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FRESIS 1.0: A fluid–rigid–elastic structure interaction solver

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ABSTRACT

FRESIS is developed based on a full-Eulerian mathematical framework and can be addressed as a tool for reproducible, extendable and efficient research in fluid–rigid–elastic structure interaction field. Due to the flexible algorithm which is implemented in Fortran, any application that requires the solution of fluid–rigid–elastic structure interaction problem, could benefit from FRESIS.

Code metadata

Current code version	v1.0
Permanent link to code/repository used for this code version	https://github.com/SoftwareImpacts/SIMPAC-2023-169
Permanent link to Reproducible Capsule	https://codeocean.com/capsule/8126636/tree/v1
Legal Code License	MIT License
Code versioning system used	git
Software code languages, tools, and services used	Fortran, CodeBlocks, Visual Studio Code
Compilation requirements, operating environments & dependencies	Fortran compiler
If available Link to developer documentation/manual	https://doi.org/10.1088/1873-7005/acba44
Support email for questions	i.farahbakhsh@aut.ac.ir

1. Introduction

Developing a monolithic solver for incompressible fluid flow comprising the rigid and elastic structure(s) is still addressed as an interesting and challenging topic of researches among the computational fluid dynamics community. Therefore, one can find a vast field of applications for employing such solvers, which include some problems in aerospace engineering like coupling vibrations in a structure containing liquid, in ocean engineering like sloshing phenomena in LNG carrier tanks, and not surprisingly in biological systems which in turn covers many fields of research in bioinspired and biomimetic systems.

A novel solution strategy has been developed in order to simulate the interaction of any types of elastic structure(s) with incompressible fluid and rigid structure(s) simultaneously [1]. Retrieving the vorticity field and recalculating a solenoidal velocity field at the fluid–rigid structure(s) interface accompanying the derivation of a vorticity transport equation for the whole domain containing the elastic structure(s) are the kernels of the proposed algorithm which is shown in Fig. 1.

FRESIS 1.0, using a monolithic framework, considers a system consisting of a fluid, elastic and rigid structure(s) as a one-continuum and simulates the interaction of structure(s) and fluid using the idea of a force-free immersed boundary method [2–4]. The development repository of the code is accessible at https://github.com/imanfarahbakhsh/FRESIS1.0.git and the permanent link to reproducible capsule is https://codeocean.com/capsule/8126636/tree/v1.

2. Software design and functionality

FRESIS 1.0 includes two modules and nineteen main subroutines which solves governing equations of fluid–rigid–elastic structure interaction in a monolithic framework based on the vorticity-stream function formulation of Navier–Stokes equations. For imposing the rigid structure's effect in the flow field [2], the vorticity field recovers from consecutive execution of subroutines FORCING_FUNCTION_VS, SOLVER, U_V, ZERO_FIELD_VELOCITY and VOR_DEFINITION and resolving the stream function is done using subroutine SOLVER

