ADVANCED TECHNIQUES FOR GRAY AREA MITIGATION IN DES SIMULATIONS AND THEIR EFFECTS ON THE SUBSONIC ROUND JET ACOUSTIC SPECTRA

A.P. Duben[1], J. Ruano[2], J. Rigola[2] and F.X. Trias[2]

[1] **_Keldysh Insitute of Applied Mathematics (KIAM), Moscow, Russia_**
[2] **_Heat and Mass Transfer Technological Center (CTTC), Universitat Politècnica de Catalunya - BarcelonaTech (UPC), Barcelona, Spain_**

jesus.ruano@upc.edu, aduben@keldysh.ru

Abstract

The research dedicated to the investigation of different gray-area mitigation approaches towards accurate aerodynamics and aeroacoustics is presented. The recent modifications of hybrid RANS-LES DDES approach based on combinations of new adapting subgrid length scales ($\tilde{\Delta}_\omega$, Δ_{SLA} and Δ_{lsq}) and LES models (σ and S3QR) are considered. The object of investigation is an immersed subsonic turbulent jet. The simulations are carried out on a set of refining meshes using two different scale-resolving numerical algorithms realized in the compressible codes NOISEtte and OpenFOAM. The evaluation of different approaches is focused on the analysis of far field noise. The results show that all the considered techniques provide appropriate accuracy to predict the noise generated by the turbulent jet. The study clearly demonstrated the importance of both numerical scheme and subgrid turbulence model. The peculiarities of considered approaches are revealed and discussed.

1 Introduction

Computational AeroAcoustics (CAA) requires accurate numerical solutions in the hydrodynamic region as these feed the acoustic solver. If hydrodynamics and turbulence are not well-resolved, acoustics will neither be. In this context, two main issues in the numerical method can be studied: how does the numerical discretization of the differential operators affect the quality of the results and, if turbulence is modelled, how does this modelization affect the results.

As acoustics is highly sensitive to the quality of the hydrodynamic fields used to compute noise, high-order schemes are in great demand. In this sense, Bogey (2018) or Shur et al. (2005,2016) both used high-order schemes when simulating jets using structured meshes. However, these kinds of methods have two main problems: first, their implementation on general mesh, i.e. unstructured meshes, is not straightforward. And second, the kinetic energy is not well-preserved if symmetric schemes are not used. Consequently, instead of using high-order schemes, one other option is to use 2nd order low-dissipative ones on meshes satisfying special quality requirements. Tyacke et al. (2017) or Fuchs et al. (2018) both used 2nd order schemes when simulating a jet. Another option is to use 2nd order higher-accuracy schemes with extended numerical stencils. Bres et al. (2017) and Duben and Kozubskaya (2019) exploit algorithms based on such kind of schemes for jet aerodynamics and noise simulation.

The other issue of the algorithm that affects the acoustics is how the turbulence is modelled. Hybrid RANS-LES methods have the most interesting balance between accuracy and computational cost as they can simulate high Reynolds numbers without requiring excessively large meshes. Inside these hybrid methods, one of the most widely used and extensively validated approach is the non-zonal DES family, which is still studied and evolving nowadays. Their recent investigations are focused on solving the so-called gray-area problem that appears when solving shear layers. This problem is mainly the delay of RANS-to-LES transition from steady RANS to the mesh-resolved turbulence. The usual methodology to mitigate the gray-area phenomena is the joint usage of an special length scale, such as Δ_ω (Chauvet et al., 2007), $\tilde{\Delta}_\omega$ (Mocket et al., 2015), Δ_{SLA} (Shur et al., 2015) or Δ_{lsq} Trias et al. (2017), with advanced LES models, such as σ or WALE models (Nicoud et al., 2011) or S3QR model (Trias et al., 2015) instead of Smagorinsky.

Our research is dedicated to the investigation of different gray-area mitigation (GAM) approaches towards accurate aerodynamics and aeroacoustics. The recent paper continues the study Pont-Vílchez et al. (2021) where their evaluation for shear layers is based on incompressible flow problems and focused on aerodynamics. We present the results of simulation of the immersed subsonic turbulent jet on a set of refining meshes. Analysis of the characteristics of the jet plume region is partly demonstrated in Pont-Vílchez et al. (2021). Here we are mostly aimed at evaluation of the jet aeroacoustics. The far field jet noise is very sensitive to the properties of any GAM approach because it is fully defined by the correctness of simulation of the shear layer evolution. Inappropriate amount of subgrid turbulent viscosity (either lack or redundancy) in any part of the shear layer can result in not only the delay of RANS-to-LES transition but either generation of spurious (related with numerics) noise or its damping at particular Strouhal numbers.

