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Embedded Large Eddy Simulation Method for Predicting Flow-Induced Noise

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ABSTRACT

Prediction of flow-induced noise is of considerable interest in a range of applications. Computational fluid dynamics (CFD) using the Large Eddy Simulation (LES) approach offers the possibility of obtaining acoustic predictions directly from time-resolved pressure fluctuations. However, the application of LES in design studies remains limited by its high computational cost. One approach to reduce the cost is Embedded LES (ELES), in which LES is applied only in user-selected regions of interest which are known to dominate noise production, while applying the Reynolds-Averaged Navier Stokes (RANS) equations elsewhere. To test this concept, ELES has been implemented in the open source OpenFOAM CFD code, and the method was applied to model the trailing edge noise due to flow around a NACA0012 aerofoil. Simulations were run using ELES, with LES calculations limited to a region surrounding the trailing edge of the aerofoil. For comparison, a full LES covering the whole flow domain was also carried out, with both compared against published experimental results. For the ELES, the finite volume mesh contained approximately 13 million cells, whereas for full LES, the mesh contained approximately 40 million cells. All other modelling settings were kept the same. From the predicted pressure fluctuations, the trailing edge surface pressure and far-field pressure spectra were obtained. The results obtained using ELES were in good agreement with the full LES results at a fraction of the computational cost, thus providing a way forward for developing more affordable LES for flow noise predictions.

1 INTRODUCTION

There is a strong demand for noise reduction in relation to aircraft, ground and marine vehicles, wind turbines and other turbomachinery, so it is essential that the quantification of noise emission is incorporated into engineering design processes. Flow noise may arise from a number of mechanisms, and may be tonal or broadband in nature. One noise source of widespread interest is the broadband noise from a trailing edge, which occurs in relation to propellers, turbines and aircraft wings to name a few. It arises due to the large pressure fluctuations produced when uncorrelated turbulent eddies from the upper and lower boundary layers interact with the edge (Wagner, Hüttl, & Sagaut, 2007).

There has been considerable interest in recent years in developing computational methods to predict trailing edge flow noise, and a variety of approaches have been developed. In the most fundamental approaches (see, for example Sandberg & Sandham, 2008), acoustics predictions can be obtained based exclusively on resolved pressure fluctuations. However, such methods are prohibitively expensive for most applications, and hence various approximate methods have been developed. Most studies reported in the literature employ a hybrid method, in which the near-field acoustic sources are obtained from a fluid flow simulation, while mathematical models or acoustic analogies are applied to obtain the far-field sound spectra.

Flow simulation in hybrid methods may be based on the Reynolds-Averaged Navier Stokes (RANS) equations (e.g. the Rnoise model, as described in Herr et al., 2015). However, in this approach only time-averaged statistics of the turbulence are available as a basis for acoustic modelling. The use of Large Eddy Simulation (LES) may be preferable, since the acoustic sources can be obtained directly from the resolved pressure fluctuations, which may improve reliability of the predictions. For example, Wang and Moin (2000) obtained predictions for trailing edge noise based on incompressible LES and the acoustic analogy of Ffowcs Williams and Hall (1970). Wolf and Lele (2012) used compressible LES in conjunction with the equation of Ffowcs Williams and Hawkings

(1969) to predict the noise from an aerofoil with a rounded trailing edge. However, despite continued improvements in the performance of computers, the cost of large eddy simulations remains very high when applied to real engineering applications. To reduce this cost, various modifications to the 'standard' LES methods have been proposed.

One approach to reduce the computational cost is to adopt wall-modelled LES (WMLES), where only the eddies in the outer part of boundary layers are explicitly resolved, while the turbulence in the inner part of the boundary layers is modelled. This achieves significant reductions in mesh size, especially at higher Reynolds numbers. George and Lele (2016) applied WMLES to the flow over a NACA0012 aerofoil to obtain the wall pressure spectrum at the trailing edge, and then obtained the far-field spectrum using acoustic analogies. Good agreement with experimental data was demonstrated.

Another approach to reducing the computational cost of LES is through embedded LES (ELES). This is an approach in which LES is applied in user-selected regions only, while the RANS equations are employed elsewhere in the computational domain (see Fröhlich & von Terzi, 2008; Mockett, Haase & Thiele, 2015). The method employs special procedures to couple the velocities, pressures and turbulence quantities at interfaces (Fröhlich & von Terzi, 2008). In particular, at interfaces when fluid flows from a RANS region to an LES region, resolved turbulent fluctuations are introduced by means of a synthetic turbulence algorithm. The properties of the synthetic turbulence, such as energy content and length scales, are set in accordance with upstream RANS turbulence parameter values.