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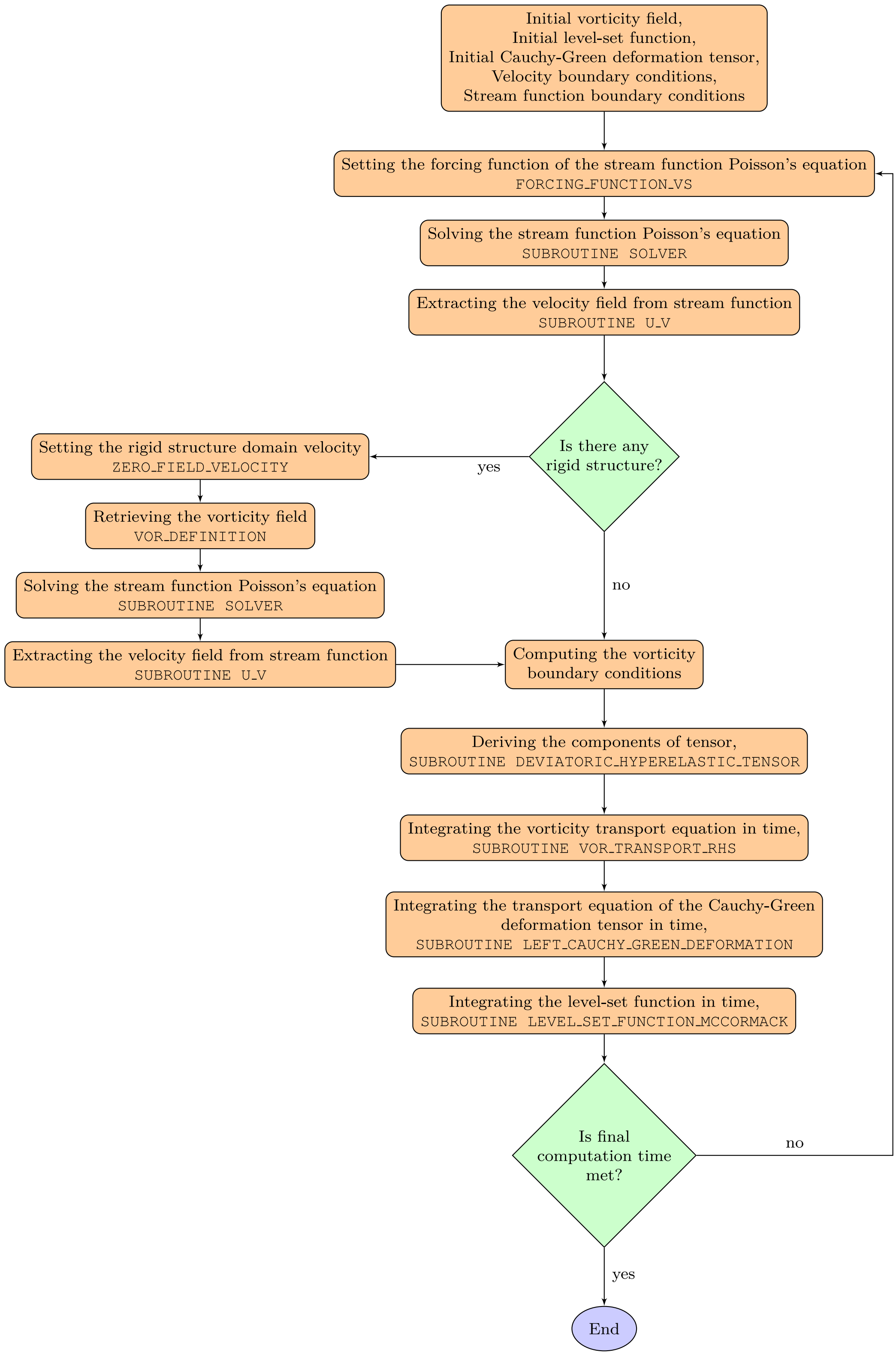

Fig. 1. Software structure.

and subroutine `U_V` obtains the physical velocity field. Recalling the subroutine `SOLVER` to obtain the stream function and, consequently, the velocity field based on the new vorticity field, imposes a doubled computational cost for solving the elliptical part of the formulation. The current version's redundant computational cost is dramatically decreased by recalling an optimized geometrical multigrid solver, i.e., subroutine `MGLIN`.

To add the effect of elastic structure(s) in the governing equations in a monolithic framework, the Cauchy stress tensor, which includes the constitutive equation of the elastic structure(s), is added to the

