Procedia Computer Science
Volume 66, 2015, Pages 150–157
YSC 2015. 4th International Young Scientists Conference on Computational Science

Development of a Dynamic Library for computational aeroacoustics applications using the OpenFOAM Open Source Package

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Abstract

A large number of available computational fluid dynamics codes include tools for analysis of computational aeroacoustics problems. Such tools are proprietary as well as the codes themselves. Actually, the level of development of such codes as OpenFOAM makes it possible to implement enough opportunities for complication of physical models and increasing the scale of the issues described. In our paper, we develop a dynamic library libAcoustics which may be compiled independently of any modules of the main OpenFOAM package and the type of solvers being used in the model. The implemented Curle's analogy in library makes it possible to obtain acoustic spectra under the conditions of turbulent flows around arbitrary solids in a medium moving at a low velocity of flow. Calculation of the acoustic field was made for 3D test case of Cylinder – NACA 0012 Wing Profile configuration. The analogy allows user to define solvers settings through standard user I/O dictionaries of the OpenFOAM. A complete implementation of the analogy is capable of producing parallel computation. The libAcoustics library is free and is available for download on demand.

Keywords: computational aero-acoustics, computational fluid dynamics, numerical simulation, acoustic analogy

Selection and peer-review under responsibility of the Scientific Programme Committee of YSC 2015

doi:10.1016/j.procs.2015.11.018

1 Introduction

There are some aspects of aeroacoustics that significantly affect the quality of our lives. At the household and engineering levels it is necessary to correctly count noise from different sources like home appliances, musical instruments, airplane, train, car and engine. At present, the issues of computational aeroacoustics are widespread problems related to computational fluid dynamics [1]. The most widespread commercial CFD codes, such as ANSYS CFX or FLUENT, contain methods for calculating acoustic noise both at industrial and research levels. More recent open CFD codes are just started to be complemented with solvers and utilities for numerical simulation of aeroacoustics problems. For instance, starting from v. 2.2.1 (2013 release), OpenFOAM includes a noise utility allowing for analyzing the acoustic spectrum in the near field. This utility is an additional software that uses the standard probes output of the OpenFOAM functionObjects library and performs Fast Fourier Transform to process pressure versus time fluctuations at certain points.

Several authors have previously made calculation attempts to run flow and aeroacoustics simulations using OpenFOAM open-source software package. Eugene de Villiers studied the noise source intensity on the front face of a car mirror using FW-H (Ffowcs-Williams and Hawkings) analogy and DES (Detached Eddy Simulation) model [2]. The 3D fine mesh included 3.3×10^6 cells. Unfortunately, it isn't given any details about FW-H analogy implementation. C.J. Doolan run the acoustic computations using two-dimensional flow data and a compact form of Curle's theory (analogy) with spanwise approach and temporal statistical models that introduced random perturbations into the time-domain signals for tandem cylinders configuration [3]. The scientific group from University of Southampton has done the simulation with Improved Delayed DES model for NACA 65(12)10 aerofoil case [4]. The Curle's acoustic analogy approach has been implemented into OpenFOAM. But there also were no details about its implementation. In paper [5] the authors from University of Rome run 3D flow turbulent simulation using modified version of solver pisoFoam taking into account the influence of Coriolis and centrifugal forces and LES model for industrial 224JFM Fan with 16 blades. The formulation of method consisted of FW-H equations and Farassat's solutions for rotating surfaces. The FW-H analogy was implemented in Matlab package as a separate module. The mesh includes 9×10^6 nodes and y+ value was about 1.