Some recent developments in ELES have been outlined in the Go4Hybrid study (Mockett & Wallin, 2018), which benchmarked various methods from different research groups. The study highlighted the importance of generating synthetic turbulence, which is as realistic as possible. Unphysical velocity fluctuations can be damped out very quickly by the equation solver, or else it may take a large distance downstream of the interface before 'real' turbulence develops. To make synthetic turbulence as realistic as possible, it should consist of a field of coherent eddies with the correct turbulent kinetic energy, and length scales, anisotropy and spatial inhomogeneity. The best synthetic turbulence algorithms have been found to be those based on either the coherent eddy method (also called the synthetic eddy method), or the method of randomized Fourier modes (also called the Synthetic Turbulence Generator, or STG) (Mockett & Wallin, 2018). In the method of coherent eddies, discrete structures mimicking individual eddies are generated at random positions and convected through the inlet or RANS-LES interface. In the method of randomized Fourier modes, a continuous field of turbulence is created through the superposition of a large number of randomized harmonic waves.

Embedded LES has been successfully used in a number of published studies. For example, Probst et al. (2017) modelled the flow over a wall-mounted hump and obtained good predictions using either the coherent eddy or the randomised Fourier modes methods. The mesh size with the ELES approach was about 5 million, compared to a mesh requirement of 400 million cells in a full wall-resolved LES of the same configuration. However, some studies (see, for example Shur et al., 2018) have noted the presence of spurious pressure fluctuations when applying synthetic turbulence at an interface, which could limit the usefulness of ELES for acoustics predictions as these could overwhelm the real noise sources. Hence, it has been proposed to add synthetic turbulence as a source term in the momentum conservation equation (so-called volumetric forcing), which has been found to suppress unphysical pressure fluctuations (Shur et al., 2018; Akkermans et al., 2018).

This paper reports on progress in a study which is aimed at reducing the computational costs associated with flow noise predictions. To achieve this goal, the study employs methods as suggested in the literature, including wall-modelled LES and embedded LES. The aim is to eventually apply the developed methods to real engineering applications. However, as an initial test case, the study considers the trailing edge noise generated by flow over a NACA0012 aerofoil at zero angle of attack, which is a suitable candidate for ELES as the noise source is localised at the trailing edge. This is a configuration for which experimental flow and acoustics data have been published, in the BANC-II Study (see Herr et al., 2013). This was one of a number of test cases used to compare various simulation codes in that study, and it was also a test case for WMLES in the work of George and Lele (2016).

The method for ELES was implemented within the framework of the open source OpenFOAM code (version 4.1). For comparison, an LES analysis was also carried out for the whole of the computational domain, which required a mesh approximately three times as large. Comparisons have been made between the predictions from LES of the whole domain and ELES, and the experimental data.

2 METHOD

2.1 Test Case Geometry

The test case for assessing the method was the flow over a NACA0012 aerofoil. The configuration follows Case 1 as defined in the BANC-II study (Second Workshop on Benchmark Problems for Airframe Noise Computations, see Herr et al., 2013). The aerofoil has a chord length of 0.4 m and a sharp trailing edge to avoid tonal noise generation associated with vortex shedding from a blunt edge. Physical tripping was achieved by means of a tape placed across the foil surfaces at a location 5% of chord length from the leading edge, which ensured a repeatable laminar-to-turbulent transition of the boundary layer, and also avoids tonal noise due to Tollmein-Schlichting waves. The incoming flow of air has an angle of attack of 0°, and the far-field velocity is 56 m/s, giving a Reynolds number of 1.5×10^6 based on chord length. The experimental flow-related data provided in the BANC-II study are based on the work of Herrig et al. (2013), and include the pressure coefficient along the surface, and the mean and turbulent velocity components along a line normal to the chordwise-spanwise plane, just beyond the trailing edge at 100.38% of chord length. The acoustic data consists of the unsteady wall pressure spectrum, obtained from embedded pressure transducers located close to the trailing edge (at 99% of chord length), and the far-field noise spectrum evaluated at a distance of 1 m from the trailing edge, in the direction normal to the chordwise-spanwise plane.

2.2 LES method

The LES method is based on a time-stepping solution of the spatially-filtered Navier-Stokes equations. Flow structures larger than the filter size are calculated explicitly, whereas small scale structures are modelled. The subgrid-scale turbulence was modelled using the eddy viscosity model proposed by Kim and Menon (1997). Wall modelling was used as a means of reducing the mesh requirements. This relaxes the mesh spacing requirements in the wall normal direction, so that a wall y^+ of about 40 could be applied (where $y^+ = y\,u_T/\nu$, y is the wall distance, u_T is the friction velocity and ν is the kinematic viscosity) compared to wall-resolved LES where wall $y^+ < 1$ is required. The eddy viscosity in the cells adjacent to the walls was set using the equation of Spalding (1961).

