

An efficient parallel immersed boundary–Lattice Boltzmann fluid–structure coupling method with application to free surface impact on elastic structures

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Abstract

Fluid–structure interaction (FSI) problems involving free-surface flows and elastic bodies remain a significant challenge in computational mechanics due to their complex coupling behavior, large interface deformations, and high computational demands. To address these challenges, this study proposes a high-efficiency, fully coupled numerical framework that integrates flexible plate models based on the Absolute Nodal Coordinate Formulation (ANCF) with an Immersed Boundary–Lattice Boltzmann Flux Solver (IB–LBFS). The proposed approach enables accurate simulation of both free-surface flow dynamics and the nonlinear response of elastic structures undergoing large deformations. In the fluid domain, the IB–LBFS method combines the mesoscopic lattice Boltzmann scheme with macroscopic flux reconstruction, along with a volume-force-based immersed boundary technique. An implicit boundary correction strategy is introduced to enforce no-slip conditions, while computational efficiency is enhanced through sparse matrix compression and a conjugate gradient iterative solver for velocity correction. For the structural domain, a four-node ANCF shell element with 48 degrees of freedom is employed, allowing accurate representation of large rigid-flexible motion without the need for coordinate transformations, thereby ensuring stable and precise structural dynamics analysis. The framework is validated through a dam-break scenario involving impact on an elastic vertical barrier. The simulation results show strong agreement with benchmark solutions obtained from space–time finite element and particle finite element methods. The method effectively captures free-surface evolution, structural modal behavior, and detailed pressure and displacement histories. Furthermore, compared to conventional space–time finite element approaches, the proposed solver achieves approximately a 33.3% reduction in computational time per FSI step under equivalent mesh conditions.

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1. Introduction

In the field of Fluid-Structure Interaction (FSI) simulation, solving the interaction between free surface flow and flexible structures accurately and efficiently is one of the long-standing challenges in engineering science [1,2]. Such problems are widely found in the fields of hydraulic construction, aerospace, ocean engineering and biomechanics, etc. Especially in the complex scenarios involving transient strong impacts, large deformations at interfaces and nonlinear responses of the structures, the stability, accuracy and efficiency of the numerical algorithms are required to be higher. For example, the physical process of dam failure impacting an elastic baffle involves high-

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speed free liquid surface propagation, transient fluid-structure coupling response and fluid-structure coexistence boundary treatment, and the traditional methods often suffer from insufficient accuracy or heavy computational burden in describing these phenomena. Therefore, it is of great theoretical value and engineering significance to develop a fluid-solid coupling solution framework that combines physical consistency, numerical stability and parallel efficiency [3,4].

In recent years, the Lattice Boltzmann Method (LBM) has gained wide attention in numerical simulation of fluid dynamics due to its concise evolution format, good parallel adaptability and natural multi-phase modeling capability [5]. Compared with the traditional Navier-Stokes direct discretization method, the LBM utilizes the microscopic particle distribution function to construct the evolution of macroscopic flow variables of macroscopic flow variables, thus realizing the efficient treatment of complex boundary and interface motions. However, the boundary accuracy and local mesh update efficiency of the standard LBM are still limited when dealing with dynamic boundary or complex structural coupling problems, and the computational errors are easy to accumulate, especially under high Reynolds number or large deformation structural coupling conditions [6,7].

For this reason, the Immersed Boundary Method (IBM) was introduced into the LBM framework to form the IB-LBM method, which realizes the fluid response modeling under non-structural boundary conditions by introducing the interaction force between the Lagrangian boundary nodes and the Eulerian fluid mesh [8]. The method does not rely on mesh reconstruction, has good geometric adaptability and numerical stability, and shows significant advantages in modeling problems such as complex interfaces and biological flows. However, IB-LBM still faces a series of challenges in practical engineering applications: on the one hand, the introduction of boundary volume forces complicates the construction of matrix equations of the system and increases the computational burden; on the other hand, the accurate modeling of the structural part under large deformations of higher-order nonlinearities still relies on the traditional finite element method (FEM), which is naturally deficient in rigid-body motion capture and mass array retention [9, 10].

To solve the accuracy problem of modeling large deformations of flexible structures, Absolute Nodal Coordinate Formulation (ANCF) has been proposed and rapidly developed [11]. This method avoids the cumbersome process of local coordinate rotation and rigid-body mode separation by directly expressing the nodal displacement and derivative variables in the global coordinate system, and realizes the organic combination of mass array contactization, rigid motion fidelity and efficient modal response. Especially in the coupling calculation with the flow field, ANCF has excellent ability to describe the response of large deformation and low stiffness structure, which has become an important development direction of the current FSI modeling of flexible body [12, 13].

In the existing literature, [14] used a spatio-temporal finite element method based on the ALE (Arbitrary Lagrangian-Eulerian) framework to study the elastic-structural problem of dam failure impacts, and successfully realized the coupled simulation of the free-surface and structural response, but suffered from the problems of long computation time, frequent mesh updates, and high coupling cost. In [15], the particle finite element method (PFEM) was proposed to deal with the two-phase flow-structure problem, which can effectively track the flow surface but has deviations in the treatment of high-density ratio and gas-liquid interface pressure. In addition, [16] proposed a virtual elastomer-based FSI coupling method to achieve structural modal dominance by regulating the spatial distribution of the virtual body moduli, so as to avoid the interference of the virtual body on the modal analysis, but it still needs a dense mesh support to obtain higher accuracy. [17] A hybrid IB-LBM and ANCF methodology for flexible multibody-fluid interactions, integrating immersed boundary techniques, turbulence modeling, and structural prediction to improve dynamic response accuracy and energy conservation.

In summary, the current mainstream FSI simulation methods still have the following outstanding problems in dealing with high-precision boundary reconstruction, large deformation modeling of flexible structures, and efficient numerical solution parallelism:

Low boundary processing accuracy and high computational cost: When LBM is combined with IB, the introduction of boundary volumetric force terms requires the introduction of decoupling

complex interpolation and convolutional integration operations between the Eulerian-Lagrangian grids, which leads to the time-consuming construction of matrices. The Eulerian-Lagrangian coupling between fixed fluid grids and moving structural nodes relies on interpolation functions for transferring velocity and force information. However, interpolation inaccuracies may introduce force prediction errors and reduce coupling stability, particularly in fluid-structure interaction problems involving large structural deformations.

Lack of rigid-flexible motion unity in structural modeling: traditional FEM is difficult to accurately handle rigid-flexible mixed motions, especially when dealing with large-scale deformations, which require a large number of mesh refinements to maintain computational accuracy. Advanced data analysis enables effective extraction of response characteristics from complex engineering systems, supporting accurate evaluation of deformation, vibration, stress evolution, and fluid-structure interaction behavior.

Insufficient parallelism of algorithms, limiting large-scale problem solving: the existing methods have serious coupling between the background mesh and the boundary matrix processing, making it difficult to accelerate effectively in chunks; the direct method is mostly used in the solution of linear equations, and there is a lack of iterative optimization strategy.

