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# OPENCFS: OPEN SOURCE FINITE ELEMENT SOFTWARE FOR COUPLED FIELD SIMULATION - PART ACOUSTICS

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## ABSTRACT

Although many numerical simulation tools have been developed and are on the market, there is still a strong need for appropriate tools capable to simulate multi-field problems. Therefore, openCFS provides an open-source framework for implementing partial differential equations using the finite element method. Since 2000, the software has been developed continuously. The result of is openCFS (before 2020 known as CFS++ Coupled Field Simulations written in C++). In this paper, we present for the first time the open-source software with a focus on the acoustic module.

**Keywords** Open Source FEM Software · Multiphysics Simulation · C++ · Acoustics · Aero-Acoustics · openCFS

## 1 Introduction

Since its initial foundation phase in 2000 by Manfred Kaltenbacher at the Department of Sensor Technology of the Friedrich-Alexander-University Erlangen-Nuremberg, several university institutes were involved in the development of the former finite element software CFS++ [1]. In 2020, CFS++ went open source and provides an object-oriented finite element framework for research. The software includes several physical fields

- Acoustics (*openCFS-Acoustics*)
- Electrodynamics (*openCFS-Edyn*)
- Mechanics (*openCFS-Mechanics*)
- Piezoelectrics (*openCFS-Piezo*)
- Heat transfer (*openCFS-Heat*)

and is specialized on coupling those fields [13]. Within this contribution, we concentrate on the openCFS module *openCFS-Acoustics*. An application of this module for an aeroacoustic simulation of a ducted fan is given in Fig. 1. The paper is organized as follows: In Sec. 3, we provide the generic finite element formulation of the wave equation as implemented in openCFS. In Sec. 2, 3, 4, and 5, we show how to implement a finite element formulation in the framework of openCFS. We start by stating the wave equation and derive its weak formulation for finite element implementation, discuss the calling structure of openCFS and show the implementation. In Sec. 6, we show the basic building blocks of a finite element simulation using openCFS. Section 7 references publications and developments using openCFS. The motivation of this publication is to encourage users to use and develop openCFS with us (the usage is free of charge under the MIT license). Finally, in Sec. 8, we summarize the topics of the software and motivate future research.

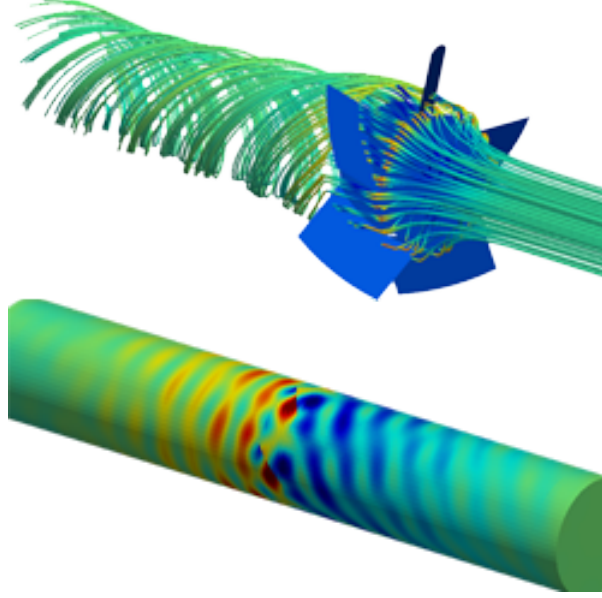


Figure 1: Aeroacoustic simulation of a ducted fan.