The Amiet's theory was used to predict noise in the far field for rod-airfoil case in paper [6]. The incompressible solution obtained using pisoFOAM with LES model. The mean and rms velocity profiles, near field velocity spectra, and far field acoustic pressure spectra are compared between estimates and measurements. LES (Large Eddy Simulation), Improved LES and DES together with an acoustic model, similar to the conventional Ffowcs-Williams & Hawkings or Lighthill-Curle's models, have here been used to study the flow and acoustic noise emitted from the trailing edge of a flat airfoil with a 45° asymmetrically trailing edge and an elliptical leading edge in paper [7]. The flow as well as the emitted acoustic noise is compared to and in close agreement with the experimental data obtained in an open, anechoic wind tunnel. As a rule, in all these works various acoustic analogies and modern fluid dynamics models are used, but details of program realization aren't listed.

2 The architecture of the libAcoustics library

2.1 Main features and implemented acoustic analogy

The developed library overlays the whole bunch of the OpenFOAM solvers. It lies on the same level as post-processing utilities of the package (see Fig.1). Such mechanisms are also implemented in proprietary computational fluid dynamics codes. However, the way it was implemented in the OpenFOAM allows operation as dynamical library in real time together with solvers. The library can use both solution data and solver data when calculation continues and the last option is preferred because large amount of different information about solution is converted in specific files. These files are the result of applying the acoustic analogy and contain only pressure fluctuation at certain points.

In this paper we also show the results of flow simulation using libAcoustics and simple Curle analogy. In accordance with it the acoustic pressure fluctuations induced by the body in the far-field observation point are proportional to aerodynamic forces acting on that body. Thus, the equation of the Curle analogy is [8,9]:

$$p'(\tilde{x},t) = \frac{1}{4\pi c_0}\frac{x_i}{r^2}\left[\frac{\partial F_i}{\partial t} + \frac{c_0 F_i}{r}\right].$$

Where c_0 – speed of sound, r – distance to observer, F_i – aerodynamic force.

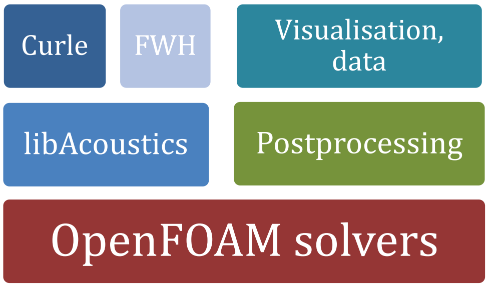


Figure 1: The hierarchy of the OpenFOAM solvers and the place of the libAcoustics library

The Curle analogy allows determination of the acoustic noise in near and far-field. For many engineering applications non-dimensional frequencies are in range of 0.1 < St < 2, so assumptions in the Curle analogy derivation are used reasonably [9]. The way analogy was implemented allows approximately account of three-dimensional effects in two-dimensional simulations by coefficient for correction of the pressure fluctuation in span-wise direction.

The results of computational aeroacoustics simulations using libAcoustics contain not only rough pressure fluctuations data but also Sound Pressure Levels (SPL) obtained after Fast-Fourier Transform using following well-known formula:

$$SPL(dB) = 20\log_{10}\left(\frac{p'(\tilde{x},t)}{2\cdot 10^{-5}}\right).$$

Where $p'(\tilde{x},t)$ – pressure fluctuations as function of the Observer position (x) and time (t).

2.2 Interaction with OpenFOAM

The library libAcoustics uses a native OpenFOAM functionObject API mechanism (see fig. 2). Usually class functionObject is used for post-processing operations and calculations. All objects of the class can be called from solvers and do not have an influence on the simulation process.

The main idea of using functionObject class for the implementation of the libAcoustics is in the following points:

1. We have a prototype of the class that provides data for post-processing and contains virtual function for post-processing;
2. The user creates new class that is non-dependent from this prototype and the class contains virtual functions for post-processing;
3. Implementation of the user class is in the non-dependent dynamic library.

All implemented object of the class functionObject are situated in the special array (*functionObjectList* class); array of *functionObjectList* is a part of Time class. The Time class is responsible for running all objects of the *functionObject* class through the whole simulation. All objects of the *functionObjectList* are constructing from *controlDict* dictionary of the OpenFOAM (see Fig. 2).