2 Case formulation

The immersed jet exiting from a conical nozzle at $M_{\text{jet}} = 0.9$ and $\text{Re}_D = 1.1 \cdot 10^6$ based on the jet diameter D and jet exit velocity U_{jet} is considered. The jet aeroacoustics was investigated experimentally by Viswanathan (2004). The computational domain, mesh and boundary conditions can be obtained from the study was carried out by Shur et al. (2010). This case was used in different investigations: Shur et al. (2015,2016), Duben and Kozubskaya (2019) and partly in Pont-Vílchez et al. (2021). The simulation of the jet follows a two-stage approach when nozzle and jet-plume computation is performed using RANS at the first stage, while only the jet-plume region is considered at the second stage, with profiles from the first stage imposed at the nozzle exit boundary surface. These profiles of gas-dynamic and turbulence model variables were provided by M. Shur and M. Strelets from Peter the Great St. Petersburg Polytechnic University. The structured (hexahedral) meshes Grid 1, Grid 2 and Grid 3 from the paper Shur et al. (2010) are used for computations. They have 64, 80 and 160 cells in the azimuthal direction and contain 1.52M, 4.13M and 8.87M nodes in total, correspondingly.

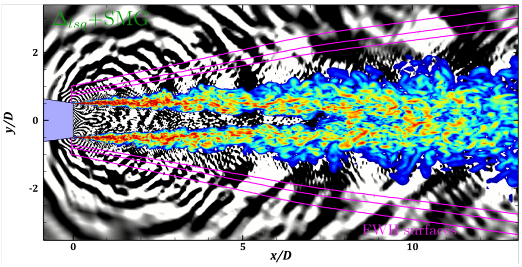

Figure 1: Instantaneous flow field in the jet plume region (from the f_lsq simulation using NOISEtte).

3 Description of numerical algorithms

The vertex-centred unstructured numerical algorithm realized in the research code NOISEtte is based on quasi-1D vertex-centered EBR (Edge-Based Reconstruction) schemes (Abalakin et al., 2020). It exploits the adapting blend of 4th order centered and 5th order upwind schemes (Duben&Kozubskaya, 2021) using a special hybridizing function (Guseva et al., 2017). The parameter which controls the amount of diffusivity of the discrete convection scheme, σ_{upw}, is limited in both the upper and the lower limit via a known previous distribution (Duben&Kozubskaya, 2021). The 4th order Runge–Kutta explicit numerical scheme is used for time integration.

OpenFOAM is based on a collocated unstructured finite-volume approach. The used convective scheme consists in the hybrid convection scheme of Travin et al. (2000), which provides a blend of a 2nd order central scheme and a 1st order upwind scheme. The temporal integration is done via implicit second-order scheme already implemented in OpenFOAM. The used solver to compute the simulations in this work has been sonicFoam.

The integration surfaces (marked by magenta solid lines in Figure 1) for performing acoustic post-processing consist in a set of conformal surfaces to the underlying mesh, i.e. three different kinds of integration surfaces are considered, one for each mesh. Each of these integration surfaces is subdivided onto different sets; this enables the possibility to use all or only different parts of the integration surface.

To predict far-field acoustics, the Lighthill acoustic analogy in the form of a modified version of the integral Ffowcs Williams and Hawkings (FWH) method is used.

The NOISEtte postprocessor is based on formulation 1A proposed by Farassat in terms of retarded times.

Acoustic post-processing of the OpenFOAM results is done via an in-house FWH solver. This solver is based on Ffowcs-Williams Hawkins equation after performing Fourier Analysis, obtaining the equivalent FWH equation but in Fourier space. This, effectively, removes the requirement of retarded time computations, which is substituted by its equivalent in Fourier space: a phase shift between observer and source.