The mesh requirements in the wall-parallel directions followed the guidelines provided by Park and Moin (2016), who found that the mesh spacings required for acoustics calculations are considerably finer compared to LES applications where interest is mainly limited to basic flow statistics, or drag and lift coefficients. The streamwise dimensionless spacing in this study was $\Delta x^+ = 52$ and the spanwise spacing was $\Delta z^+ = 32$ (compared to recommended values of $\Delta x^+ = 50$ and $\Delta z^+ = 31.25$ according to Park and Moin, 2016, where x and z are non-dimensionalised in a similar fashion to y, as above). The mesh extended a distance equal to 20% of chord width in the spanwise direction to ensure that the simulated span was in excess of the correlation lengths of turbulent eddies. A structured hexahedral mesh was created surrounding the foil and extending to a distance about twice the maximum boundary layer thickness. The mesh then blends with a coarser unstructured mesh covering the far field. The total number of mesh cells was 40.7 million.

The simulation includes a numerical tripping technique, in order to model the physical tripping tape applied in the experimental method. Periodic boundary conditions were applied in the spanwise direction. A zero-slip condition was applied at the foil surface (with the wall function used to obtain the velocity in cells adjacent to the wall). Time integration was performed using a semi-implicit second-order backward differencing scheme. Convective fluxes across cell faces were calculated by blending 75% linear interpolation with 25% of an upwind biased scheme. Diffusive fluxes were obtained from a combination of central differencing and gradient face interpolation. The PISO algorithm is used to handle pressure-velocity coupling. The time step was set to 6.4×10^{-7} seconds, which corresponded to an average maximum Courant number of approximately 0.3. To flush out the effects of initial conditions, the simulation was first run for three flow-past times (amounting to 0.021 s of real time, where the flow-past time is defined as the chord length divided by the far-field velocity) . The simulation was then restarted and run for approximately 15 flow-past times to calculate flow statistics and extract acoustics data.

2.3 Embedded LES method

ELES was performed in OpenFOAM using a multi-region solver, enabling the RANS and LES calculations to be carried out in user-defined regions. The LES region, which is the main flow noise source, surrounds the trailing edge as shown in Figure 1. The RANS-to-LES interface intersecting the boundary layers was placed at a position corresponding to 70% of the chord length from the leading edge. Generalised coupled boundary conditions allowing two-way coupling have been developed, which treat each boundary within each domain either as an inlet or outlet according to the mean flow direction. However, in this study a one-way coupled method was used. A RANS simulation of the whole domain was firstly calculated using the Shear Stress Transport (SST) *k*-ω turbulence model, and the resulting pressure and velocity fields were used to set the initial and boundary conditions for the LES zone. The simulation was then continued for the LES zone only, since the focus was on predicting trailing edge noise, and computation of just this region was considered sufficient for the purpose

The mesh spacings in the LES region were the same as for the full LES, giving a mesh with about 13 million cells for that region. However, the RANS simulation was treated as two dimensional, so the mesh in that region consisted of only approximately 52,000 cells. Model settings such as differencing schemes and the time step were identical to those used in the full LES, and the simulation was run for a similar amount of real time.

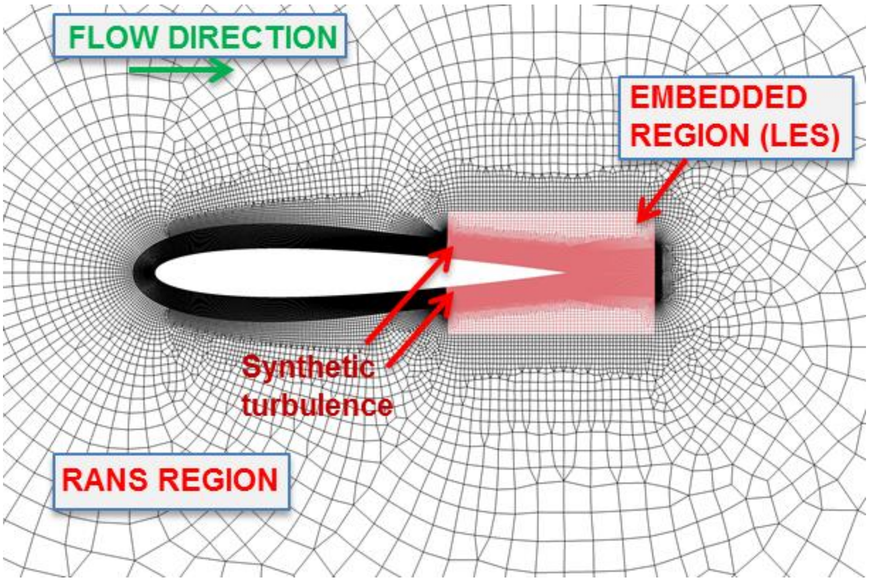


Figure 1 Mesh regions and layout for embedded LES of the NACA0012 aerofoil.

