

WAVE™ has numerous tools and capabilities to perform acoustic characterisation and noise simulations of full engines, partial models, and individual components such as an exhaust muffler. For the testing and simulation of individual components, WAVE™ includes an acoustic piston / speaker and an anechoic termination to construct a test bench (see Figure 7) which is capable of determining the transmission loss and / or acoustic level difference of a component between two locations. The benefit of running partial and component models is greatly reduced running times. For example, a full engine model may take four hours to run but a test bench run of a complex meshed muffler would take ten minutes. Engine source characteristics can be extracted from full engine models for later use in partial systems.

In addition to these capabilities, WavePost™ provides acoustic-specific post-processing capabilities, including noise radiation models and acoustic processing and analysis tools. For example, resonances and standing waves can be identified using speed sweeps and spatial animations.

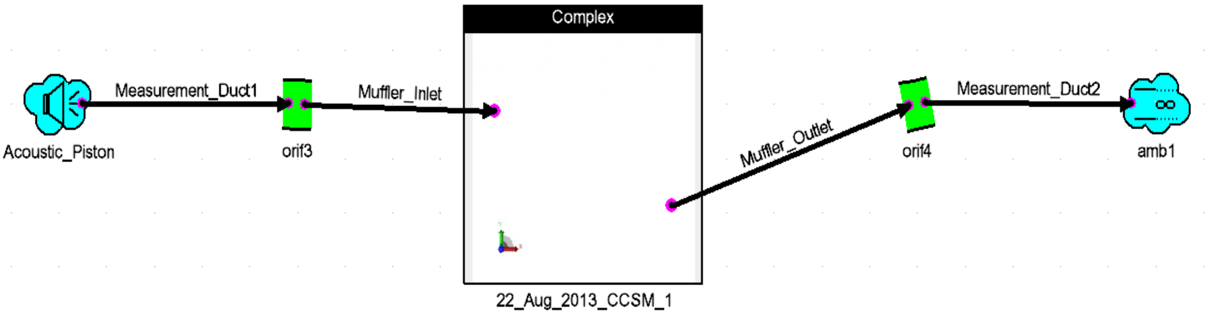

Figure 7. Schematic model of transmission loss acoustic test bench

3. Results and Discussion

3.1 Acoustic Validation Data

Significant early work targeted at piston engine helicopters was conducted by the US National Advisory Council on Aeronautics (NACA) in the 1950s [17, 18]. This work comprised extensive experimental measurements benchmarked against theoretical calculations using classical mathematical models. As noted in their report, the correlation between their theoretical calculations and measured results with respect to transmission loss magnitude reduced as the complexity of the mufflers increased e.g. multi-chamber mufflers. Approximately 80 mufflers and exhaust elements were evaluated without flow on a transmission loss experimental set-up at a temperature of 27 °C and selected items were then tested on a running engine. These studies were very well documented and are widely used for validation of exhaust system testing and modelling.

3.2 Simple NACA Models

The simple NACA mufflers listed in Table 1 were modelled in WAVE™ and the results for “Helmholtz Resonators with Variable Length of Tube” mufflers (31, 25, and 32) are compared below.

Table 1. Summary of NACA simple mufflers

Description	No of Chambers	NACA Muffler No	Variable
Expansion Chamber	Single	1,2,3,4	Expansion ratio
Expansion Chamber	Single	5,6,2,7	Length
Quarter Wave Tube	n/a	68,69,70	Length
Helmholtz Resonator	n/a	24,25,26	Volume
Helmholtz Resonator	n/a	29,25,30	Area of Tube
Helmholtz Resonator	n/a	31,25,32	Length of Tube

NACA mufflers 31, 25, and 32 are Helmholtz resonators with fixed volumes, fixed tube areas, and tube lengths of 11, 173, and 345 mm respectively. Figure 8 from NACA [18] shows the dimensions, calculated transmission losses, and experimental results and Figure 9 shows WAVE™'s modelling of the predicted transmission losses. The high frequency peak predicted by WAVE™ for muffler 32 is due to a half-wave effect in the fixed tube rather than a Helmholtz resonator characteristic. As expected, increasing the tube length increases the effective mass of the Helmholtz resonator and thereby reduces the tuned frequency as shown in the figures. The WAVE™ modelling results show good agreement with NACA results for the overall shapes and magnitude of transmission losses.

