Using Empirical Data to Validate the Role of Computational Fluid Dynamics in Various Stages of Aero-Acoustic Simulations.

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1 Introduction

As a full-service provider of engineering solutions for environmental noise control, it's essential to employ a multifaceted approach to performance estimation. Traditional empirical data, essentially sourced from laboratory testing, are cost-prohibitive and often restricted to standard parameters and simplified conditions. By recognizing these shortcomings, our goal is to integrate computational modeling into the engineering design process. Computational modeling overcomes these limitations and can adapt more effectively to varying environmental conditions. However, it demands a comprehensive understanding of the underlying physics and detailed input data, which present new challenges. Our approach begins by validating our existing empirical data against simulation results. To achieve this, our methodology involves breaking down the key performance parameters—pressure drop (PD) and insertion loss (IL)—into their fundamental physical principles. Initially, we focus on addressing the aerodynamic components, which include pressure drop and airflow-generated noise.

2 Methodology

2.1 Simulation Setup

The simulations for PD and airflow-generated noise are conducted using Siemens STAR-CCM+ and Simcenter 3D software, focusing solely on the internal airflow volume. The structural effects are accounted for by specifying the equivalent roughness on the walls, whereas the acoustic loads are considered irrelevant to the aerodynamic performance. The setup adheres to the ASTM E477-20 standard, featuring five and 10 equivalent duct diameter lengths upstream and downstream respectively for laminar flow, ensuring flow is fully developed before entering the silencer.

2.2 Pressure-Drop Model

A simple pressure-drop model employing a steady-state Reynolds-Averaged Navier-Stokes (RANS) solution with k-ε turbulence has been implemented in Simcenter 3D, with results presented in Figure 2A. However, due to the limitations of k-ε in near-wall flow behavior, and the critical impact of wall-friction on pressure drop, a more advanced CFD model was developed in STAR-CCM+. This enhanced model implements an SST k-ω turbulence model for a fully developed turbulent flow. The selection of the SST k-ω model is based on its ability to effectively resolve near-wall turbulence through the k-ω model and mimic k-ε behavior in free-stream flows [1]. Accurate resolution of near-wall flow necessitates a sufficiently fine wall mesh capable of resolving the viscous sublayer (y^+=1). The wall mesh size (y_p) is calculated using Equation 1 [1].

$$y_p = \frac{y^+ \nu}{U_\tau} \quad (1)$$

Where ν is the kinematic viscosity of air and U_τ is the friction velocity. Monitors are also placed during the simulation to ensure $y^+ \leq 1$ at all locations as illustrated in Figure 1.

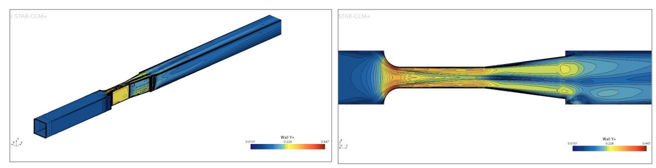

Figure 1: y^+ monitor in RANS simulation

Boundary conditions are configured to replicate real-life scenarios. The inlet and outlet are modeled as a velocity-inlet and pressure-outlet boundary, respectively. The surface of the fluid domain is treated as no-slip and rough, with the equivalent roughness of duct material applied to accurately simulate surface interaction.

2.3 Aero-acoustic Model

Aero-acoustic phenomena necessitate the use of an unsteady solver, such as Large-eddy Simulation (LES), capable of capturing large-scale fluctuations that contribute to noise generation. Our aero-acoustic simulation follows a two-step CFD modeling process [2]. Initially, a steady-state RANS solution establishes the minimum mesh size necessary for the LES model to accurately resolve noise generation up to the targeted frequency range. Subsequently, the LES model quantifies the airborne noise generation. The results from the aero-acoustic simulation are then integrated into the vibro-acoustic simulation for a comprehensive analysis of acoustic performance. In future work, as we explore insertion loss values in greater depth, more details about the aero-acoustic setup will be provided.

3 Results & Discussion

PD simulations are conducted for flow rates from 500 to 2500 fpm, with measurements taken at specified locations according to the ASTM E477–2.5 and 5 equivalent duct diameters upstream and downstream, respectively. The comparison between empirical and calculated pressure drop results is presented in Figure 2A. Although the k-ε model results closely match empirical data, simulating this model on larger

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geometries revealed a decreased correlation, thereby justifying the use of an alternative model. The trends in the SST k-ω results align with the empirical data but consistently registering lower by a constant factor. The Pearson correlation coefficient between the empirical and the SST k-ω data was 0.99 indicating an extremely strong correlation. Based on this relationship, it can be deduced that there may be real-world losses in PD that are captured in laboratory testing but not as effectively in CFD modeling. A scaling factor is applied to account for the constant difference and aid in identifying the parameters leading to it. A scaling factor is applied to account for the constant difference and aid in identifying the parameters leading to it, seen in Figure 2B.

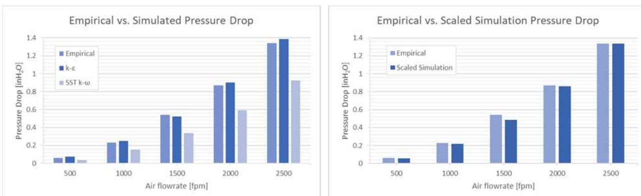

Figure 2. A) Empirical vs. Simulation PD values; B) Empirical vs. Scaled Simulation PD value

In the aero-acoustic simulation, the airborne generated noise is computed as surface pressure values, which are then exported into the subsequent vibro-acoustic simulation, to be further explored in future studies. For this analysis, airflow-generated noise is quantified by measuring the difference in sound pressure levels between the inlet and outlet. The simulation is conducted at a flow rate of 1000 fpm and extends up to a frequency of 1000 Hz, with the results presented in Table 1.

Table 1: Airflow-generated Noise.

Frequency (Hz)	Airflow-generated Noise (dB)
63	3.916
125	0.969
250	3.400
500	1.845
1000	3.069

Although the airflow-generated noise lacks empirical validation due to the absence of corresponding data, it serves as a valuable tool for understanding how aerodynamic components influence acoustic performance at higher flow rates.

4 Conclusion

This investigation highlights the potential of computational modeling to simulate the aerodynamic aspects of industrial silencers, effectively reducing reliance on costly empirical methods. Two turbulent models were employed, with SST k-ω model showing a higher correlation with empirical data. Further refinement is needed to address discrepancies between empirical and computational results. Future studies will extend this approach to explore the aero-vibro-acoustic behavior in detail.

References

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