## 2 Wave equation

**Equation 2.1 (Wave equation)** Given  $c$ ,  $p_0^a(\mathbf{x})$ ,  $dp_0^a(\mathbf{x})$ ,  $p_{\Gamma_D}^a(\mathbf{x}, t)|_{\Gamma_D}$ ,  $u_{n\Gamma_N}^a(\mathbf{x}, t)|_{\Gamma_N}$ , domain  $\mathbf{x} \in \Omega$ , and time  $t \in [0, T]$  find  $p_a$  such that

1. Partial differential equation:

$$\frac{1}{c^2} \frac{\partial^2 p_a}{\partial t^2} - \nabla \cdot \nabla p_a = f \quad \text{in } \Omega \times [0, T]$$

2. Boundary conditions:

$$p_a(\mathbf{x}, t) = p_{\Gamma_D}^a(\mathbf{x}, t) \quad \text{at } \Gamma_D \times [0, T]$$

$$\nabla p_a(\mathbf{x}, t) \cdot \mathbf{n} = u_{n\Gamma_N}^a(\mathbf{x}, t) \quad \text{at } \Gamma_N \times [0, T]$$

3. Initial conditions:

$$p_a(\mathbf{x}, 0) = p_0^a(\mathbf{x}) \quad \forall \mathbf{x} \in \Omega$$

$$\frac{\partial}{\partial t} p_a(\mathbf{x}, 0) = \dot{p}_a(\mathbf{x}, 0) = dp_0^a(\mathbf{x}) \quad \forall \mathbf{x} \in \Omega$$

Regarding the definition of the wave equation on the domain  $\Omega$ , the Dirichlet boundary  $\Gamma_D$ , and the Neumann boundary  $\Gamma_N$  (see Fig. 2), we derive the weak formulation of the wave equation.

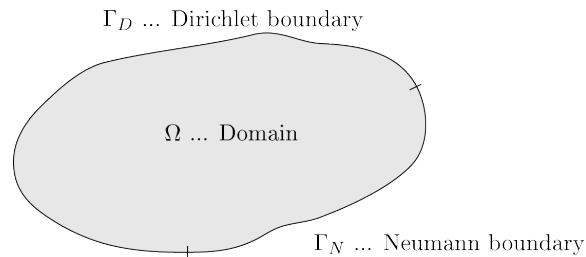


Figure 2: Domain of the wave equation.

### 3 Finite Element Formulation

We define the solution function space for the acoustic pressure  $p_a \in \mathcal{V} = \{v \in H^1(\Omega) | v = p_0^a \text{ at } \Gamma_D\}$  and the test function space  $w \in \mathcal{W} = \{u \in H^1(\Omega) | u = 0 \text{ at } \Gamma_D\}$ . Using this function space, we can obtain the weak formulation of the wave equation. Additionally, we restrict the function spaces to a discrete (limited number of functions) solution function space  $p_a^h \in \mathcal{V}^h \subset \mathcal{V}$ ;  $\mathcal{V}^h = \{v^h \in H^1(\Omega) | v^h = p_0^a \text{ at } \Gamma_D\}$  and a discrete test function space  $w^h \in \mathcal{W}^h \subset \mathcal{W}$ ;  $\mathcal{W}^h = \{u^h \in H^1(\Omega) | u^h = 0 \text{ at } \Gamma_D\}$ . In doing so, we obtain the semi-discrete finite element form.

**Equation 3.1 (Weak formulation (semi-discrete))** Given  $c$ ,  $p_0^a(\mathbf{x})$ ,  $dp_0^a(\mathbf{x})$ ,  $p_{\Gamma_D}^a(\mathbf{x}, t)|_{\Gamma_D}$ ,  $u_{n\Gamma_N}^a(\mathbf{x}, t)|_{\Gamma_N}$ , domain  $\mathbf{x} \in \Omega$ , and time  $t \in [0, T]$ . Find  $p_a^h \in \mathcal{V}^h$  such that  $\forall w^h \in \mathcal{W}^h$  the equation holds:

1. Weak form:

$$\int_{\Omega} \frac{1}{c^2} w^h \ddot{p}_a^h d\Omega + \int_{\Omega} \nabla w^h \cdot \nabla p_a^h d\Omega - \int_{\Gamma_N} w^h u_{n\Gamma_N}^a ds = \int_{\Omega} w^h f d\Omega$$

2. Boundary conditions:

$$p_a(\mathbf{x}, t) = p_{\Gamma_D}^a(\mathbf{x}, t) \quad \text{at } \Gamma_D \times [0, T]$$