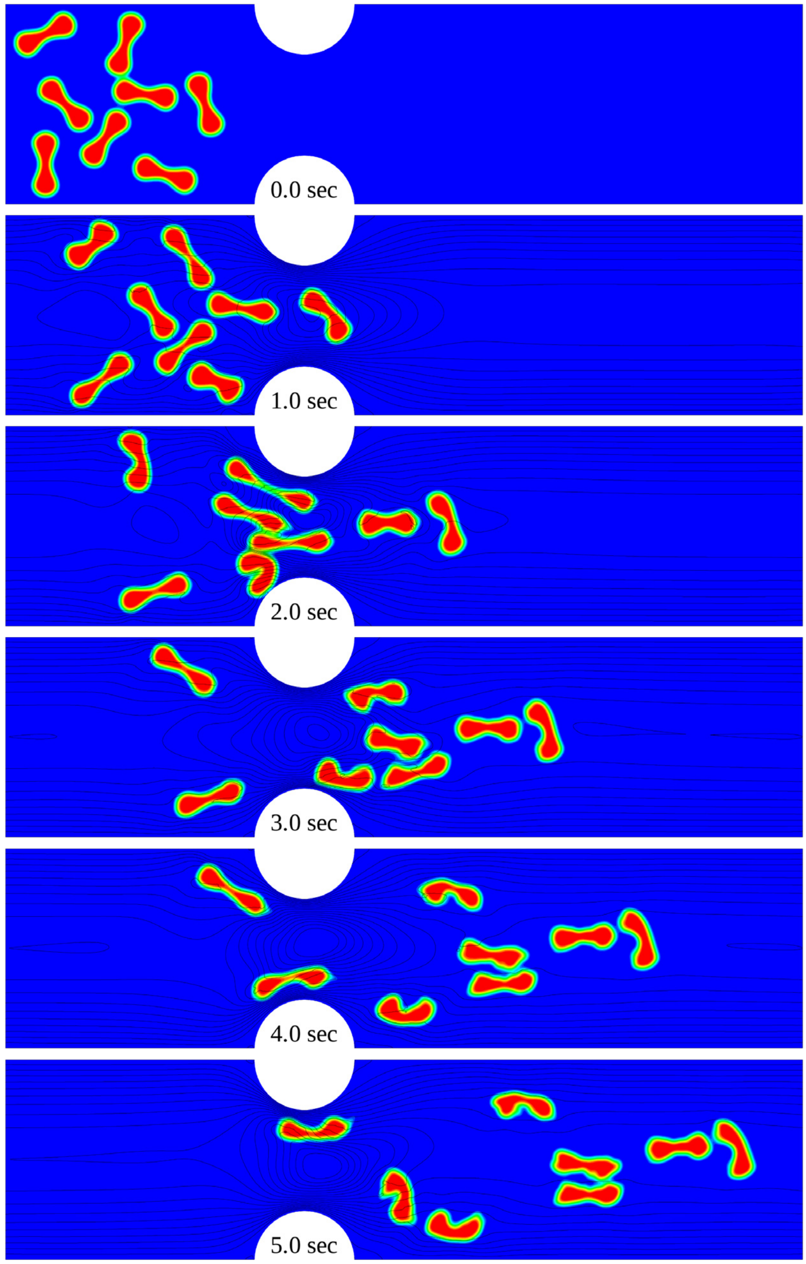

Fig. 2. Deformation of a bunch of neo-Hookean biconcave particles in the Poiseuille flow restricted by two rigid semicircle structures.

right-hand side of the Navier–Stokes equation. To calculate this tensor's components in terms of the Cauchy–Green deformation tensor, subroutines `DEVIATORIC_HYPERELASTIC_TENSOR` and `LEFT_CAUCHY_GREEN_DEFORMATION` are used. In this software, the level set function is used to determine the interface between fluid and elastic structure(s). Subroutines `LEVEL_SET_FUNCTION_MCCORMACK`, `LEFT_CAUCHY_GREEN_DEFORMATION` and `VOR_TRANSPORT_RHS` are used for the time integration of the transport equations of level set function, Cauchy–Green deformation tensor and vorticity, respectively. The results from the stream function, velocity and vorticity field in any arbitrary time steps, which are adjustable in the module, are saved as `.DAT` or `.PLT` files for post-processing by subroutine `WRITE_TOTAL_SOL_VS`. A sample of results from `FRESIS 1.0`, which depicts the interaction of a bunch of biconcave elastic structures with the fluid Poiseuille flow under the effect of stenosis, is shown in Fig. 2.