2.4 Synthetic turbulence

An important part of the ELES method is the generation of synthetic turbulence at the RANS to LES inlet, which is crucial to the rapid development of resolved turbulence. The chosen algorithm for the study was based on the method of superposition of a large number of harmonic waves or Fourier modes. This method is one of the approaches which has been found to give the best results according to various studies (see, for example Mockett & Wallin, 2018). It provides good control over the turbulence energy, Reynolds stresses and eddy length scales, and has the advantage of being able to specify a complete turbulence spectrum, which the coherent eddy method cannot achieve. Also, the method generates a divergence-free velocity field, at least in the homogeneous condition, which is expected to improve the stability of the equation solver. The method used here generally follows the method of Davidson and Billson (2006), and also includes features suggested by Shur et al. (2018). A field of turbulent velocity fluctuations, $\mathbf{u}'(\mathbf{x},t)$, is generated from a summation over *N* (~600 in this study) Fourier modes, as given by:

$$\mathbf{u}'(\mathbf{x},t) = 2\sum_{n=1}^{N} u_n(t) cos(\mathbf{k}_n \cdot \mathbf{x} + \varphi_{\boldsymbol{n}})\, \boldsymbol{\sigma}_n \quad (1)$$

In this equation, $\mathbf{x}$ is the position vector and t is time, while $\mathbf{k}$ and $\boldsymbol{\sigma}$ are vectors which are chosen to be uniformly and randomly distributed over a unit sphere, but are constrained in such a way as to be mutually orthogonal, ensuring that the velocity field is divergence free. Random phase shifts, φ_n, are chosen from a uniform random distribution in the interval $(0, 2\pi)$. The amplitude of each mode, u_n, is chosen so as to conform to a user-specified energy spectrum, which in this case was a modified von Kármán spectrum. The summation over the amplitudes of all modes is made equal to the average turbulent kinetic energy, k, as determined from the precursor RANS simulation. The integral length scale in the von Kármán spectrum is determined from the average values of k and ω (the specific energy dissipation rate) in the precursor RANS simulation. Following Davidson and Billson (2006), the procedure adopted was to generate a velocity field with a new set of values for $\mathbf{k}$, $\boldsymbol{\sigma}$ and φ_n at each time step. Temporal coherence was achieved using an asymmetric time filter to blend the new and old velocity fields.

The algorithm was first tested by adding the synthetic turbulence at the interface. This was found to lead to very large spurious pressure fluctuations, with the potential to overwhelm the real noise sources. Therefore, following approaches in other studies such as by Shur et al. (2018) and Akkerman et al. (2018), an alternative method was developed in which synthetic turbulence is introduced as a source term in the momentum conservation equation. A field of velocity fluctuations, $\mathbf{u}'(\mathbf{x}, t)$, is generated as above, but is then used to define a source term, $S(\mathbf{x}, t)$, in defined regions downstream of the RANS-LES interface encompassing the boundary layer thickness, according to:

$$S(\mathbf{x}, t) = \xi(t)\frac{\rho \mathbf{u}'(\mathbf{x},t) V_{cell}(\mathbf{x})}{\Delta t} \quad (2)$$

where $\xi(t)$ is a globally applied proportionality factor, ρ is fluid density, $V_{cell}(\mathbf{x})$ is the cell volume, and Δt is the time step. A control loop is used to adjust the proportionality factor and hence the source strength, based on the difference between the target value for the turbulent kinetic energy and the actual average value in a monitoring region immediately downstream of the forced region.

2.5 Acoustics analysis

Pressure data from the LES and ELES simulations were recorded at a number of monitoring points placed on the surface of the foil near the trailing edge. Pressures were recorded every 80 time steps (a sampling frequency of 19.5 kHz). Data were then analysed to provide the one-third octave band level pressures. The surface pressure spectrum was then generated from the Fourier transform of the pressure histories, averaging over the monitoring positions.

Far-field noise was determined from two acoustic analogy methods, for positions along lines at ± 1 m from the trailing edge, in the direction normal to the chordwise-spanwise plane and intersecting the trailing edge. The far field noise is derived from the radiation of the pressure fluctuations over the whole of the surface. The modelling methods tested were the Ffowcs Williams and Hawking (1969) analogy (FWH) and the analytical scattering model of Roger and Moreau (2005).