By combining the immersed boundary-lattice Boltzmann flux solver (IB-LBFS) and the absolute nodal coordinate flexible structural element (ANCF Plate Element), this paper suggests an effective numerical simulation framework for fluid-structure coupling and builds a comprehensive free-surface-structural response solving link to address the aforementioned issues. The efficiency and stability of the solution are greatly increased by utilizing the following crucial optimization techniques:

A sparse structure optimized boundary force matrix construction method is proposed, which reduces the computation time of the volumetric force matrix generation by filtering the relationship between the adjacent mesh points;

A one-dimensional compressed storage and conjugate gradient method is adopted to solve the modified velocity equation system efficiently iteratively to achieve high parallelism while maintaining accuracy;

A spatially distributed elastic modulus strategy is introduced to realize the virtual elastic body by using the spatially distributed elastic modulus strategy and the modal. The spatially distributed elastic modulus strategy and modal superposition method are introduced to realize stable mesh control and deformation tracking with the assistance of a virtual elastomer.

2. Immersed Boundary-Lattice Boltzmann Flux Solver

2.1 Governing Equations of Fluid Flow

In fluid-structure interaction (FSI) problems, the macroscopic behavior of incompressible fluid flow is described by the Navier-Stokes equations, which consist of mass and momentum conservation laws under the Eulerian framework [18].

The mass conservation (continuity) equation is:

$$\nabla \cdot \mathbf{u} = 0 \quad (1)$$

where $\mathbf{u}$ represents the velocity vector of the fluid.

The momentum conservation equation is given by:

$$\rho \left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = -\nabla p + \mu \nabla^2 \mathbf{u} + \mathbf{f} \quad (2)$$

where ρ is the fluid density, p is the pressure, μ is the dynamic viscosity, and $\mathbf{f}$ denotes body forces including interactions with solid boundaries, gravity, and other external effects.

These equations provide the theoretical foundation for conventional CFD methods. However, directly solving them becomes challenging in complex fluid–structure interactions or free surface problems. To overcome this, we adopt the Lattice Boltzmann Method (LBM) combined with the Immersed Boundary (IB) method to solve the governing equations indirectly, enabling efficient simulation of interactions between fluids and immersed elastic structures [19,20].

In the following sections, we will construct the discrete velocity model for the LBM evolution equations and incorporate source terms to integrate IB treatment seamlessly, thus establishing a robust numerical framework for Multiphysics coupling.

In the Lattice Boltzmann Method (LBM) for flux computation, momentum transport is characterized by two main components: the momentum flux term $\rho \mathbf{u}$ and the stress flux tensor Π . These represent, respectively, the convective transport of momentum and the contributions from both inviscid pressure forces and viscous effects.

The momentum flux $\rho \mathbf{u}$ denotes the momentum density per unit volume and is defined as:

$$\rho \mathbf{u} = \sum_i f_i \mathbf{c}_i \quad (3)$$

where f_i is the particle distribution function along the discrete velocity direction $\mathbf{c}_i$, ρ is the fluid density, and $\mathbf{u}$ is the macroscopic velocity.

The stress flux tensor Π consists of two parts: the inviscid part arising from pressure and the viscous part resulting from the velocity gradient. It is expressed as:

$$\Pi = \rho \mathbf{u} \mathbf{u} + p \mathbf{I} - \mu \quad (4)$$

where p is the static pressure, $\mathbf{I}$ is the identity tensor, and μ denotes the dynamic viscosity coefficient of the fluid, Π is the momentum flux tensor. This formulation captures the essential momentum transport properties described by the traditional Navier–Stokes equations while preserving the multiscale modeling strengths inherent in the LBM.

In fluid–structure interaction problems, these flux terms are essential for accurately computing the boundary forces and interface interactions. When embedded within the immersed boundary framework, they enable bidirectional coupling between fluid and structure, ensuring physical consistency throughout the simulation [21].

Based on the LBGK (Lattice Bhatnagar–Gross–Krook) model, the equilibrium distribution function f_α^{eq} is a fundamental component used to approximate the local equilibrium state of fluid particles in the lattice Boltzmann method (LBM). It enables the recovery of macroscopic fluid dynamics from microscopic particle interactions. The D2Q9 lattice arrangement was chosen because it offers an efficient compromise between computational speed and accuracy for the simulation of incompressible flows in 2D space. The relaxation factor was set within the stable range to avoid instabilities, reduce the influence of compressibility effects, and to obtain reliable predictions for the range of Reynolds numbers used. These choices make it possible to perform stable simulations of fluid–structure interaction problems in these operating conditions.

Under the assumptions of low Mach number and incompressible flow, the equilibrium distribution function for the commonly used D2Q9 model can be expressed as:

$$f_\alpha^{\text{eq}} = w_\alpha \rho \left[1 + \frac{\mathbf{c}_\alpha \cdot \mathbf{u}}{c_s^2} + \frac{(\mathbf{c}_\alpha \cdot \mathbf{u})^2}{2c_s^4} - \frac{\mathbf{u} \cdot \mathbf{u}}{2c_s^2} \right] \quad (5)$$

Where: f_α^{eq} is the equilibrium distribution function in the α – th direction, w_α is the weight coefficient associated with direction α , ρ is the fluid density, $\mathbf{u}$ is the macroscopic velocity, $\mathbf{c}_\alpha$ is the discrete lattice velocity in direction α , c_s is the lattice sound speed, typically $c_s^2 = \frac{1}{3}$.

This expression is derived from a second-order Taylor expansion of the Maxwell–Boltzmann distribution and ensures consistency with the incompressible Navier–Stokes equations at the

macroscopic level [22,23]. The equilibrium distribution function serves as the target toward which the particle distribution relaxes during the collision step in the LBGK model, thereby ensuring numerical stability and physical accuracy. The proposed framework integrates numerical response analysis with fluid–structure coupling simulation to characterize deformation, stress evolution, and wave propagation behavior in engineering structures.

In the Immersed Boundary–Lattice Boltzmann–Free Surface (IB-LBFS) method, the selection of lattice velocity directions $\mathbf{e}_\alpha$ and corresponding weight coefficients w_α depends on the specific lattice velocity model employed (e.g., D2Q9, D3Q19). These parameters are essential for constructing the equilibrium distribution function and directly influence the accuracy and stability of the algorithm.

Specifically, the lattice velocities $\mathbf{e}_\alpha$ are typically chosen from a symmetric set of discrete directions to represent the propagation of microscopic particles, while the weights w_α ensure that the summation rules satisfy mass and momentum conservation.

Based on these definitions, the governing equation system of the IB-LBFS method includes the lattice Boltzmann equation for fluid evolution, constraints from the immersed boundary method, and equations for free surface tracking. The overall formulation is as follows:

- Lattice Boltzmann Equation (LBE):

$$f_\alpha(\mathbf{x} + \mathbf{e}_\alpha \delta t, t + \delta t) = f_\alpha(\mathbf{x}, t) - \frac{1}{\tau} [f_\alpha(\mathbf{x}, t) - f_\alpha^{eq}(\mathbf{x}, t)] + F_\alpha \quad (6)$$

where: f_α : distribution function in the direction α ; τ : relaxation time; f_α^{eq} : equilibrium distribution function; F_α : external force term (including body forces introduced by the immersed boundary).

- Immersed Boundary (IB) Constraints:

These enforce the kinematic and dynamic coupling between solid boundaries and fluid using methods such as Lagrangian multipliers or modification of distribution functions to ensure velocity matching at the interface.