3. Impact overview

`FRESIS 1.0` is broadly used and under active development. Its initial version was originally created for and used in [4] for simulating the fluid-elastic structure(s) interaction. Based on previous studies with focus on developing a methodology for imposing the rigid structure(s) in the flow field using a novel force-free immersed boundary method [2,3], the current version of `FRESIS 1.0` is developed [1]. Any application that requires a monolithic framework to solve a system of governing equations for the interaction of fluid and structures with various behaviors, from hyperelastic to rigid, could benefit from `FRESIS 1.0` as a whole or any of its parts.

Thanks to a novel force-free immersed boundary algorithm and the soft lubrication effect, which likely brings the elastic–elastic and elastic–rigid structures hydrodynamic repulsions, `FRESIS 1.0` enables the user to capture the structure–structure collisions in flow field without imposing any extra artificial effect in the numerical method [4].

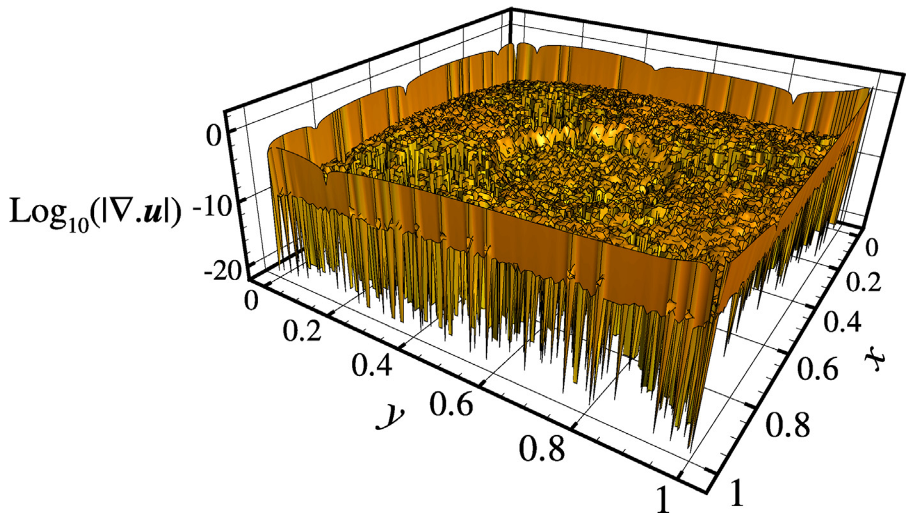

Fig. 3. The distribution of the velocity divergence for the coarse grid of 129 × 129.

For guaranteeing mass conservation, the correctness of elastic structure(s) shape recovery and solenoidality of the velocity field are examined using software in several benchmarks [1,4]. Fig. 3 illustrates the field of velocity divergence when the software was run for the cavity flow test case with an immersed rigid obstacle. In most adverse conditions at the middle of the field in the interface of fluid and structure, the velocity divergence takes the values of order 10^{-10}, which is an acceptable accuracy for a coarse grid of 129 × 129 [1].

4. Limitations

FRESIS 1.0, in the current version, has high flexibility to deal with fluid–rigid–elastic structure interaction problems. Based on the structure of the proposed method, the vorticity field must be recovered for imposing the rigid structure to the flow field, and the stream function Poisson's equation must be resolved based on the new vorticity field. Solving the redundant stream function Poisson's equation in each time step inflicts a duplicative computational cost for the elliptic solver part of the code. To reduce this computational cost, the solvers of the elliptic part of the equations have been improved, and in the current version, as mentioned in Section 2, we have used a geometric multigrid solver. For future versions of FRESIS, solvers with 4th and 6th-order accuracy are under development, and Krylov subspace solvers [5] will be used as a preconditioner for the algebraic multigrid method.

5. Future applications

Due to the flexibility of the proposed algorithm of this software, a wide field of applications can be predicted for it. The possibility of adding buoyancy effects, the ability to define two-phase fluid, and considering the heat transfer between the structure and the fluid, will be addressed in the next versions of FRESIS. The synergy of these capabilities with its current capabilities in using different constitutive equations for elastic structure(s) causes this software to be employed in solving various practical problems in biomedical, marine, aerospace and automotive engineering.

Declaration of competing interest

There are no financial interests/personal relationships which may be considered as potential competing interests.

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