4 Results and discussion

The results of simulations using both NOISEtte and OpenFOAM are presented in Figures 2-5. The curves obtained from different simulations are labelled as follows. The first character means the mesh used: meshes Grid 1, Grid 2 and Grid 3 are marked by ”c”, ”m” and ”f”, respectively. The results using $\tilde{\Delta}_\omega$ (Mocket et al., 2015), Δ_{SLA} (Shur et al., 2015) or Δ_{lsq} (Trias et al., 2017) are labelled by ”omeg”, ”sla” and ”lsq”, respectively. The usage of alternative (not Smagorinsky, as in the original DES formulation) subgrid LES models σ or S3QR is marked by ”sig” or ”s3qr”. The overall sound pressure levels’ (OASPL) distributions (noise directivity) are presented in Figure 2. Figures 3, 4 and 5 demonstrate 1/3rd octave integrated spectrums at the observer angles $\theta = 60°$, $\theta = 130°$ and $\theta = 150°$, respectively ($\theta = 180°$ corresponds to the jet downstream direction).

Analysing the results, the following observations and conclusions could be revealed. First of all, it is common for all the considered approaches, mesh refinement leads to better correspondence both with the reference data and with each other, except simulations using Δ_{lsq} (see noticeably overestimated noise levels obtained on the "m" mesh, m_lsq).

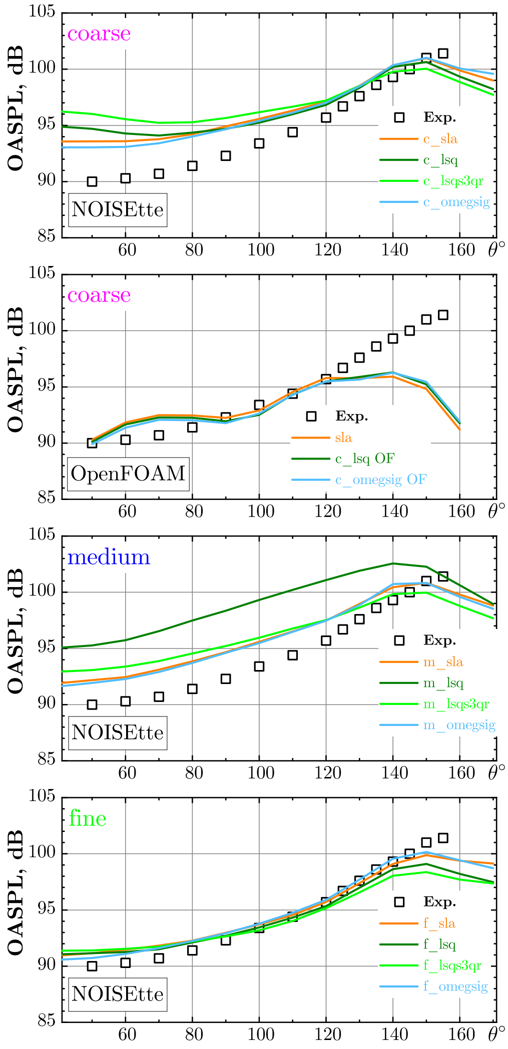

Figure 2: Noise directivity obtained using different approaches.

Evaluating the OASPL distributions (Figure 2) it is seen that the usage of Δ_{lsq} (especially with the S3QR model) results in overestimation of the noise levels at lower observer angles and underestimation at the higher ones at the same time. The first could be due to the spurious noise generation in the initial shear layer region (responsible for higher Strouhal numbers, $St \geq 1$): it is clearly seen on the top of Figure 3 that displays the results on the most coarse mesh, Grid 1. Note that only fine mesh (Grid 3) allows to predict the OASPL within the error lower than 1 dB compared to the experiment. The prominent underestimation of noise levels at $\theta > 130°$ comes from "noise deficit" at lower Strouhal numbers in the range $0.2 < St < 0.5$ (see Figure 5). These trends are well correlated with the distributions of averaged ratio between turbulent and molecular viscosity presented in Figure 6. So lower values of ν_t/ν lead to a slight overestimation of noise levels, especially at the observer angles upstream of the nozzle exit.