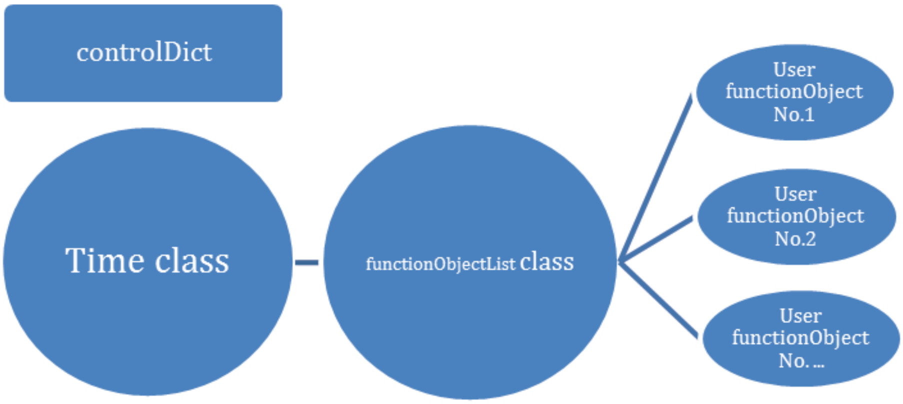


Figure 2: User's class objects are using functionObject

The simulation using libAcoustics library needs the following data and parameters:

1. *User data*. The user must define following input data before simulation: name of the patches or face sets, which are used for integration, names of the pressure and density fields, start and end time, frequency range, observer (microphone) position, sound speed, characteristic length, Fast-Fourier Transform settings for obtaining SPL data. For instance, when using Curle analogy, user should set a type name "Curle" in functionObject dictionary.
2. *Force distribution on the surface of the body*. This type of data is obtaining during the simulation and functionObject gets necessary pressure distribution and face normal vector using relevant OpenFOAM basic classes and object.
3. *Time derivative numerical scheme*. The numerical scheme for boundary force time derivative can be of two different types: Euler and upwind.
4. *Sound observer settings*. The reference pressure and observer position are saved in separate objects in the different class soundObserver and thus need to be set in separate sub-dictionary. The separation of the soundObserver data allows to generalize different types of analogies and enhance code re-use when new analogies will be implemented. Also in soundObserver sub-dictionary user must set parameters for objects of the Fast-Fourier Transform class FoamFftwDriver from third-party library Fftw3. The FoamFftwDriver process pressure fluctuations obtained from analogy and returns list of the frequencies and amplitudes for given acoustic pressure. Then SPL is calculated in the output file that is saved at the end.
5. *Saving data sequence*. The library uses OFstream OpenFOAM class to save data on the hard drive. Pressure fluctuations and noise SPL data are saved in specific files for each observer.
6. *Parameters of parallel mode calculation*. In the case of using parallel algorithms we need to take into account the following points:

a) The patches could be in the different sub-domains; to provide simulations we need to go through all processors and collect all necessary data using special callings;

b) Fast-Fourier-Transform and writing operations could be executed on a single processor (master).