3. Initial conditions:

$$p_a(\mathbf{x}, 0) = p_0^a(\mathbf{x}) \quad \forall \mathbf{x} \in \Omega$$

$$\frac{\partial}{\partial t} p_a(\mathbf{x}, 0) = \dot{p}_a(\mathbf{x}, 0) = dp_0^a(\mathbf{x}) \quad \forall \mathbf{x} \in \Omega$$

Inserting the finite element ansatz ( $n_n$  number of finite element nodes)

$$p_a \approx p_a^h = \sum_{b=1}^{n_n} N_b p_{a,b};$$

$$w \approx w^h = \sum_{a=1}^{n_n} N_a w_a;$$

The basis functions are known. The coefficients are the unknowns and model the physical solution. The semi-discrete form (space discrete, time continuous) can be expressed by an algebraic system of equations

$$\mathbf{M}_{\underline{p}_a} \ddot{\underline{p}}_a + \mathbf{K}_{\underline{p}_a} \underline{p}_a = \underline{f} + \underline{f}_{Neumann}.$$

In openCFS, the operators of the weak form are implemented and the discretization of the equation system is done by the software and the underlying mesh of the domain.

### 4 Software module openCFS-Acoustics

The finite element software is object-oriented and programmed in C++. As a typical finite element software the following time discretization is possible:

- Time is discretized by a time-stepping scheme.
- Time is transformed into the Fourier space (time-harmonic simulation).
- The system of equations is transformed into an eigenvalue system.

Important for the general understanding of the software is the life-cycle structure during an openCFS run (see Fig. 3).

### 5 Implementation details

We assume that one only implements a partial differential equation and no adaptations to the driver have to be made. The core concepts are first the finite element space, finite element function, and finite element forms.

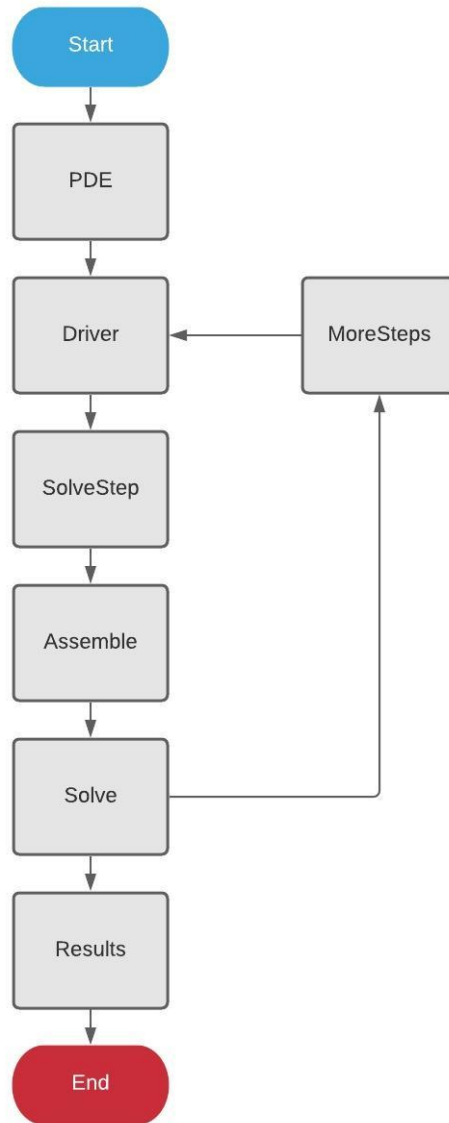


Figure 3: openCFS life-cycle during a run.

- Finite element space manages the equation numbers for the associated unknowns. It holds and manages associated reference elements. It also knows how to incorporate boundary conditions. Furthermore, it distinguishes between geometrical elements (mesh representation) and computational elements (how the physical quantities are approximated).
- Finite element function is the representation of the function space and knows its particular selection from different possibilities.
- Linear forms are integrators for the right-hand side of a partial differential equation.
- Bilinear forms, also called integrators, are the realizations of the left-hand side of a weak formulation and are constructed by the operators (e.g. a gradient operator). In the case of the presented wave equation, we use symmetric bilinear forms to construct the algebraic system.