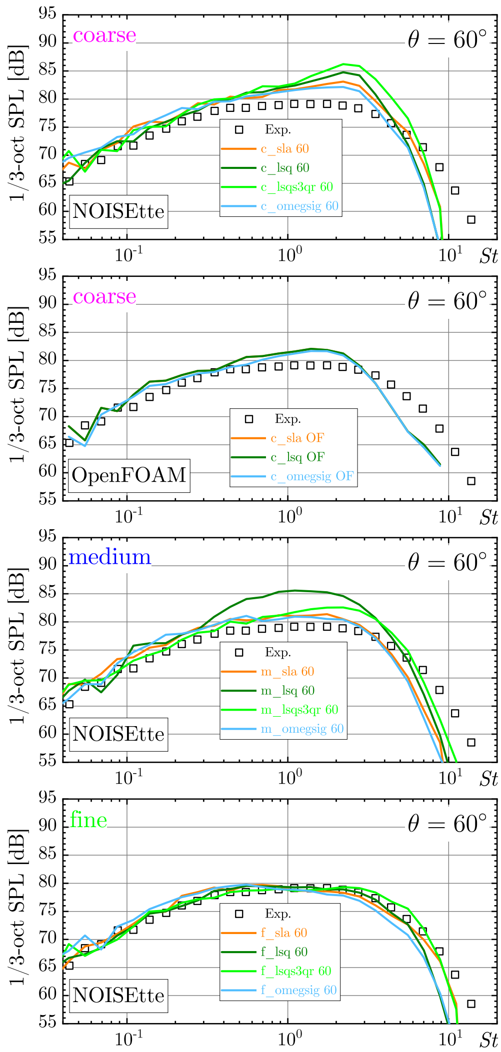

Figure 3: 1/3rd-octave integrated spectrums at the observer angle $\theta = 60°$.

It could be seen from the 1/3rd octave spectrums' distributions that usage of $\tilde{\Delta}_{\omega} + \sigma$ LES model leads to earlier decay of the spectrum compared to the remaining approaches. The explanation for it lies in the higher levels of ν_t/ν provided by the σ LES model too.

An unexpected noticeable overestimation of the results obtained using the DDES with Δ_{lsq} subgrid length scale on Grid 2 (see m_lsq curves on the graphs) could be related to the delay of RANS-to-LES transition in the initial shear layer. While it is moved farther downstream of the nozzle exit, it could result in the generation of spurious noise. Nevertheless, this effect requires more research, which will be done in the future.

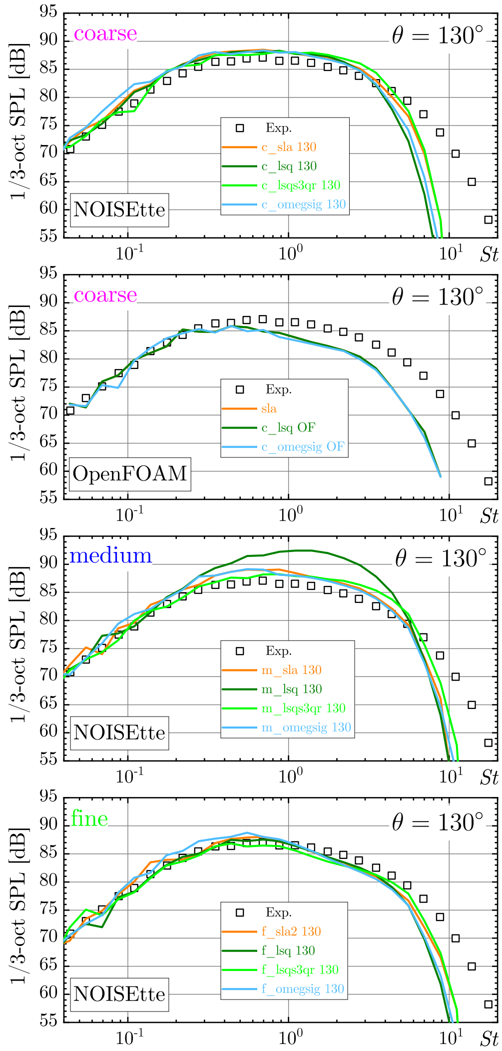

Figure 4: 1/3rd-octave integrated spectrums at the observer angle $\theta = 130°$.

The OpenFOAM results are characterized by distinguished trends compared with the NOISEtte ones. As it is seen from the Figure 2 (2nd from the top), while the predicted noise levels are well compared with the experiment for $\theta < 120°$ (deviation does not exceed 2 dB), they are highly underestimated for the remaining observer angles, farther downstream the nozzle exit. In contrast to the NOISEtte, all the considered approaches provide very similar far field results, both for overall values and spectral distributions. This obvious difference is related to the fact that NOISEtte exploits a higher-accuracy numerical scheme with extended stencils in contrast to OpenFOAM, where a simple 2nd order scheme is applied. So the OpenFOAM results depend on it more than the subgrid LES model. Due to larger numerical dissipation, the noise levels are not so overestimated in the region $1 < St < 4$ for $\theta < 60°$. At the same time, they are strongly underestimated (more than 10 dB for $St > 0.2$ at $\theta < 150°$) for higher observer angles: the accuracy provided by the scheme used in OpenFOAM is not enough to resolve large vortexes mostly responsible for the noise propagating far downstream the nozzle exit. It could be concluded that usage of higher accuracy numerical scheme (as used in the NOISEtte simulations) allows to reveal the peculiarities of different GAM approaches on coarser meshes.