3 RESULTS AND DISCUSSION

3.1 Fluid flow predictions

Simulation predictions from the full LES and embedded LES have been compared against the experimental data provided in the BANC-II study (Herr et al., 2013). Figure 2(a) shows the mean pressure coefficient, C_p, on the surface, plotted as a function of distance along the foil (with $x = 0$ corresponding to the position of the leading edge). The pressure coefficient is given by:

$$C_p = \frac{P}{(0.5\,\rho U_\infty^2)} \quad (3)$$

where P is the pressure and U_∞ is the far-field velocity. The full LES and ELES both give good agreement with the experimental data. Note that the pressure coefficient is the same on suction and pressure sides, since the angle of attack is zero.

Figure 2(b) shows the mean velocity profile normal to the chordwise-spanwise plane at a position just beyond the trailing edge, where the location $y = 0$ corresponds to the foil axis. Both methods give the same velocity profile, which agrees reasonable well with the experimental profile. Also, it is seen that the predicted boundary layer thickness is correct.

Figure 3 shows the profiles for Reynolds stresses near the trailing edge in the three coordinate directions (x being the streamwise direction, y is normal to the chordwise-spanwise plane, and z is the spanwise direction) according to the full LES and ELES carried out in this study, and according to the experimental data. The predicted values according to the full LES and ELES are similar. Comparison with experimental data shows that the velocity fluctuations fall to zero at the same distance as in the experimental data, and thus again, there is good agreement in terms of the boundary layer thickness. However, turbulent fluctuations are overestimated in comparison to the data close to the trailing edge, especially for the streamwise component. In the simulations carried out by George and Lele (2016) for this same test case, although they found good agreement for the spanwise and normal components, they still found that the streamwise component was overpredicted. They suggested that there may be a limitation in the experimental method which affects its accuracy at locations very close to the trailing edge.

Since the turbulence, as represented by the Reynolds stress components, has been overpredicted with both full LES and ELES, this suggests that the current method has deficiencies common to both. Therefore, it seems that further improvement is needed in the current wall-modelling LES method. The study of George and Lele (2016) has demonstrated that it is possible to achieve accurate results with WMLES, but their model settings were different. Aspects requiring further investigation include the choice of sub-grid viscosity model and choice of differencing schemes. It is also likely that the wall modelling method needs improvement. According to Larsson et al. (2016), the practice of basing calculations on the cell centres nearest to the surface (as done here) inevitably leads to errors, as the wall function is necessarily fed inaccurate information. Instead, the wall function should operate at a greater distance from the wall inside the boundary layer. It is planned to test this concept in future work.

Figure 4 illustrates the turbulent structures in the boundary layer, by means of isosurface plots of the *Q* parameter, defined as:

$$Q = 0.5(\mathbf{\Omega}^2 - \mathbf{S}^2) \tag{4}$$

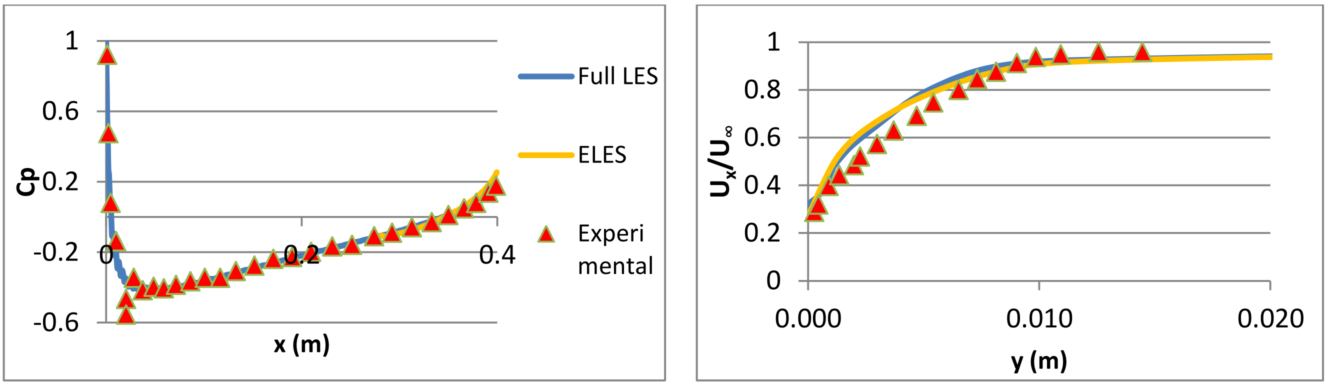
where $\mathbf{\Omega}$ is the vorticity tensor and $\mathbf{S}$ is the strain rate tensor. Some differences can be seen between the full LES and ELES. In the ELES, the structures are sparser along the foil surface, as a certain transition distance is required to achieve the development of ‘real’ turbulence. However, closer to the trailing edge, the structures maintain a somewhat coarser appearance. The difference compared to the full LES may be attributed to the synthetic turbulence injection algorithm. Either the transition distance here is too short, or perhaps more likely, the difference results from the use of volume forcing. With volume forcing, the turbulence field is not specified directly, but instead the velocity field is only forced towards a target state without ever quite getting there, as the force term is balanced out by other terms in the Navier-Stokes equations. Further work is planned to improve the synthetic turbulence method.