- Free Surface Tracking (FS):

The volume fraction function ϕ represents the fluid–gas interface and evolves according to the mass conservation equation:

$$\frac{\partial \phi}{\partial t} + \nabla \cdot (\phi \mathbf{u}) = 0 \quad (7)$$

where $\mathbf{u}$ is the fluid velocity vector, $\nabla \cdot$ denotes the divergence operator representing the net fluid flux through a control volume, $\frac{\partial \phi}{\partial t}$ is the temporal rate of change of the fluid volume fraction.

In summary, the IB-LBFS coupling method integrates the lattice Boltzmann model for flow simulation, the immersed boundary technique for fluid–structure interaction, and a free surface model for interface evolution, providing an efficient framework for simulating complex boundary problems with free surface impacts.

2.2 Discrete Solution

The governing equation is discretized in time, and the evolution process is divided into a predictor step and a corrector step:

$$f_\alpha(\mathbf{x} + \mathbf{e}_\alpha \delta t, t + \delta t) = f_\alpha(\mathbf{x}, t) - \frac{1}{\tau} [f_\alpha(\mathbf{x}, t) - f_\alpha^{eq}(\mathbf{x}, t)] + \delta t \cdot F_\alpha \quad (8)$$

where $f_\alpha(\mathbf{x}, t)$ is the particle distribution function in the α lattice direction (dimensionless), $\mathbf{x}$ is the spatial position vector, $\mathbf{e}_\alpha$ is the discrete lattice velocity vector, δt is the time step, τ is the dimensionless relaxation time controlling the fluid viscosity and collision process, $f_\alpha^{eq}(\mathbf{x}, t)$ is the equilibrium distribution function.

- Predictor Step

In the predictor step, ignoring external forces and boundary effects, the particle distribution function is advanced only by the relaxation term:

$$f_{\alpha}^*(\mathbf{x}, t) = f_{\alpha}(\mathbf{x}, t) - \frac{1}{\tau} [f_{\alpha}(\mathbf{x}, t) - f_{\alpha}^{eq}(\mathbf{x}, t)] \quad (9)$$

where f_{α}^* is the intermediate distribution function, $f_{\alpha}^*(\mathbf{x}, t)$ is the post-collision particle distribution function in the α -th lattice direction, $f_{\alpha}(\mathbf{x}, t)$ is the pre-collision particle distribution function, $f_{\alpha}^{eq}(\mathbf{x}, t)$ is the equilibrium distribution function.

- Corrector Step

The influence of external forces and immersed boundary conditions is then incorporated by correcting the intermediate state:

$$f_{\alpha}(\mathbf{x} + \mathbf{e}_{\alpha} \delta t, t + \delta t) = f_{\alpha}^*(\mathbf{x}, t) + \delta t \cdot F_{\alpha}(\mathbf{x}, t) \quad (10)$$

where F_{α} is the force term introduced based on Guo et al.'s forcing scheme, $f_{\alpha}(\mathbf{x} + \mathbf{e}_{\alpha} \delta t, t + \delta t)$ is the updated particle distribution function after the streaming step, $f_{\alpha}^*(\mathbf{x}, t)$ is the post-collision particle distribution function, $F_{\alpha}(\mathbf{x}, t)$ is the lattice force term accounting for external body forces and immersed boundary interactions. typically expressed as:

$$F_{\alpha} = w_{\alpha} \left(1 - \frac{1}{2\tau} \right) \left[\frac{\mathbf{e}_{\alpha} - \mathbf{u}}{c_s^2} + \frac{(\mathbf{e}_{\alpha} \cdot \mathbf{u}) \mathbf{e}_{\alpha}}{c_s^4} \right] \cdot \mathbf{F} \quad (11)$$

where $\mathbf{F}$ is the total body force, w_{α} is the weight, $\mathbf{u}$ is the macroscopic velocity, and c_s is the lattice speed of sound, F_{α} is the discrete force term in the α -th lattice direction, w_{α} is the lattice weighting coefficient, $\mathbf{e}_{\alpha} - \mathbf{u}$ represents the relative velocity between the lattice and fluid, $(\mathbf{e}_{\alpha} \cdot \mathbf{u})$ denotes the dot product of the lattice velocity and macroscopic velocity.

In summary, through the above two-step discrete evolution, the IB-LBFS algorithm can efficiently handle the dynamic response of complex boundaries and free surface variations in fluid-structure interactions, providing a solid numerical foundation for imposing immersed boundary conditions and updating macroscopic variables.

The equilibrium distribution function is derived using the Chapman–Enskog multiscale expansion, through which the continuity and momentum equations are recovered. Guo's forcing scheme incorporates immersed boundary forces while preserving mass and momentum conservation, enabling the IB-LBFS framework to recover the incompressible Navier–Stokes equations under low-Mach-number flow conditions and ensuring stable fluid–structure interaction.

$$\frac{\partial(\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \mu \nabla^2 \mathbf{u} + \mathbf{F} \quad (12)$$

where ρ is the fluid density, $\mathbf{u}$ is the fluid velocity vector, p is the pressure field. μ represents the dynamic viscosity of the fluid, $\nabla^2 \mathbf{u}$ denotes the velocity diffusion term. $\mathbf{F}$ is the external force density including immersed boundary interaction forces.

$$\mu = \rho c_s^2 \left(\tau - \frac{1}{2} \right) \delta t \quad (13)$$

where μ is the dynamic viscosity, ρ is the fluid density, c_s is the lattice sound speed, τ is the relaxation time, and δt is the time step.

The momentum exchange between the immersed boundary and surrounding fluid is governed by the forcing term, which transfers structural interaction forces into the lattice Boltzmann framework while preserving momentum conservation. The coupling can be expressed as:

$$\mathbf{F} = \frac{\partial(\rho\mathbf{u})}{\partial t} + \nabla \cdot (\rho\mathbf{u}\mathbf{u}) + \nabla p - \mu \nabla^2 \mathbf{u} \quad (14)$$

Where $\mathbf{F}$ represents the immersed boundary force density applied to the fluid, ρ is the fluid density, $\mathbf{u}$ denotes the fluid velocity vector. The terms $\frac{\partial(\rho\mathbf{u})}{\partial t}$ and $\nabla \cdot (\rho\mathbf{u}\mathbf{u})$ represent the temporal change and convective transport of momentum, respectively.

The IB-LBFS model reproduces the incompressible Navier-Stokes equations in the low-Mach number regime via the Chapman-Enskog multiscale expansion and Guo's forcing approach. In particular, the forcing function $\mathbf{F}$ properly accounts for the force interaction from the immersed boundary to the surrounding fluid without violating the conservation properties of mass and momentum.

Through the interface reconstruction (shown in Figure. 1), the density ρ , momentum flux $\rho\mathbf{u}$, and inviscid-viscous flux tensor Π at the interface are first obtained. Subsequently, the density distribution of the flow field as well as the intermediate velocity field $\mathbf{u}^*$ are calculated by solving the governing equations using the cellular finite volume method. This process ensures the accurate transfer of the physical quantities of the fluid at the interface and provides critical data support for the subsequent updating of the flow field and imposition of boundary conditions.