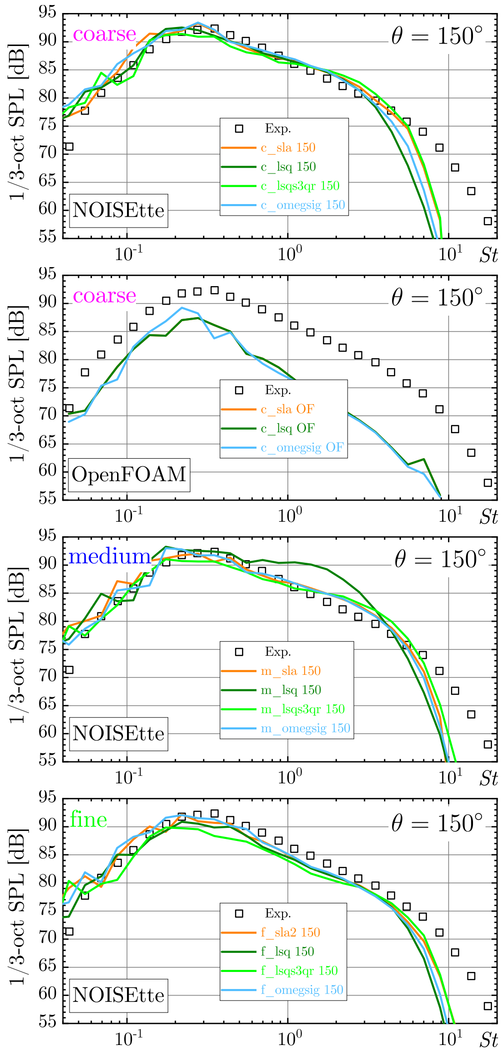

Figure 5: 1/3rd-octave integrated spectrums at the observer angle $\theta = 150°$.

5 Conclusions

The simulation results of the immersed subsonic turbulent jet on a set of refining meshes are presented. Two different numerical algorithms realised in the codes NOISEtte and OpenFOAM are considered. The results show that all the GAM approaches provide appropriate accuracy to predict the noise generated by the turbulent jet. The study clearly demonstrated the importance of both numerical scheme and subgrid turbulence model. So usage of higher accuracy numerical scheme allows to estimate the sensitivity of dif-

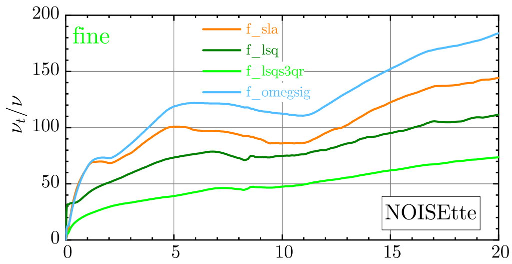

Figure 6: Average of the turbulent to molecular viscosity ratio over the lip line starting from the jet nozzle exit (results on the Grid 3).

ferent GAM approaches more precisely. Nevertheless, a more thorough analysis of the results is to be done for better evaluation of the advantages, disadvantages and limitations of the considered GAM approaches. In addition, for a more detailed assessment of the capabilities of the techniques under consideration and to obtain a conclusion about the convergence of the results, it is necessary to conduct computations on another finer mesh, that is planned for the nearest future.

Acknowledgments

A.D. was supported by Moscow Center for Fundamental and Applied Mathematics, Agreement with the Ministry of Science and Higher Education of the Russian Federation, No. 075-15-2019-1623. The NOISEtte computations were carried out using the equipment of the shared research facilities of HPC computing resources at Lomonosov Moscow State University and the computing resources of the federal collective usage center Complex for Simulation and Data Processing for Mega-science Facilities at NRC "Kurchatov Institute" (http://ckp.nrcki.ru/). J.R was supported by a FI-DGR 2015 predoctoral contract financed by Generalitat de Catalunya, Spain. This work has been financially supported by the Ministerio de Economía y Competitividad, Spain (No. ENE2017-88697-R).