3.2 Acoustics predictions

To investigate whether the ELES method can be used as a substitute for full LES to assess flow-induced noise, results are presented here comparing the surface pressure and far-field pressure spectra obtained from each method.

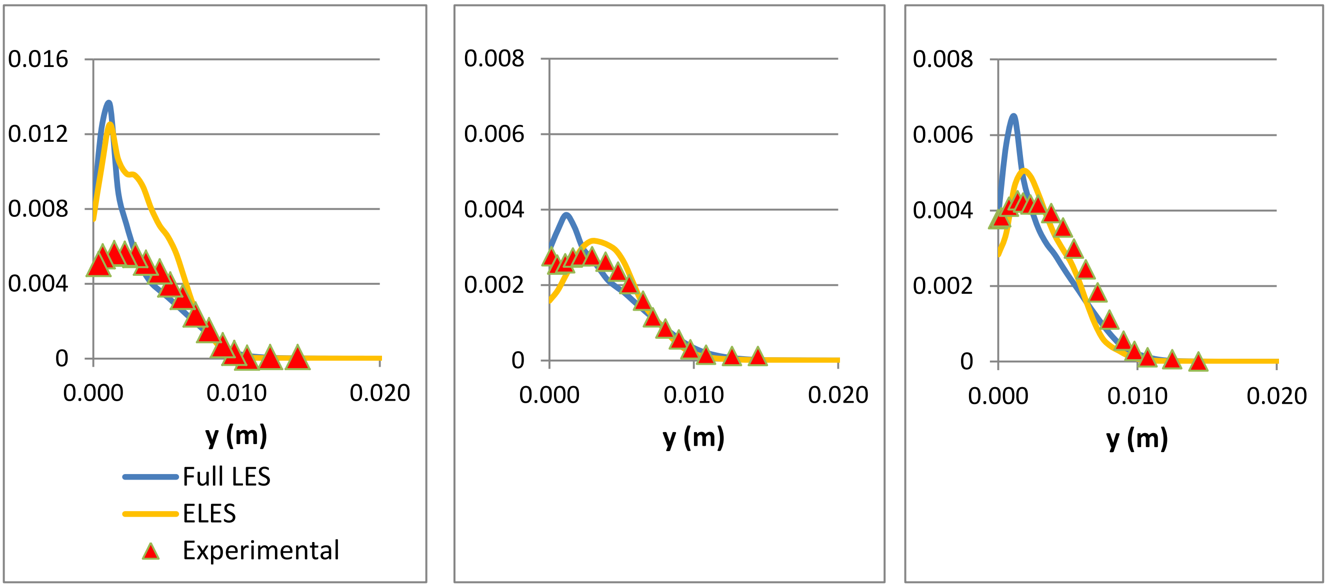
Figure 5 shows the power spectral density of the surface pressure near the trailing edge (at 99% of chord length), as predicted with the full LES and the ELES methods. The computational methods show similar levels and profiles, however the broadband peak predicted with the ELES method is approximately 5 dB higher than predicted with the full LES method. Away from this broadband peak, agreement between the full LES and ELES methods is typically between 1 – 2 dB.

Figure 6 (a) shows the one-third octave band level of the far-field noise obtained using the FWH analogy. The one-third octave band level predicted using the ELES analysis combined with the FWH analogy is within 3 dB of the results obtained using the full LES method. The largest discrepancy is observed at lower frequencies with the agreement between ELES and full LES within 1 to 2 dB at higher frequencies. Figure 6 (b) shows the one-third octave band level of the far-field noise obtained using the analytical scattering model. The one-third octave band level predicted using the ELES analysis combined with the analytical scattering model is within 3 dB of the results obtained using the full LES method. The largest discrepancy is observed at the broadband peak with the agreement between ELES and full LES typically within 1 to 2 dB at frequencies away from this peak.



(a) (b)

Figure 2 Comparison of full LES and ELES predictions from this study for a NACA0012 aerofoil with experimental data of Herr et al. (2013) for: (a) pressure coefficient as a function of distance along chord; (b) mean velocity profile normal to chord just beyond the trailing edge (100.38% of chord) – velocities normalized by far-field velocity, U_∞.



