

Numerical Simulation of Fluid–Flexible Fin Fluid–Structure Interaction Based on a Fractional Model

Beibei Zhang, Zhuofan Hu, Xinqi Bi

School of Science, Beijing University of Civil Engineering and Architecture, Beijing 100044, China
Beijing Key Laboratory of Functional Materials for Building Structure and Environment Remediation, Beijing 100044, China

INTRODUCTION & AIM

- **Background:** Existing studies have confirmed that fluid–structure interactions (FSI) between flexible structures and fluids can enhance heat transfer in enclosed or ventilated cavities, with the relevant characteristics affected by structural elasticity, flow parameters, and other factors.
- **Problem:** Current integer-order models fail to account for the viscoelastic memory effect of time-fractional Maxwell fluids and lack the application of fractional derivatives, making it difficult to accurately characterize the dynamic flow–deformation interaction.
- **Aim:** Taking the square cavity flow with flexible fins as the research object, and based on the advantages of the Caputo fractional derivative, this study introduces the Caputo fractional Maxwell shear stress into the constitutive relation and incorporates time-fractional derivatives into the momentum and energy equations, respectively, to establish the governing equations, thereby constructing an FSI model. The aim is to reveal the regulatory mechanism of fractional-order memory effects on the flow field.

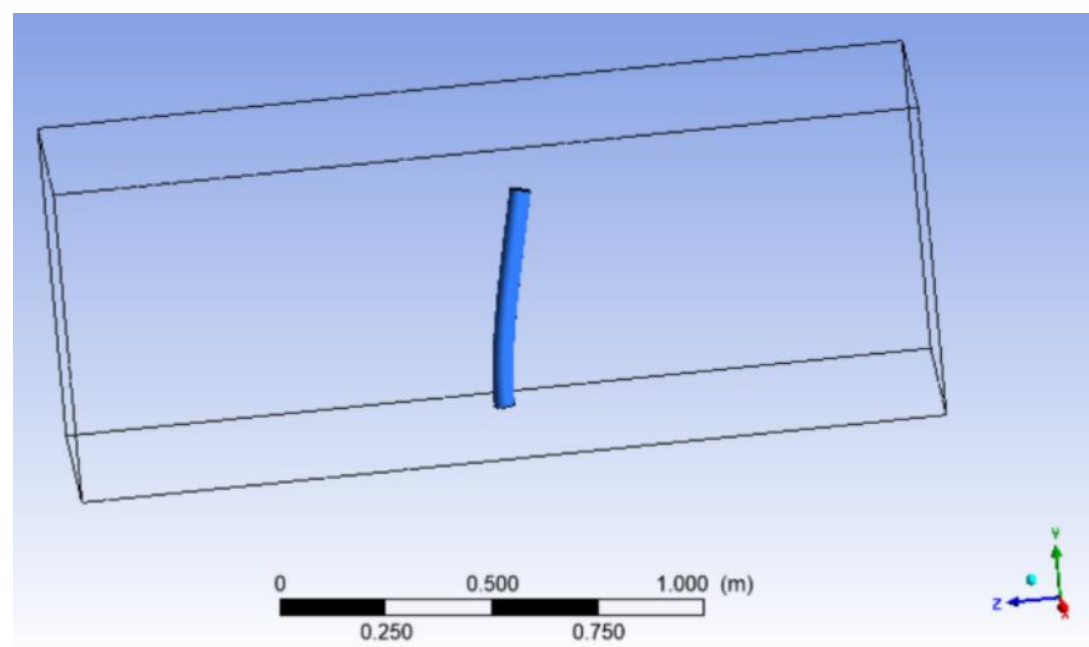


Figure 1. Square cavity with a flexible fin.

METHOD

- **Physical model:** A two-dimensional square cavity with a flexible fin mounted on the bottom wall. The left side is the fluid inlet, the right side is the outlet, and the cavity is filled with a time-fractional Maxwell fluid. (See Figure 1)