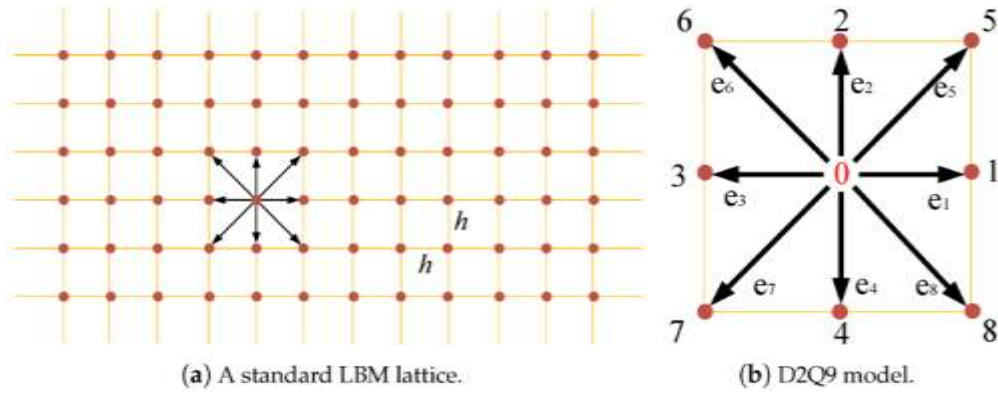


Fig. 1. LBM reconstruction at the adjacent cell interface

To satisfy the no-slip boundary condition, an implicit boundary correction method is introduced, which transforms the calculation of the volume force term $\mathbf{F}$ into solving the flow field velocity correction $\delta\mathbf{u}$ induced by the solid boundary. According to the no-slip condition, the velocity vector $\mathbf{U}^{n+1}(\mathbf{X}_{IB})$ at the immersed boundary point $\mathbf{X}_{IB}$ should be equal to the flow velocity at the corresponding location in the flow field. This interpolation relationship can be expressed as:

$$\mathbf{U}^{n+1}(\mathbf{X}_{IB}) = \sum_{\alpha} w_{\alpha} \mathbf{u}(\mathbf{x}_{\alpha}) + \delta\mathbf{u}(\mathbf{X}_{IB}) \quad (15)$$

where $\mathbf{X}_{IB}$ denotes the position on the solid boundary, $\mathbf{x}_{\alpha}$ are the neighboring flow field grid points, w_{α} are the corresponding weighting coefficients, and $\delta\mathbf{u}(\mathbf{X}_{IB})$ represents the velocity increment due to boundary correction. By solving this interpolation equation, the flow velocity is corrected to satisfy the no-slip boundary condition on the solid surface.

The interpolation kernel function $\phi(r)$ enables smooth transfer of velocity and force information between the Eulerian fluid grid and the Lagrangian boundary points. Its compact support restricts the interpolation to neighboring grid points, reducing numerical errors while preserving local force conservation.

$$\phi(r) = \begin{cases} \frac{1}{4} \left(1 + \cos\left(\frac{\pi r}{2}\right) \right), & |r| \leq 2, \\ 0, & |r| > 2. \end{cases} \quad (16)$$

where $\phi(r)$ is the kernel function for interpolation, r is the normalized distance between a point in the Eulerian domain and a boundary point in the Lagrangian domain, and $|r|$ is the magnitude of

the normalized distance. The kernel function is non-zero only within the region $|r| > 2$ to maintain localized, conservative, and stable information exchange between the fluid and structural domains.

The velocity correction at the solid boundary grid points, treated as an unknown variable, is assumed to be $\delta \mathbf{u}_{lB} \Delta s_l$. An interpolation is performed from the Lagrangian boundary grid points on the solid surface to the Eulerian flow field grid points, expressed as:

$$\delta \mathbf{u}(\mathbf{x}_\alpha) = \sum_l \phi(\mathbf{x}_\alpha - \mathbf{X}_{lB}) \delta \mathbf{u}_{lB} \Delta s_l \quad (17)$$

where $\mathbf{x}_\alpha$ represents the Eulerian flow field grid points, $\mathbf{X}_{lB}$ are the Lagrangian points on the solid boundary, $\phi(\cdot)$ is the interpolation kernel function, $\delta \mathbf{u}_{lB}$ is the velocity correction at the Lagrangian point, and Δs_l denotes the corresponding boundary segment length or area associated with the Lagrangian point. This interpolation allows the boundary velocity correction to be transferred to the neighboring flow field grid points to enforce the no-slip condition accurately.

The product $\mathbf{u}_{kB} \Delta s_k$ is defined as the unknown vector $\mathbf{X}$. Equation (17) can then be rearranged into a linear system of equations expressed as:

$$\mathbf{A}\mathbf{X} = \mathbf{B} \quad (18)$$

where matrix $\mathbf{A}$ and vector $\mathbf{B}$ are derived from the interpolation relations and boundary conditions. Specifically, $\mathbf{A}$ encapsulates the influence coefficients representing the relationship between velocity corrections at boundary points and their impact on the flow field grid, while $\mathbf{B}$ contains the terms related to the desired no-slip velocity conditions at the solid surface. Solving this linear system yields the boundary velocity corrections necessary to enforce the implicit no-slip boundary condition within the immersed boundary framework.

Here, NN denotes the total number of Lagrangian surface points constituting the solid boundary, and M represents the total number of Eulerian grid points in the flow field. The term D_{ij} is the continuous kernel interpolation function used to map quantities between the Lagrangian and Eulerian meshes. For the three-dimensional case, this interpolation function is defined within a critical radius RR , ensuring localized influence and smooth transfer of velocity corrections from boundary points to nearby fluid grid points. This formulation enables accurate and stable coupling between the immersed boundary and the surrounding fluid domain.

3. IB-LBFS: Computational Acceleration and Parallel Algorithm Optimization

In the simulation of unsteady moving boundary flows using the IB-LBFS method, a significant portion of computational time is consumed by operations related to the coefficient matrix $\mathbf{A}$ of the velocity correction equation—specifically, matrix assembly, storage, and the solution of the linear system. To enhance computational efficiency, three key algorithmic optimizations have been implemented [24]:

3.1 Acceleration of Matrix $\mathbf{A}$ Generation Through Physical Insight

Due to the presence of dynamic boundaries, at each unsteady time step, the interpolation coefficients D_{ij} between boundary Lagrangian points and Eulerian background grid points must be recalculated. According to equation (12), A_{ij} is derived from D_{ij} . Each column vector of $\mathbf{D}$ represents the influence of one Lagrangian boundary node ($j = 1, \dots, N$, where N is the total number of boundary points) on all Eulerian grid points ($i = 1, \dots, M$, with M as the total Eulerian points). Since the number of Eulerian points relevant to each boundary node is very limited relative to the total grid size, both $\mathbf{D}$ and $\mathbf{A}$ are sparse matrices. Furthermore, Eulerian points contributing to the boundary influence must lie within a spherical radius R centered at the boundary node. Therefore, during the assembly of $\mathbf{A}$, any correlation between boundary points separated by distances greater than $2R$ can be neglected. This filtering condition substantially reduces the reconstruction time of matrix $\mathbf{A}$.

3.2 Exploitation of Matrix AA's Sparsity and Symmetry Via One-Dimensional Storage

Since D is an $M \times N$ real sparse matrix, and $A = D \cdot D^T$, matrix A is symmetric positive definite. During the assembly process, only the lower triangular part of AA needs to be scanned and stored as a one-dimensional vector containing the nonzero elements and their positions (see Figure 2). This storage scheme drastically reduces memory usage and computational overhead related to sparse matrix operations.