(a) (b) (c)

Figure 3 Comparison of normal Reynolds stresses for full LES and ELES predictions from this study and experimental measurements, for a profile normal to the chordwise-spanwise plane at a location just beyond the trailing edge (100.38% of chord), for: (a) streamwise; (b) normal; (c) spanwise directions. Values normalized by the square of the far-field velocity, U_∞^2.

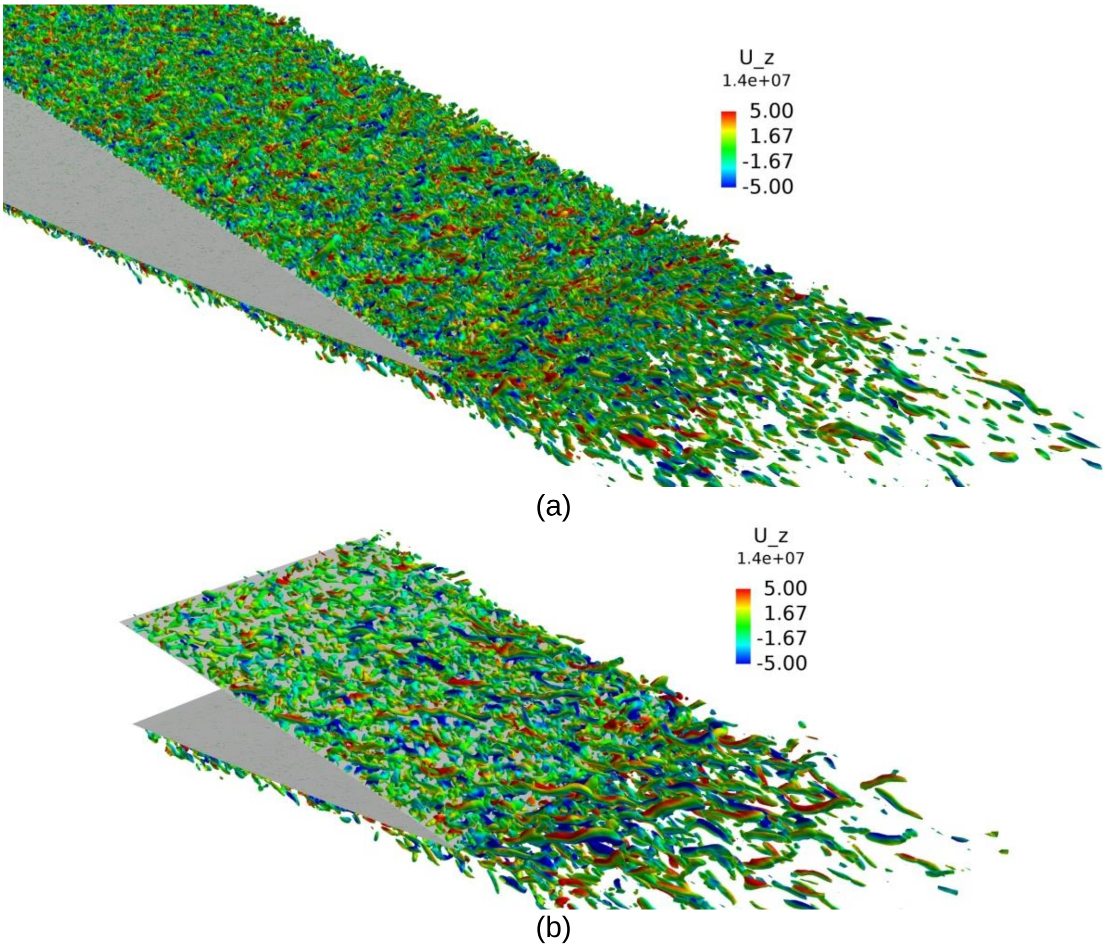


Figure 4 Isosurface plot for $Q = 1.4\times10^7$, coloured by instantaneous spanwise velocity component (m/s) for a NACA0012 aerofoil: (a) full LES; (b) embedded LES

Comparisons between the predicted spectra and measurements have indicated insufficient agreement thus far, for both computational methods. Predicted sound levels are too high, which can be attributed to the overprediction of Reynolds stresses in the inner region of the boundary layer. However, the focus of this paper has been to make an assessment as to whether the ELES method can substitute for full LES in noise predictions. Based on the comparison between the methods, the results thus far are very encouraging. The ELES method generated similar results at a substantially reduced cost, as can be judged from the computation times. With parallel computing on a cluster, the full LES simulation required 187,060 core-hours to compute 15 flow-past times (0.11 seconds of real time), whereas the same simulated time required just 85,030 core-hours using ELES, i.e. a saving of 55% in computational effort[1].

Further work is currently ongoing to improve the accuracy of the predicted Reynolds stresses in the boundary layer, and this is expected to have a flow-on effect which should improve the quantitative agreement with the measured noise spectra, for both the full LES and ELES methods.