3 Test Case "Cylinder – NACA 0012 Wing Profile"

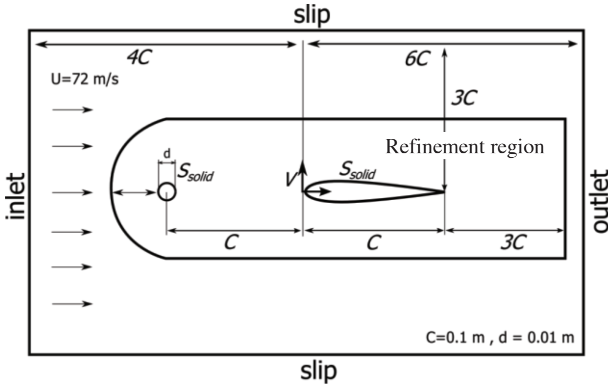
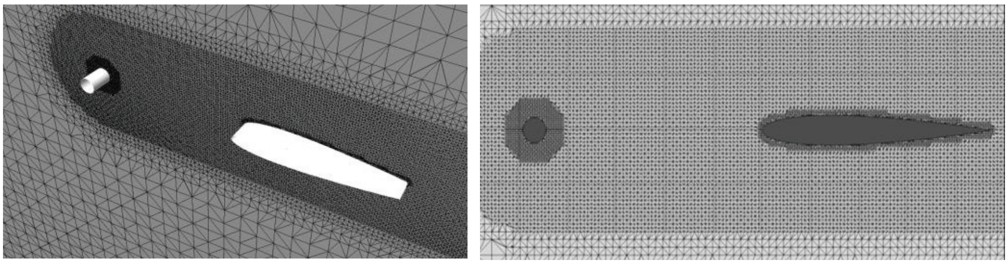


Figure 3: Domain parameters and boundary conditions scheme

This section illustrates how unsteady computational fluid dynamics calculation associated with appropriate acoustic models can be tested versus experimental data. To verify the developed library, data and results of the work [10] have been used. The experimental study investigates the acoustic spectrum upon exposure of the NACA 0012 wing profile, being installed in the trail line of a cylinder located ahead, to non-stationary flow. The paper [10] describes in detail the experimental conditions and geometric parameters of the experimental apparatus work area and the bodies being investigated. The authors give the calculation results for experimental configuration using the U-RANS and LES methods, thus creating favorable conditions for formulation of the test problem and validation of the libAcoustics library.



a b

Figure 4: Grid configuration: a – with spanwise in the Z-direction; b – grid slice with refinement

3.1 Description of the Problem

General description of boundary conditions and of the calculation domain dimensions is given in Figure 3. The main characteristic dimensions of the model in the numeric experiment are as follows: C = 0.1 m, d = 0.1C. The inflow condition and the flow parameters are based on the experimental inflow conditions [10]: U = 72 ms^{-1} (M ~ 0.2), ρ = 1.2 kgm^{-3}, ν = 1.5x10^{-5} m^{2}s^{-1}, Re_d = 4.8x10^4, Re_c = 4.8x10^5, the attack angle in discussed configuration is zero.

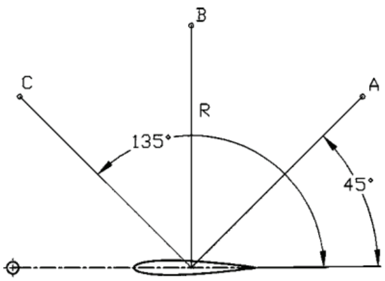


Figure 5: Observer positions

3.2 Numerical methods and subgrid-scale modeling strategy

The pisoFoam solver as part of OpenFOAM package was used for unsteady turbulent flow simulation [11]. In this work we used the LES turbulence model the main idea whereof consists in a formal mathematic separation of large and small vortex structures by means of a filtering operation [1,2]. Within this model, vortex structures which dimensions exceed the dimensions of the filter are allowed “exactly”, whereas structures of smaller dimensions are simulated using a subgrid turbulence model. In this work, we used a subgrid model with one differential equation for the turbulent kinetic energy. The time step was dt = $8x10^{-7}$ seconds and the Courant number was 0.2 max. The case was run on High Performance Infiniband Cluster (www.unihub.ru) with 36 or 60 cores. The end time T_{end}=3.0 seconds and the simulation time was about two weeks.

3.3 Grid design

Domain discretization was realized using the OpenFOAM grid generator – snappyHexMesh. A characteristic feature of the calculation grid is the presence of improvement zones near the cylinder, profile and downstream. The total 3D computational mesh size was about $2x10^6$ cells, in the spanwise direction the domain was extended for 3d = 0,03m. A fragment of the calculation grid is shown in Figure 4.