3.3 Iterative Solution of The Linear System Using The Conjugate Gradient Method

Given the symmetric positive definite nature of matrix A , the conjugate gradient method is employed to solve the linear system $AX=B$ iteratively. Compared with direct solvers such as LU decomposition and matrix inversion, the conjugate gradient method significantly accelerates the solution process.

Since the size of matrix, A depends on the number of Lagrangian boundary points N , the computational acceleration becomes more pronounced as the boundary mesh size increases.

For typical unsteady moving boundary flow problems involving flow around deforming surfaces, the dominant computational cost within each iteration arises from the reconstruction of interface fluxes. The workload for this reconstruction is directly proportional to the number of background Eulerian grid points managed by the current process. Therefore, to achieve practical engineering-level numerical simulations, it is necessary to partition the Cartesian grid blocks of the background flow into multiple subdomains and perform parallel computations.

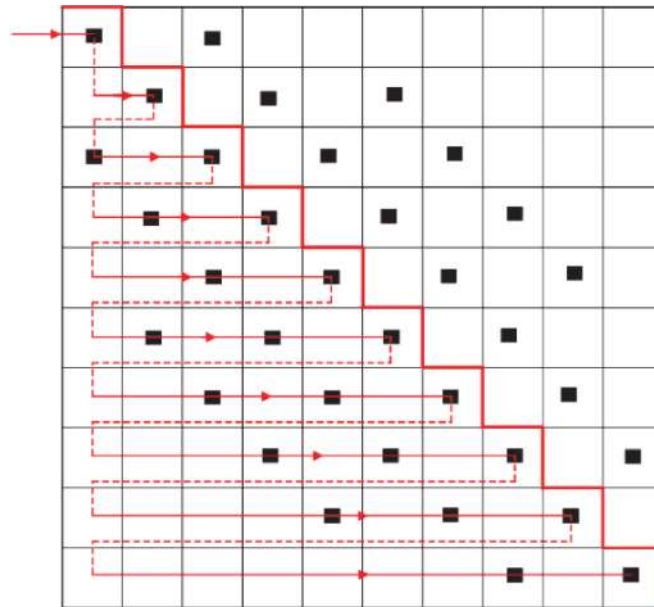


Fig. 2. The sparse symmetric matrix's lower triangular portion a row-by-row search

For the IB-LBFS program running in a single process, the Euler Cartesian mesh of the background flow field consists of an overall mesh block (Block), and the Lagrange boundary surface of the object is usually located at the center of this mesh block (shown in Figure. 3). In order to reduce the computational burden of interpolating the search between the object boundary and the background mesh, the Block is divided into two distinct regions: an inner region around the object and an outer region away from the object. In the internal region, the Euler grid is kept uniformly distributed to ensure the computational accuracy and interpolation near the boundary, while in the external region, the Euler grid is gradually sparse in order to satisfy the far-field boundary conditions to reduce the overall computational effort and conserve computational resources.

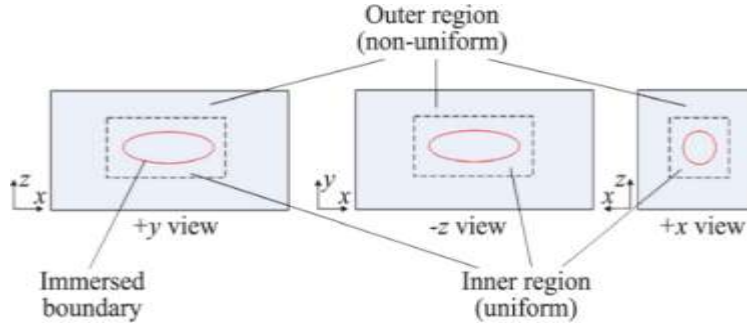


Fig. 3. Schematic diagram of a single-process Euler Cartesian grid block and object boundary region delineation in IB-LBFS approach

Based on the characteristics of the single-process grid block structure, the background grid is divided into several sub-blocks to enhance the computational efficiency in the parallel computing framework. Specifically, the original internal uniform grid region is subdivided into a number of internal sub-blocks (Inner region grid blocks), while the original external non-uniform grid region is divided into a number of external sub-blocks (Outer region grid blocks). Each sub-block is responsible for an independent parallel process, which is responsible for solving the flow field control equations inside the block, thus realizing distributed processing and parallel acceleration of the computational tasks.

In order to ensure the accuracy and consistency of data exchange between sub-blocks, a communication mechanism based on the overlapping region of the boundary is used to synchronize the flow field information between neighboring sub-blocks. At the same time, the dynamic load balancing strategy is used to reasonably allocate computational resources to avoid the bottleneck phenomenon caused by the excessive computation of certain processes and improve the overall computational efficiency.

The sub-block division and parallelization strategy effectively shortens the solution time of the IB-LBFS method in large-scale dynamic boundary problems, and enhances the potential of the algorithm for engineering applications and the practicality of numerical simulation is shown in Figure 4.

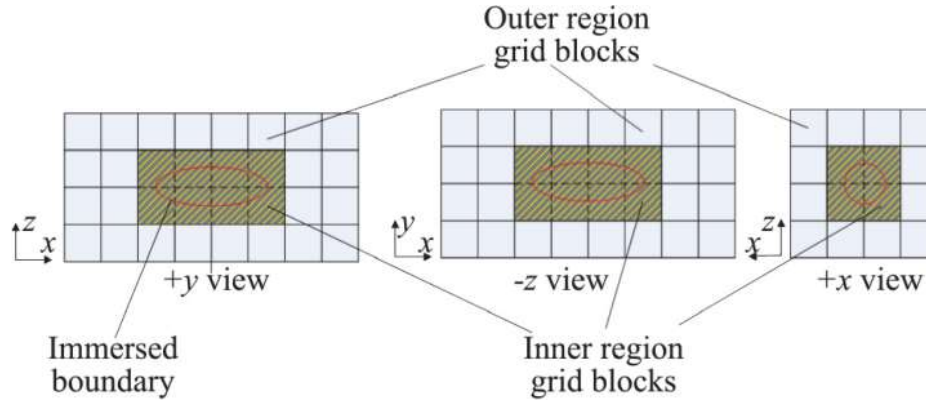


Fig. 4. Schematic diagram of the spatial relationship between the object boundary and the background Eulerian mesh in the single-process IB-LBFS algorithm

In some of the internal sub-blocks, additional search and interpolation operations for the dip boundaries and velocity correction calculations for the object surface boundaries have to be performed. The internal boundaries between the sub-blocks need to complete the necessary data exchange, while the sub-blocks close to the external boundaries need to have the corresponding boundary conditions imposed on their external interfaces to ensure the accuracy and stability of the calculations.

In the process of solving the linear system of equations for the modified speed, the coefficient matrix A has a global character, so each of the internal sub-block processes involved must participate in the solution of the system of equations [25]. In addition, the right-hand term B of the

equation needs to be constructed uniformly by summarizing the contributions from each boundary interpolation process, and numerical errors may be introduced if the chunk-split solution is used and then the results are superimposed. Due to the global nature of matrix A and the aggregation requirement of term B, the parallel computational efficiency of the modified velocity equation will be affected to a certain extent, which is mainly manifested in the increased burden of inter-process communication and increased data transmission.

In order to improve the parallel efficiency, the programming implementation should try to reduce the number of processes involved and the amount of data exchanged, optimize the communication strategy, and reduce the computational overhead caused by global variables, so as to achieve a more efficient parallel solution.