[1] The full LES was run using 1000 cores and took 187 hours (wall clock time), whereas the ELES was run with using 500 cores and took 170 hours. Note, however, that that no attempt was made to optimise the partitioning for parallel computing. Since the mesh cell count for ELES was only 33% of that for the full LES, even greater savings in computation time might be expected by optimising the number of cores used for ELES.

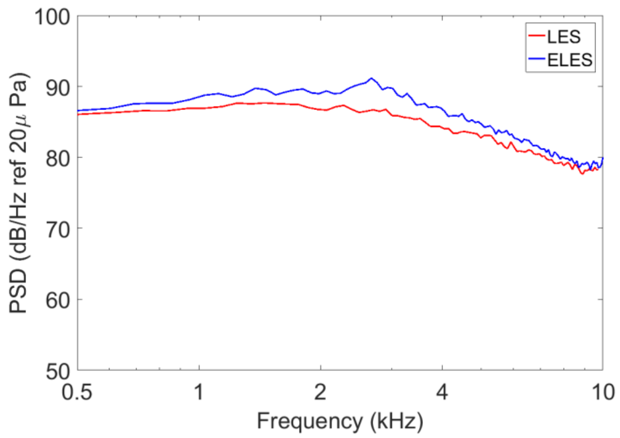


Figure 5 Comparison of the predicted surface pressure spectra obtained from the LES and ELES methods for a NACA0012 aerofoil

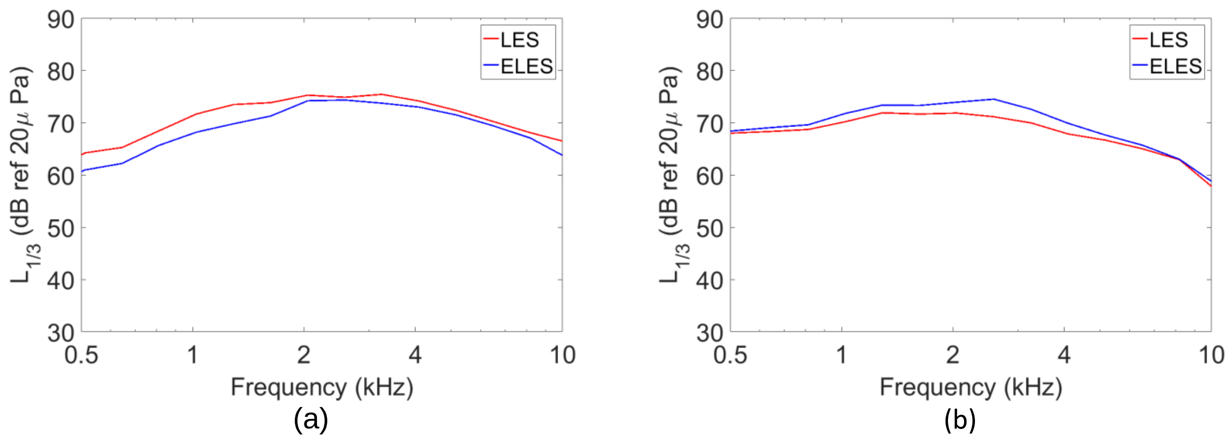


Figure 6 Comparison of the far-field spectra (at a location 1 m from the trailing edge, in the direction normal to the chordwise-spanwise plane), obtained from the LES and ELES methods for a NACA0012 aerofoil using (a) the FWH analogy and (b) the analytical scattering model of Roger and Moreau (2005)

4 CONCLUSIONS

An embedded LES method has been developed and applied to simulate the flow around a NACA0012 aerofoil at zero angle of attack. For comparison, a simulation was carried out with LES applied in the complete computational domain. Both methods were based on the same mesh resolution and used the same wall-modelled LES approach. However, for ELES the mesh size was only about 13 million cells, compared to 40 million cells for the full LES. It was found that the full LES and embedded ELES achieved comparable results, both in terms of the mean flow and turbulence characteristics, and the acoustics near-field and far-field predictions. However, the use of ELES resulted in a saving of 55% of the computational cost of a full LES.

It is clear, however, from comparisons with experimental data, that there is room for improvement in the computational method. This is an on-going study, which aims to improve the accuracy of predictions. Several aspects for further investigation have been identified:

- Modelling options in the WMLES approach should be investigated, comparing alternative sub-grid scale viscosity models, alternative differencing schemes, and improving the wall modelling approach by sampling the mesh further from the surface.

- The synthetic turbulence algorithm should be improved to obtain more realistic properties, with the aim of achieving more rapid development of realistic turbulence, with correct structural characteristics, downstream of the RANS-LES interface.

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