3.3 Complex NACA Models

The complex NACA mufflers listed in Table 2 were modelled in WAVE™ and the results for “Twin Expansion Chamber with Variable Internal Connecting Pipe Length” mufflers (12, 17, 18, 19, and 20) are compared below.

Table 2. Summary of complex NACA mufflers

Description	No of Chambers	NACA Muffler No	Variable
Expansion Chamber	Multi	2,12,13	No of Chambers
Expansion Chamber, External Connector	Two	12,14,15,16	Length of Connector
Expansion Chamber, Internal Connector	Two	12,17,18,19,20	Length of Connector

With the protrusion of the connecting pipe in the expansion chambers, acoustic waves are reflected from the baffle to the tip of the connecting pipe. When the length of protrusion corresponds to a quarter of the acoustic wavelength and its odd multiples, wave cancellation and interference will occur and lead to an increase in transmission loss. NACA mufflers 12, 17, 18, 19 and 20 consist of two expansion chambers (each 610 mm long and 305 mm diameter) with an internal connecting pipe of 1.3, 152, 305, 610 and 915 mm long respectively.

Figure 10 from NACA [18] shows the dimensions, calculated transmission losses, and experimental results and Figure 11 shows WAVE™'s modelling of the predicted transmission losses. It can be seen from the figures that the effect of pipe protrusion is to increase the transmission loss and broaden the frequency band of attenuation.

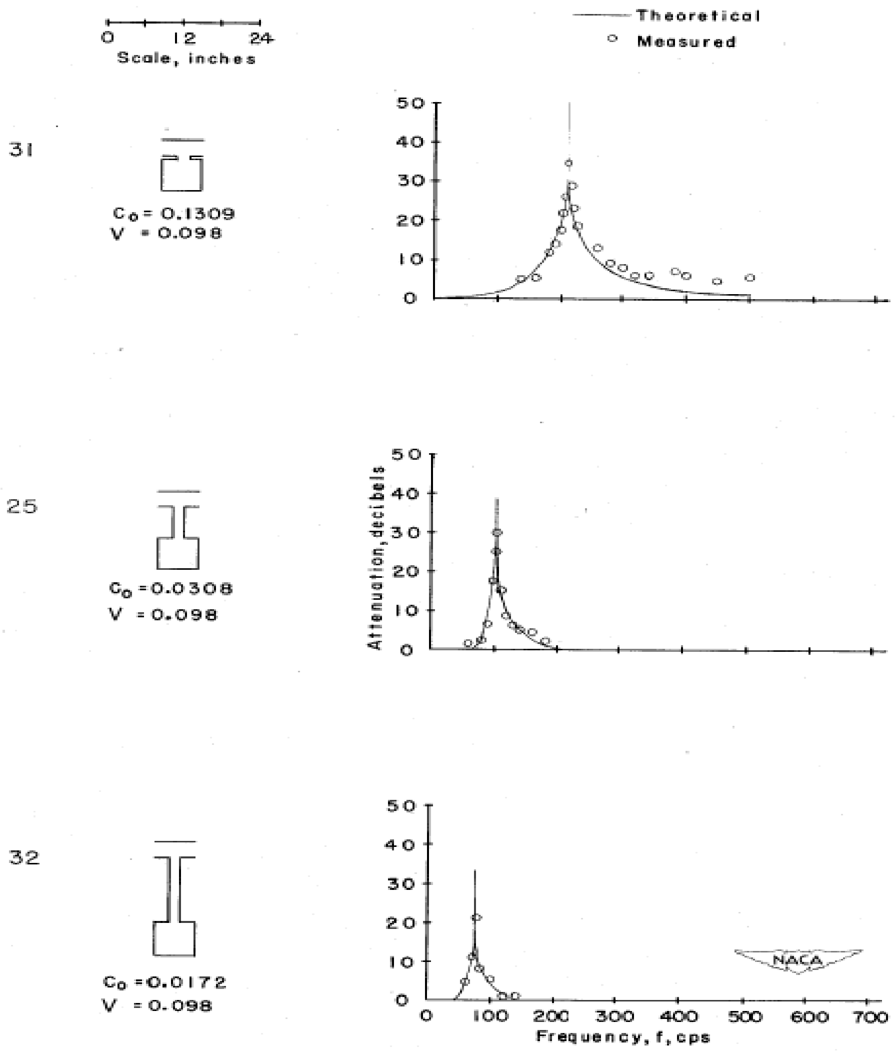

Figure 8. NACA Helmholtz resonators, effect of tube length on transmission loss [18]