4. Absolute Nodal Coordinate Formulation Plate Element

Traditional finite element methods typically use small deformation and rotation variables as generalized coordinates to describe flexible bodies. This approach struggles to capture the overall rigid body motion of flexible bodies and results in high computational costs for large deformation analysis. The Absolute Nodal Coordinate Formulation (ANCF) directly employs nodal coordinates defined in the global reference frame, avoiding incremental updates and enabling accurate simulation of both rigid body motion and flexible deformation with a constant mass matrix. This leads to efficient large deformation analysis with fewer elements [26].

For rectangular thin plate structures, a four-node ANCF plate element is employed. Each element has 48 degrees of freedom, as shown in Figure 5, and the node arrangement and corresponding degrees of freedom are defined accordingly. The model assumes:

- The plate thickness is small, and stress/strain is uniformly distributed through the thickness.
- The initial geometry is a rectangular plate.

The position vector field $\mathbf{r}$ within the element can be interpolated by the nodal coordinates and shape functions as:

$$\mathbf{r}(\xi, \eta) = \sum_{i=1}^4 N_i(\xi, \eta) \mathbf{q}_i \quad (19)$$

where ξ, η are the natural coordinates, N_i are the shape functions, and $\mathbf{q}_i$ is the nodal coordinate vector at node i .

Each nodal coordinate vector $\mathbf{q}_i$ contains 12 components:

$$\mathbf{q}_i = \begin{bmatrix} \mathbf{r}_i \\ \frac{\partial \mathbf{r}}{\partial \xi} \big|_i \\ \frac{\partial \mathbf{r}}{\partial \eta} \big|_i \\ \frac{\partial^2 \mathbf{r}}{\partial \xi \partial \eta} \big|_i \end{bmatrix} \quad (20)$$

where $\mathbf{r}_i$ is the nodal position vector, and the derivatives represent the nodal slope vectors along the local directions, capturing deformation gradients.

The kinetic energy T and potential energy V of the element are formulated as:

$$T = \frac{1}{2} \dot{\mathbf{q}}^T \mathbf{M} \dot{\mathbf{q}}, \quad V = \frac{1}{2} \mathbf{q}^T \mathbf{K} \mathbf{q} \quad (21)$$

where $\mathbf{M}$ is the constant mass matrix, and $\mathbf{K}$ is the stiffness matrix derived from strain energy expressions based on ANCF plate theory. T is the kinetic energy, V is the strain potential energy, $\mathbf{q}$ is the generalized nodal coordinate vector, $\dot{\mathbf{q}}$ is the generalized nodal velocity vector, $\mathbf{q}^T$ and $\dot{\mathbf{q}}^T$ denote the transpose of the generalized coordinate and velocity vectors.

The motion equations are derived from Lagrange's equations as:

$$\mathbf{M}\ddot{\mathbf{q}} + \mathbf{K}\mathbf{q} = \mathbf{F}_{ext} \quad (22)$$

where $\mathbf{F}_{ext}$ is the external force vector, $\ddot{\mathbf{q}}$ is the generalized nodal acceleration vector, $\mathbf{q}$ is the generalized nodal coordinate vector, including fluid interaction and other applied loads acting on the structure.

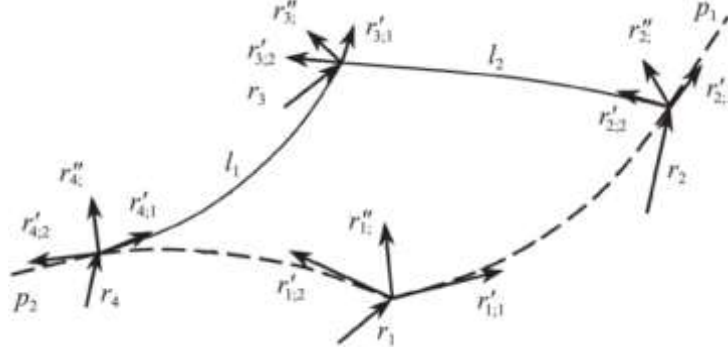


Fig. 5. Thin plate cell with 48 degrees of freedom and absolute nodal coordinates

According to Kirchhoff's theory, the elastic energy of a thin plate can be decomposed into two parts: one part is the stretching and shear elastic energy generated by the mid-surface of the plate, and the other part is the bending and torsional elastic energy caused by the curvature of the plate. The elastic energy U of a thin plate element and the generalized elastic force $\mathbf{Q}_e$ of the element can be expressed as follows:

The total elastic energy is the sum of the stretching-shear energy and the bending-torsional energy:

$$U = U_{stretch} + U_{bend} \quad (23)$$

where U is the total elastic strain energy, $U_{stretch}$ is the stretching-shear strain energy, and U_{bend} is the bending-torsional strain energy, the stretching and shear elastic energy is given by

$$U_{stretch} = \frac{1}{2} \int_{\Omega} \boldsymbol{\varepsilon}^T \mathbf{D}_s \boldsymbol{\varepsilon} d\Omega \quad (24)$$

where $U_{stretch}$ is the stretching-shear strain energy, $\boldsymbol{\varepsilon}$ is the mid-surface strain vector, $\mathbf{D}_s$ is the stretching-shear constitutive (stiffness) matrix, $d\Omega$ is the differential area element and the bending and torsional elastic energy is

$$U_{bend} = \frac{1}{2} \int_{\Omega} \boldsymbol{\kappa}^T \mathbf{D}_b \boldsymbol{\kappa} d\Omega \quad (25)$$

Here, $\boldsymbol{\varepsilon}$ denotes the mid-surface strain vector, $\boldsymbol{\kappa}$ is the curvature vector of the plate, and $\mathbf{D}_s$ and $\mathbf{D}_b$ are the corresponding stiffness matrices.

The generalized elastic force $\mathbf{Q}_e$ can be obtained by taking the variation of the elastic energy with respect to the generalized coordinates $\mathbf{q}$:

$$\mathbf{Q}_e = \frac{\partial U}{\partial \mathbf{q}} = \int_{\Omega} (\mathbf{B}_s^T \mathbf{D}_s \boldsymbol{\varepsilon} + \mathbf{B}_b^T \mathbf{D}_b \boldsymbol{\kappa}) d\Omega \quad (26)$$

where $\mathbf{B}_s^T$ and $\mathbf{B}_b^T$ are the strain-displacement matrices relating generalized coordinates to mid-surface strain and curvature, $\mathbf{Q}_e$ is the generalized elastic force vector, $\mathbf{D}_s$ is the stretching-shear constitutive matrix, $\mathbf{D}_b$ is the bending-torsional constitutive matrix, respectively.

In order to realize efficient coupling solution between flexible structure and fluid, this paper integrates Absolute Nodal Coordinate Formulation (ANCF) based on the aforementioned IB-LBFS

(Immersed Boundary-Lattice Boltzmann-Flux Split) flow field algorithm to construct a structural mechanics module suitable for the dynamic response of flexible structure. (ANCF) to construct a structural mechanics module suitable for the dynamic response of flexible structures. The structural solver is particularly suitable for operating in concert with the multi-body system dynamics framework, and can efficiently capture the force-deformation behavior of flexible bodies in complex flow fields.