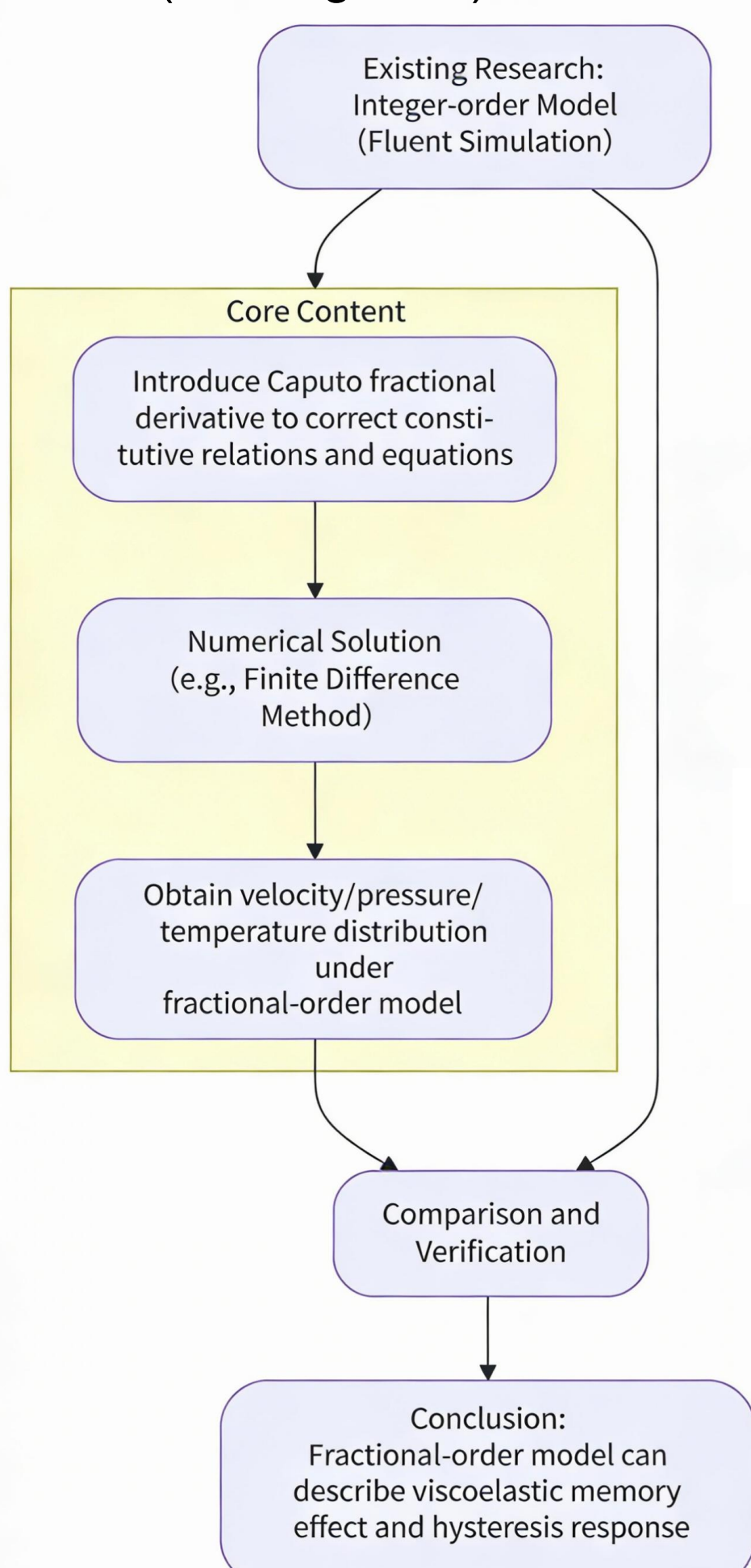


Figure 2. Technical roadmap

- **Governing equations:**
 - a. Mass conservation (incompressible flow).
 - b. Momentum equation: includes a time-fractional derivative term (Caputo type, order α).
 - c. Energy equation: includes a time-fractional derivative term.
 - d. Constitutive relation: Caputo fractional Maxwell model (stress–strain rate relationship linked via fractional relaxation time).

$${}_0^C D_t^\alpha f(t) = \frac{1}{\Gamma(1-\alpha)} \int_0^t (t-\tau)^{-\alpha} f'(\tau) d\tau, \quad 0 < \alpha < 1$$

- **Boundary conditions:** No-slip and isothermal/constant heat flux boundaries at the cavity walls. The flexible fin follows a linear elastic constitutive model. At the fluid–fin interface, velocity continuity and force balance are satisfied.
- **Numerical method:** Spatial discretization using the finite volume method (FVM). The time-fractional term is discretized using the L1 algorithm.

RESULTS & DISCUSSION

In the square cavity without a fin, comparison between the fractional-order and integer-order models shows that a smaller fractional order α leads to stronger viscous memory effects, more lagged flow response, and reduced vorticity intensity and wall shear stress.