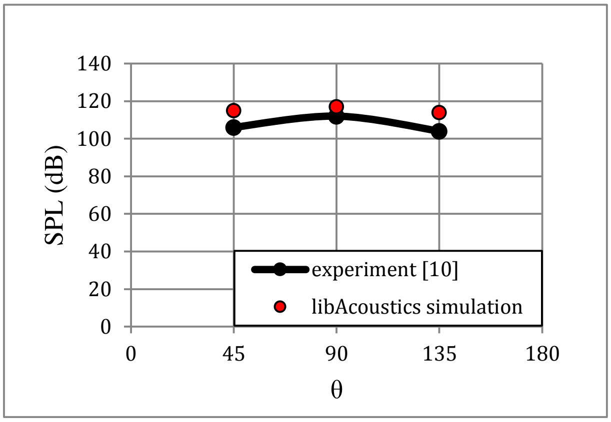


Figure 6: Directional pattern of the main Strouhal peak

3.4 Acoustic Far Field

To calculate the acoustic noise, the following data were specified: speed of sound in air C = 300 m/s. Virtual microphones (A,B,C) were located at a distance of R = 1.85m, the microphones position angle θ was set equal to 45°, 90°, and 135° degrees (see Fig. 5).

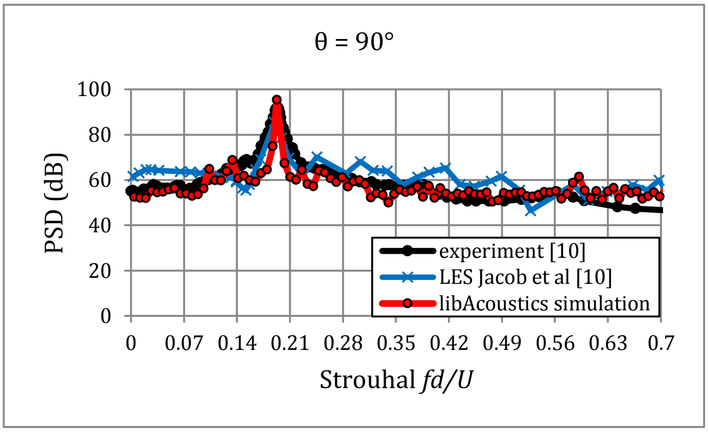


Figure 7: Far field acoustic PSD at 1.85m from airfoil center (90°) compared to measurements from Jacob et al [10]

4 Results

The maximum level of SPL (Sound Pressure Level) is reached with Strouhal number St = 0.192 and frequency f = 1385 Hz. The far field directivity of the main peak is shown in Figure 6. The calculation results for the PSD (Power Spectral Density) values versus the Strouhal number for θ = 90° are shown in Figure 7. It is visible that the obtained values coincide well with the results of work [10].

5 Conclusions

During the development of the libAcoustics library, the OpenFOAM CFD package demonstrated its flexibility. It is possible to provide a numeric definition of the following characteristics using implemented Curle's analogy:

1. sound pressure when flowing around arbitrary bodies;
2. noise spectrum in the near and far field;
3. layout of the noise orientation;
4. evaluation of the input of separate structural elements into the common spectrum of the generated noise.

This valuable experience is planned to be used to extent the library functionality and to add the FW-H analogy [12]. The FW-H analogy with different sampling surfaces can be implemented by means of software parallel paradigm Hadoop/Mapreduce for processing of Big Data results derived from LES simulations [13]. The large database can be generated by different positions of virtual microphones in case of more detailed fine grids [14]. The authors of this paper take part in the developing of Big Data cluster in the scope of special project in ISP RAS. The libAcoustics library is free and is available for download as source code on demand.

Acknowledgments

This research is funded by The Ministry of Education and Science of Russia (RFMEFI60714X0090, grant number 14.607.21.0090)

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