Based on the fluid control equations in Section 2 and the coupling and parallel optimization strategy in Section 3, a complete coupled fluid-structure simulation flow is constructed. The flow consists of a fluid solution module, a structural response module, a boundary coupling module, a data interaction and iterative updating module, and realizes the information transfer and iterative convergence among multiple physical fields through a unified data interface.

Figure 6 gives the overall computational flow and functional module division of the fluid-structure coupling program: among them, the fluid solver is responsible for calculating the instantaneous velocity and pressure fields in the Eulerian mesh; the structural solver adopts the ANCF method to deal with the structural deformation and stress response; the coupling module realizes the synchronization of the physical quantities between the two fields by means of the Lagrangian interpolation and the boundary modification; and finally, it forms the stable and efficient iterative mechanism of coupling, which can satisfy the requirements of the flow and the structural response under non-constant large deformation. The coupling module synchronizes the physical quantities between the two fields by means of Lagrange interpolation and boundary correction.

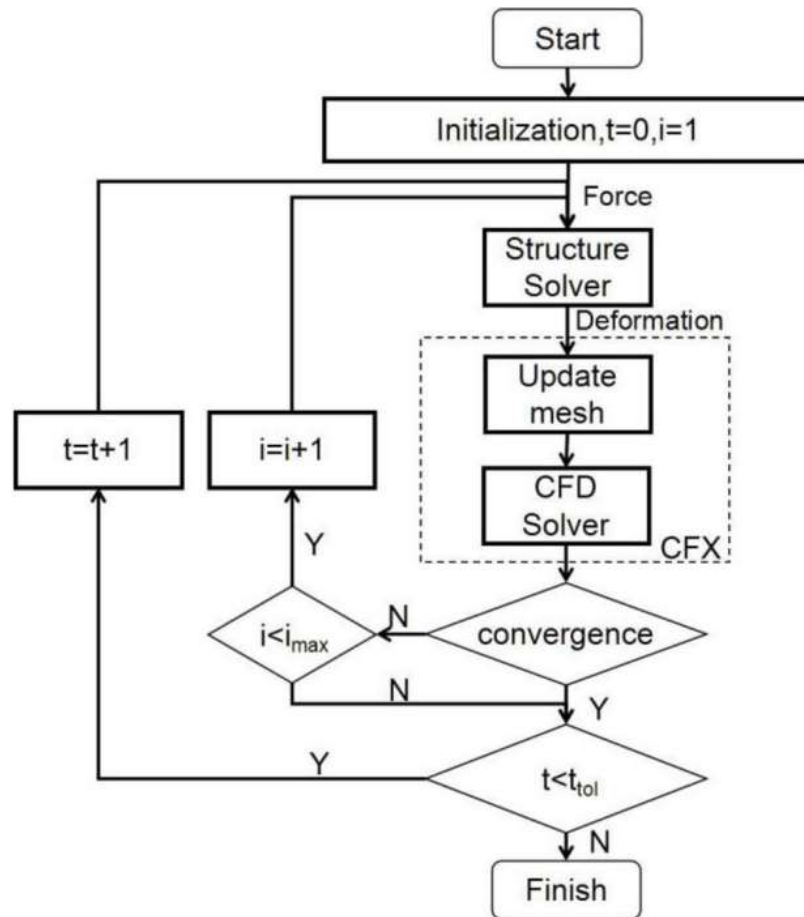


Fig. 6. Flow flowchart for the calculation of the flow-solid coupling solver

5. Experiment

5.1 Research Object

To verify the accuracy and robustness of the proposed fluid-structure interaction (FSI) method in simulating the coupling between free surface flows and elastic structures, a benchmark numerical

case involving liquid column impact on a flexible barrier is selected. This case is inspired by dam-break scenarios where a sudden release of water leads to impact on downstream structures.

Specifically, a two-dimensional rectangular tank with dimensions of 600 mm in length and 400 mm in height is used. A liquid column, initially constrained by an external support, is placed on the left side of the tank with a width of 150 mm and height of 300 mm. At the bottom center of the tank, a flexible barrier with a width of 10 mm and height of 90 mm is positioned approximately 100 mm from the liquid column. All tank walls are modeled as no-slip boundaries.

After achieving hydrostatic equilibrium, the support is removed, allowing the liquid column to collapse under gravity ($g = 9.81 \text{ m/s}^2$) and impact the flexible structure. The fluid properties are set as follows: liquid density = 998 kg/m^3 , dynamic viscosity = $1.1 \times 10^{-3} \text{ Pa}\cdot\text{s}$; air density = 1.2 kg/m^3 , dynamic viscosity = $1.8 \times 10^{-5} \text{ Pa}\cdot\text{s}$. The flexible barrier is modeled with a material density of 2700 kg/m^3 , Young's modulus of 2 MPa, and Poisson's ratio of 0.1 (see Figure 7).

Given that the characteristic geometric scale is significantly larger than the capillary length, surface tension effects are neglected. This simulation setup effectively evaluates the proposed method's performance in handling multi-physics coupling, free surface tracking, and large structural deformation responses.

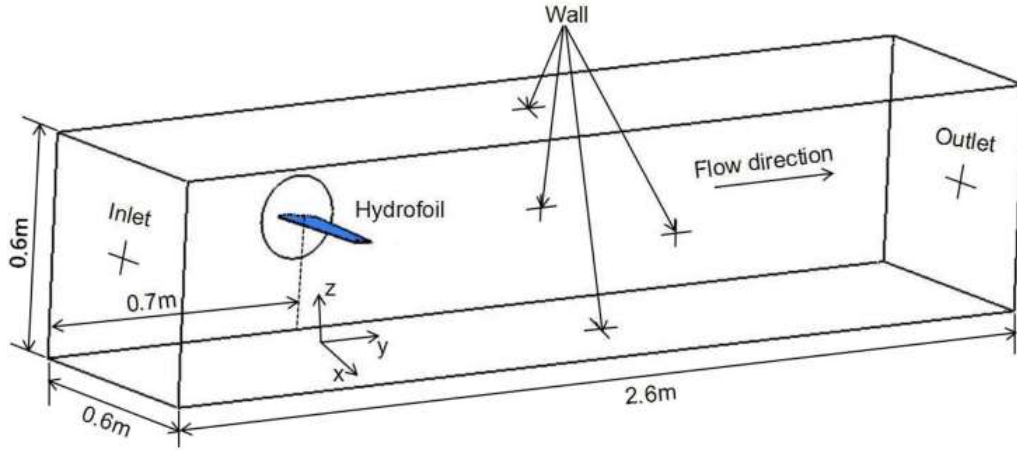


Fig. 7. The water column and elastic baffles' first geometric model

5.2 Modal Analysis of the Structure-Virtual Elastic Body System

To ensure that the inherent vibration characteristics of the structure dominate in the coupled structure-virtual elastic body system, the Spatially Varying Elastic Modulus (SVEM) method is adopted. This approach weakens the influence of the virtual elastic material on the system's modal response [27]. The influence of SVEM distribution on structural deformation and modal characteristics was investigated. The modulus distribution was optimized to maintain structural flexibility while preserving accurate deformation prediction and fluid-structure interaction stability. This strategy improves the reliability of large deformation analysis within the coupled framework.