References

Abalakin, I., Bakhvalov, P., and Kozubskaya, T. (2016) Edge-based reconstruction schemes for unstructured tetrahedral meshes. International *Int. J. Numer. Methods Fluids*, Vol. 81, No. 6, pp. 331–356.

Bogey, C. (2018) Grid sensitivity of flow field and noise of high-Reynolds-number jets computed by large-eddy simulation, *Int. J. Aeroacoust.*, Vol. 17, pp. 399–424.

Brès, G., Ham, F., Nichols, J., and Lele, S. (2017) Unstructured large-eddy simulations of supersonic jets, *AIAA J.*, Vol. 55, pp. 1164–1184.

Chauvet, N., Deck, S., and Jacquin, L. (2007) Zonal Detached Eddy Simulation of a Controlled Propulsive Jet, *AIAA J.*, Vol. 45, No. 10, pp. 2458–2473.

Duben, A., Kozubskaya, T. (2019) Evaluation of quasi-one-dimensional unstructured method for jet noise prediction,*AIAA J.*, Vol. 57, pp. 5142–5155.

Fuchs, M., Mockett, C., Shur, M., Strelets, M., and Kok, JC. (2018) Single-Stream Round Jet at M= 0.9", *Go4Hybrid: Grey Area Mitigation for Hybrid RANS-LES Methods*, pp. 125–137.

Guseva E.K.et al (2017) *J. Phys.: Conf. Ser.* 929 012099

Mockett, C., Fuchs, M., Garbaruk, A., Shur, M., Spalart, P., Strelets, M., Thiele, F., and Travin, A. (2015) Two non-zonal approaches to accelerate RANS to LES transition of free shear layers in DES, *Progress in hybrid RANS-LES modelling*, pp. 187–201.

Nicoud, F., Toda, H., Cabrit, O., Bose, S., and Lee, J. (2011) Using singular values to build a subgrid-scale model for large eddy simulations. *Phys. Fluids*, Vol. 23, No. 8, p. 085106.

Pont-Vílchez, A., Duben, A., Gorobets, A., Revell, A., Oliva, A. and Trias, F.X. (2021) New Strategies for Mitigating the Gray Area in Delayed-Detached Eddy Simulation Models. *AIAA J.*, accessed May 10, 2021. doi:10.2514/1.J059666

Shur, M., Spalart, P., and Strelets, M. (2005) Noise prediction for increasingly complex jets. Part I: Methods and tests, *Int. J. Aeroacoust.*, Vol. 4, pp. 213–245.

Shur, M., Spalart, P., and Strelets, M. (2010) LES-based evaluation of a microjet noise reduction concept in static and flight conditions, *Procedia Eng.*, Vol. 6, pp. 44–53.

Shur, M., Spalart, P., Strelets, M., and Travin, A. (2015) An Enhanced Version of DES with Rapid Transition from RANS to LES in Separated Flows, *Flow Turbul. Combust.*, Vol. 95, No. 4, pp. 709–737.

Shur, M., Spalart, P., and Strelets, M. (2016) Jet noise computation based on enhanced DES formulations accelerating the RANS-to-LES transition in free shear layers, *Int. J. Aeroacoust.*, Vol. 15, pp. 595–613.

Travin, A., Shur, M., Strelets, M. and Spalart, P. (2000). Physical and numerical upgrades in the detached-eddy simulation of complex turbulent flows, *Proceedings of the 412th Euromech Colloquium on LES and Complex Transition and Turbulent Flows*.

Trias, F.X., Folch, D., Gorobets, A. and Oliva, A. (2015) Building proper invariants for eddy-viscosity subgrid-scale models. *Phys. Fluids*, Vol. 27, No. 6, p. 065103.

Trias, F.X., Gorobets, A., Silvis, M., Verstappen, RWCP and Oliva, A. (2017) A new subgrid characteristic length for turbulence simulations on anisotropic grids, *Phys. Fluids*, Vol. 29, pp. 115109.

Tyacke, J., Naqavi, I., Wang, Z., Tucker, P., and Boehning, P. (2017) Predictive large eddy simulation for jet aeroacoustics–current approach and industrial application, *J. Turbomach.*, Vol. 139.

Viswanathan, K. (2004) Aeroacoustics of hot jets, *J. Fluid Mech.*, Vol. 516, pp. 39–82.