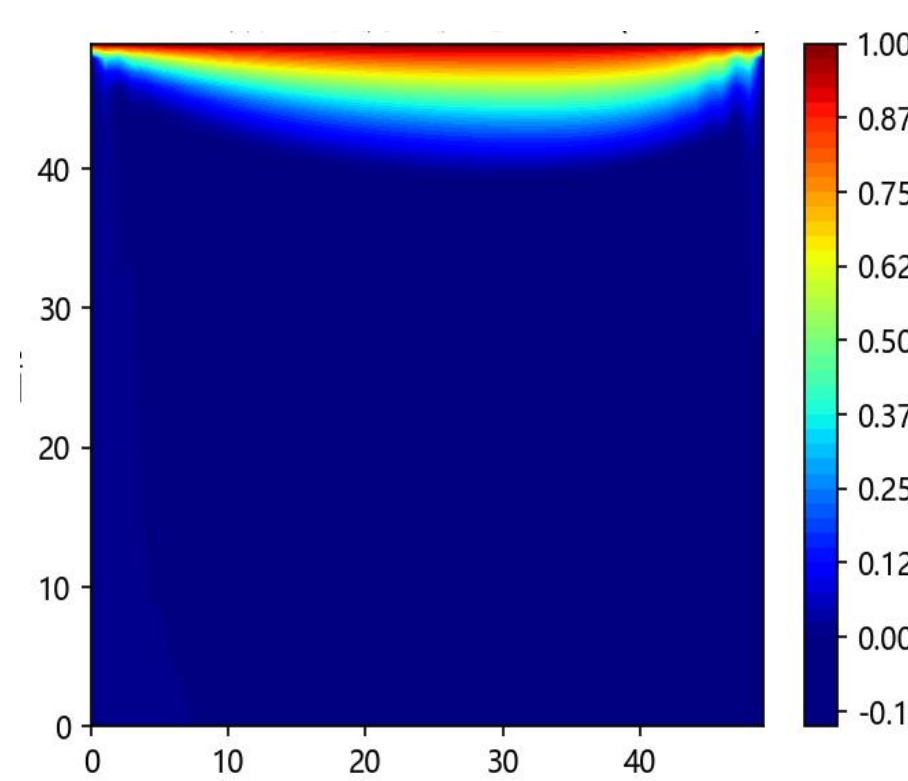


Figure 3. Integer-order velocity contour

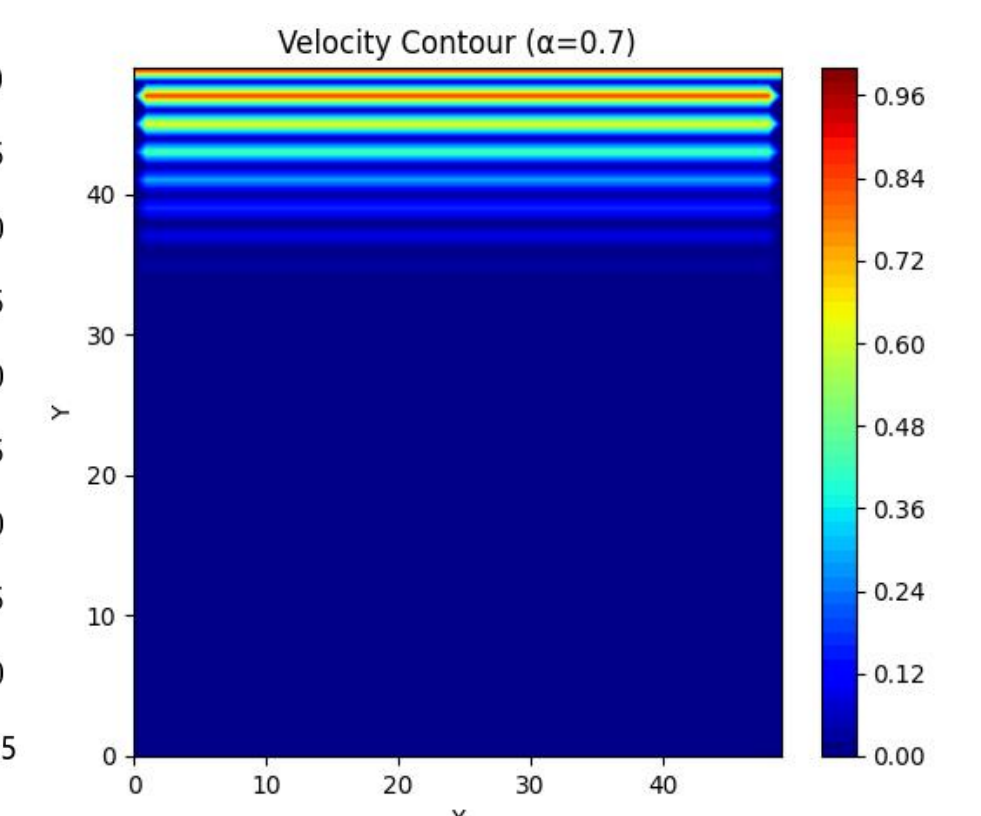


Figure 4. Fractional-order velocity contour ($\alpha = 0.7$)

In the fluid–structure interaction model of a square cavity with a flexible fin, the above findings are reproduced and validated, demonstrating the universality of fractional-order memory effects.

The Caputo fractional Maxwell constitutive model and FSI framework established in this work capture the long-term memory characteristics of time-fractional fluids, overcome the limitations of integer-order models, and provide a new numerical approach for simulating the coupling between flexible structures and complex fluids.

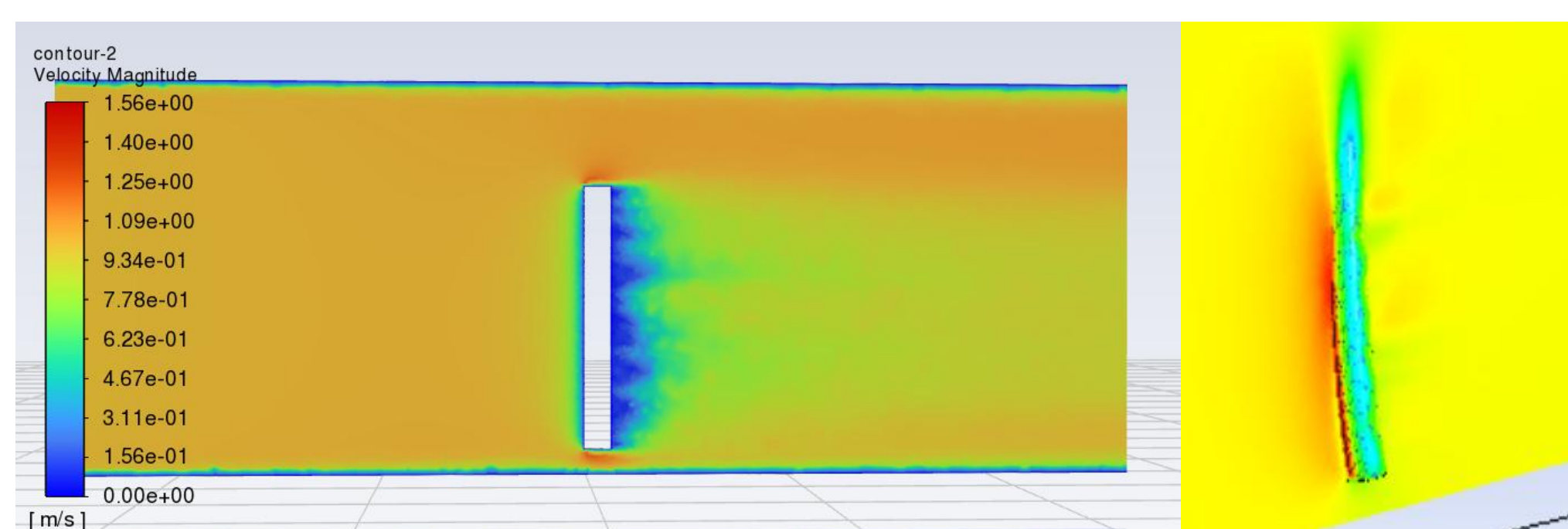


Figure 5 Velocity and Pressure Contours of Fluid-Structure Interaction with a Flexible Fin

CONCLUSION

- The Caputo fractional Maxwell model can accurately reflect the long-term memory effect of viscoelastic fluids, compensating for the shortcomings of integer-order models.
- A decrease in the fractional order α leads to a more lagged flow response, weaker vortex structures, and lower wall stress.
- The FSI framework proposed in this study provides a new numerical approach for simulating the coupling between flexible structures and fractional-order fluids.

FUTURE WORK / REFERENCES

- Consider a fractional order that varies with temperature or shear rate (nonlinear fractional model).
- Combine experiments to validate numerical results.
- Optimize the shape and arrangement of flexible fins to achieve active flow control.