## 6 Application details

The simulation file of openCFS is an XML based input format [2]. The underlying structure of our XML files is defined via a so-called XML-scheme. The path to this scheme is defined in the header of every XML file and per default it points to our default public scheme, provided on our gitlab server:

```
<?xml version="1.0"?>
<cfsSimulation xmlns="http://www.cfs++.org"
xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
xsi:schemaLocation="http://www.cfs++.org
\protect\vrule width0pt\protect\href{http://cfs-doc.mdm.tuwien.ac.at/xml/CFS-Simulation/CFS.xsd}{http://cfs-doc.mdm.tuwien.ac.at/xml/CFS-Simulation/CFS.xsd}" />
```

In general, an OpenCFS XML file consists of three main parts:

- fileFormats: definition of input-/output- and material-files
- domain: region definitions (assign material to different regions)
- sequenceStep: contains the definition of the analysis type and the PDE.

Several sequenceSteps can be concatenated and results from previous sequenceSteps can be processed to produce the desired result.

```
<!-- define which files are needed for simulation input & output-->
<fileFormats>
  <input>
    <!-- read mesh -->
  </input>
  <output>
    <!-- define output -->
  </output>
  <materialData file="../material/mat.xml" format="xml"/>
</fileFormats>

<domain geometryType="3d">
  <regionList>
    <!-- region definition -->
  </regionList>
</domain>

<sequenceStep index="1">
  <analysis>
    <!-- analysis type: static, transient, harmonic, multiharmonic, eigenfrequency -->
  </analysis>
  <pdeList>
    <!--for example consider the acoustic PDE-->
    <acoustic>
      <regionList>
        <!--define on which regions the PDE is solved-->
      </regionList>
      <bcAndLoads>
        <!--define appropriate BC's and Loads-->
      </bcAndLoads>
    </acoustic>
  </pdeList>
</sequenceStep>
```

```

        </bcsAndLoads>
        <storeResults>
            <!--define the results to be stored-->
        </storeResults>
    </acoustic>
</pdeList>
</sequenceStep>
</cfsSimulation>

```

Detailed information about the XML-input files can be found online [2].

## 7 Selected Application

### 7.1 Methods

Inside openCFS-Acoustics, non-conforming interfaces for stationary and rotating domains [13, 10, 15, 38, 23], perfectly matched layer [11, 12] and infinite domains [35], higher order finite element basis functions [9], and special aeroacoustic source models [16, 34, 25, 27, 43, 26], and special wave equation models [5, 17] are available.

### 7.2 Vibroacoustics and Aeroacoustics

Since 2016, the software provided solutions for challenges in acoustical engineering and medicine. Car frame noise [3, 6, 29, 43], fan noise [24, 39, 14, 19, 37, 40] noise emissions of the turbocharger compressor [18, 7], HVAC systems [20, 8], wind turbines [42] were computed. For post-processing, the fluid field was decomposed into a longitudinal and transversal processes [33, 32, 28]. Furthermore, the human phonation process is studied in detail [36, 41, 44, 30, 4, 21, 22, 31].

## 8 Conclusion

Although in the last years many commercial simulation tools have been developed and are on the market, there is still a strong need for appropriate tools capable to simulate multi-field problems. An implementation of a new partial differential equation (PDE) or physical coupling between PDEs into a commercial software, e.g. using provided interfaces via user routines, results in most cases in very inefficient numerical schemes. For this reason, we have decided to develop our own tool, based on the Finite Element (FE) method. The result of our effort is openCFS (before 2020 known as CFS++ Coupled Field Simulations written in C++).

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Sketches in this work have been partly created using the Adobe Illustrator plug-in LaTeX2AI (<https://github.com/stoani89/LaTeX2AI>).

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