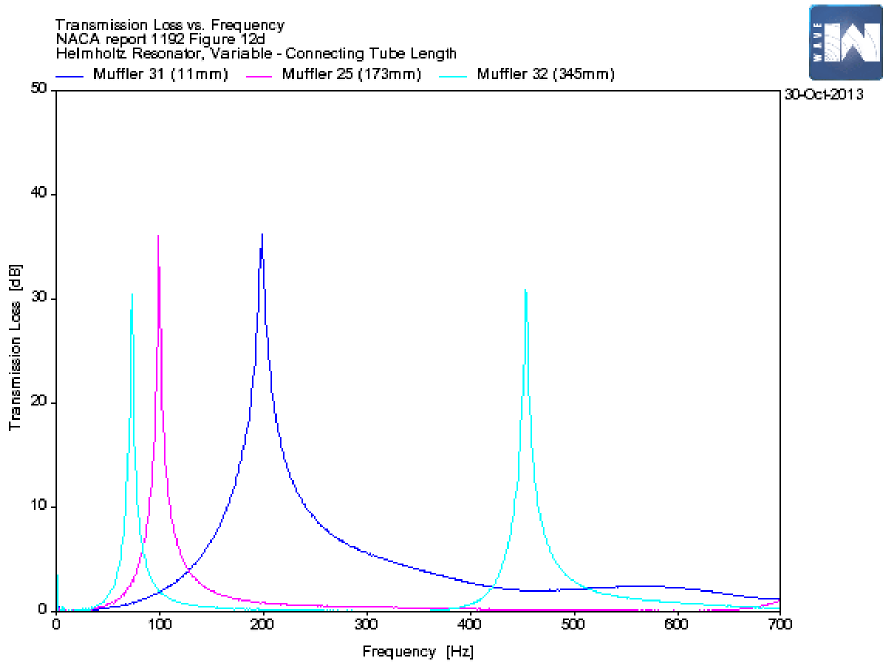

Figure 9. WAVE™ modelling results for NACA Helmholtz Mufflers in Figure 8

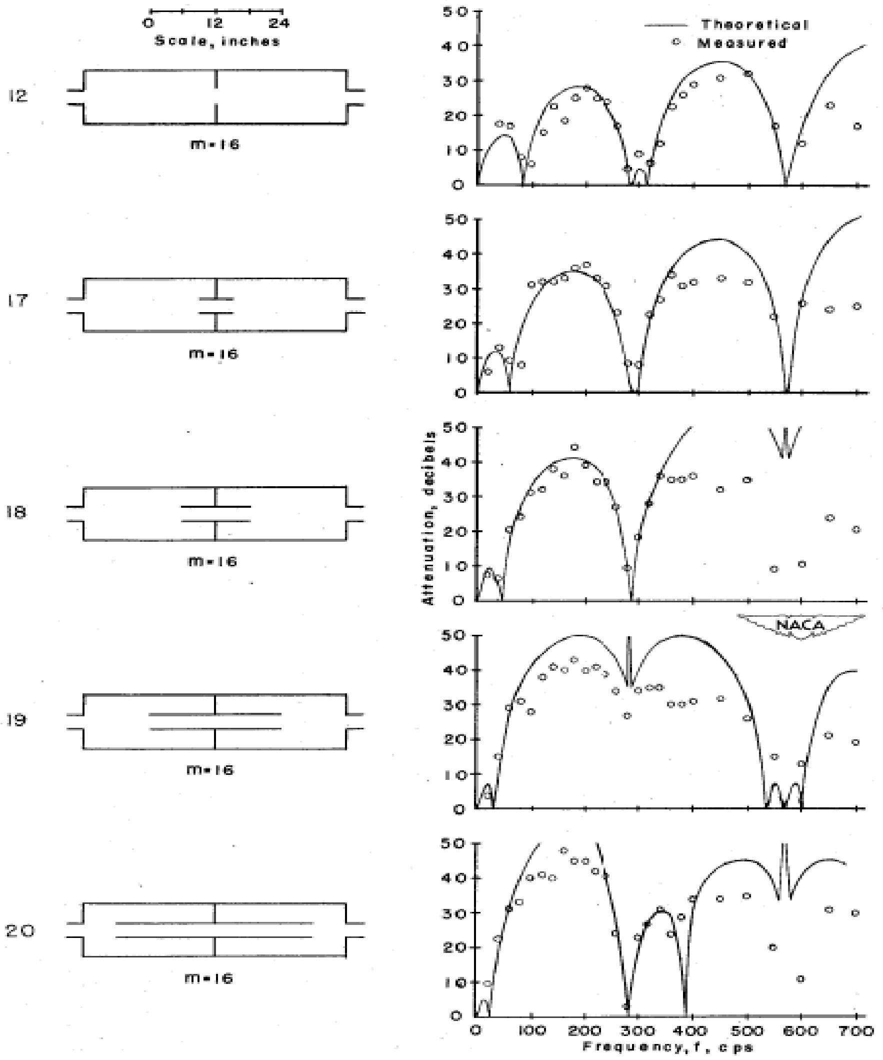

Figure 10. NACA expansion chamber mufflers, Effect of internal connecting tube length on transmission loss [18]

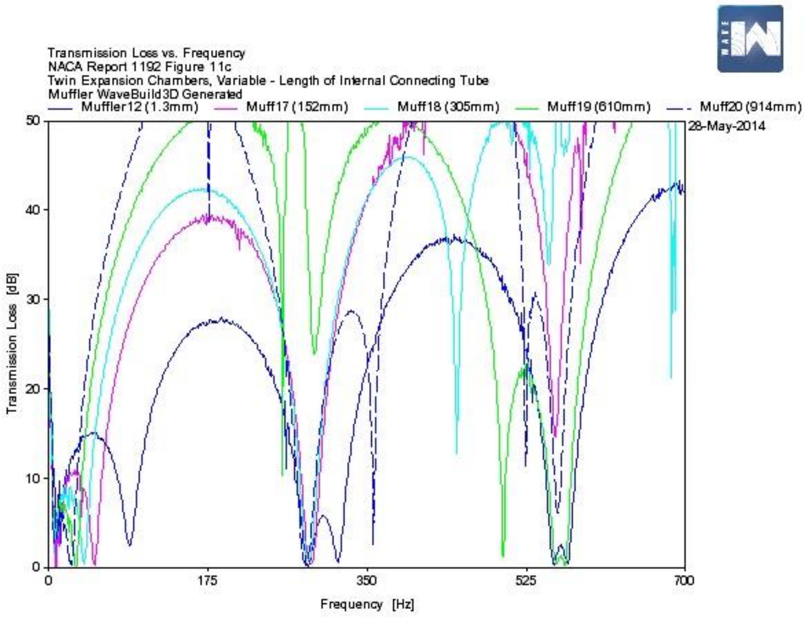

Figure 11. WAVE™ modelling results for expansion chambers shown in Figure 10

While the WAVE™ modelling results show some discrepancies with NACA results, the overall shapes and magnitude of transmission losses are in general agreement. The discrepancies in transmission loss are more evident as the complexity of the muffler increases and may require refinement of the mesh size used for the WAVE™ modelling. As an example of this increasing complexity, muffler 12 is basically two expansion chambers in series whereas mufflers 17, 18, 19, and 20 consist of two expansion chambers in series combined with internal quarter wave tubes and Helmholtz resonators. As the length of the interconnecting tube increases, the Helmholtz and quarter wave effects increase and the expansion chamber behaviour becomes less dominant.

4. Conclusions

- DSTG has developed a computer model capable of modelling the acoustic response and flow performance of an exhaust system representative of a large marine diesel based on WAVE™ software.
- DSTG has validated this computer model with published test data and limited on-engine test data.
- The computer models developed can be used for exhaust system components, complete exhaust systems or full engine-exhaust systems. The modelling flexibility permits assessment and development of systems with or without engine source data.
- WAVE™ modelling can predict engine source data from a WAVE™ engine model for later use in test bench development of exhaust systems.
- WAVE™ modelling can calculate transmission matrix parameters / four pole parameters for complex components.

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