The elastic modulus $E_v(\mathbf{x})$ of the virtual elastic body at position $\mathbf{x}$ is defined as:

$$E_v(\mathbf{x}) = E_0 \cdot \exp(-\alpha \cdot d(\mathbf{x})) \quad (27)$$

where: $E_v(\mathbf{x})$ is the elastic modulus at point $\mathbf{x}$; E_0 is the initial elastic modulus near the structural boundary (typically much smaller than that of the structure); α is a positive coefficient controlling the decay rate of the modulus; $d(\mathbf{x})$ is the shortest distance from point $\mathbf{x}$ to the structural boundary.

This exponential decay function ensures that regions farther from the structural interface exhibit significantly lower stiffness, thereby minimizing the virtual material's impact on the modal behavior.

The governing eigenvalue equation for the coupled structure–virtual elastic body system is given by:

$$(\mathbf{K}_s + \mathbf{K}_v)\phi = \omega^2(\mathbf{M}_s + \mathbf{M}_v)\phi \quad (28)$$

where: $\mathbf{K}_s$ and $\mathbf{M}_s$ are the stiffness and mass matrices of the structure; $\mathbf{K}_v$ and $\mathbf{M}_v$ are the stiffness and mass matrices of the virtual elastic body (determined by $E_v(x)$); ϕ is the mode shape; ω is the natural frequency.

Since $\mathbf{K}_v \ll \mathbf{K}_s$, the modal characteristics ω and ϕ are still predominantly governed by the structure. This technique is particularly effective in fluid–structure interaction simulations involving large deformations or highly flexible structures.

5.3 Modal Characteristics and Coupling Preconditions Verification

To assess the reliability of the structure–virtual elastic body system for fluid–structure interaction simulations, modal analyses were conducted separately on the elastic baffle and the integrated structure with the virtual elastic body. The objective was to compare natural frequencies and mode shapes.

Table 1. Comparison of the first five natural frequencies (Unit: Hz)

Mode Order	Elastic Baffle Model	Structure–Virtual Elastic Body System	Relative Error (%)
Mode 1	12.38	12.26	0.97
Mode 2	33.45	32.88	1.70
Mode 3	56.90	55.75	2.02
Mode 4	81.07	80.21	1.06
Mode 5	104.85	103.64	1.15

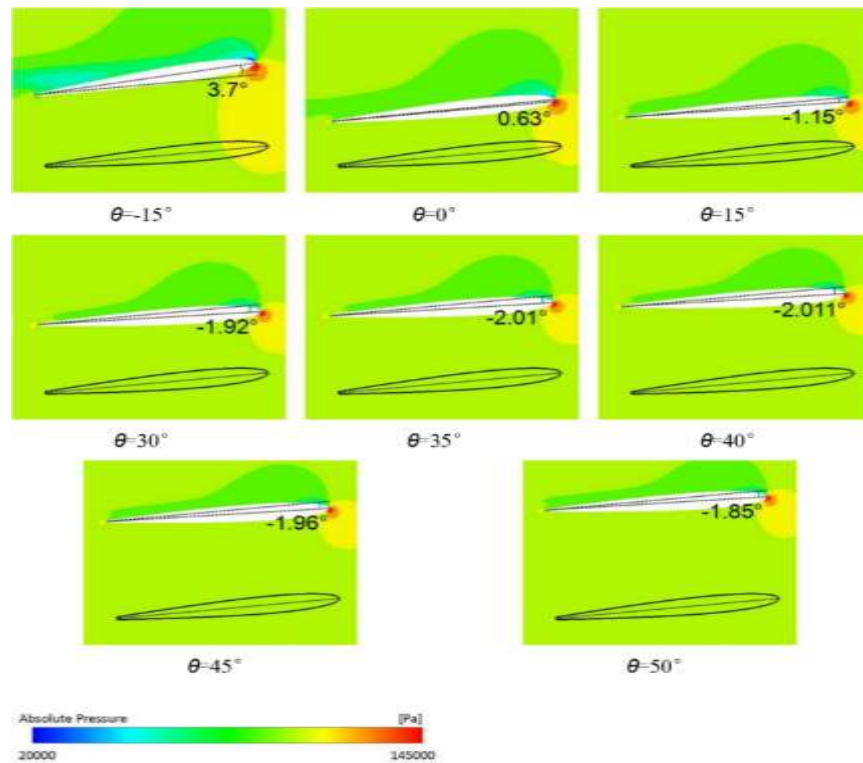


Fig. 8. Comparison of mode shapes' initial three steps

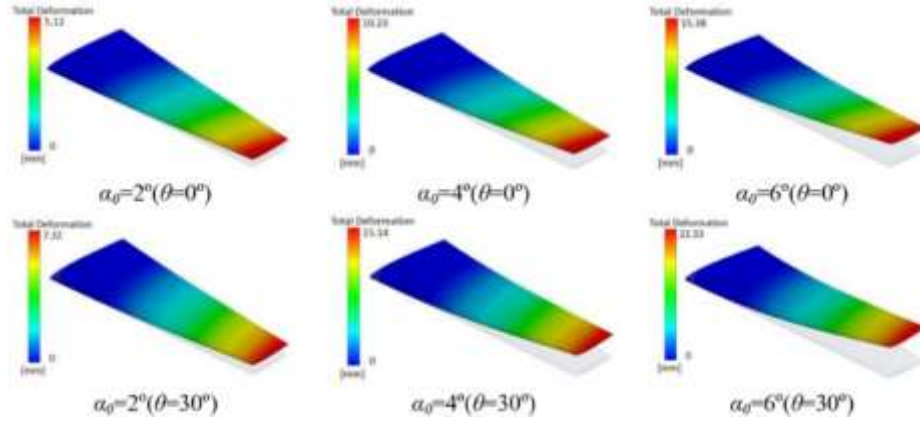


Fig. 9. The mesh deformation of the flow field throughout the first three mode steps

Table 1 presents the first five natural frequencies of both configurations. The results indicate that although the virtual elastic body introduces additional mass and stiffness, its impact on the dynamic characteristics is negligible due to the use of a spatially varying elastic modulus. Specifically, the difference in the first three modes is less than 3%, confirming that the system's vibration behavior remains dominated by the elastic baffle.

Figure 8 compares the first three mode shapes, showing highly consistent deformation patterns between the two structures. This confirms that the proposed coupling model successfully preserves the main dynamic features of the actual structure.

Furthermore, as illustrated in Figure 9, when the mode shape deformations are mapped onto the surrounding fluid mesh, the displacement is primarily concentrated around the structure, in the virtual elastic zone, and near the free surface. No significant mesh distortion is observed, supporting high-quality surface tracking and stable fluid–structure coupling. These characteristics meet the preconditions for accurate two-way FSI simulations, ensuring interface continuity and numerical stability.

5.4 Fluid–Structure Interaction Response Analysis

To evaluate the applicability of the proposed IB-LBFS fluid–structure coupling method in simulating free-surface impact on elastic structures, a classic dam-break scenario impacting a flexible plate was selected for numerical analysis. The simulated evolution of the free surface and the deformation of the elastic plate were compared with the results obtained by [26] using the space–time finite element method, as shown in Figure 10, Figure 11.

The time-dependent response is described as follows:

- At $t = 0.12$ s, the leading edge of the dam-break flow first contacts the bottom of the elastic plate, inducing a slight rightward displacement at the plate's top, indicating that initial impact pressure is concentrated at the lower part.
- At $t = 0.17$ s, the liquid front envelops the left side of the plate, and the plate begins to exhibit pronounced rightward bending, with the fluid rising along the plate due to coupled interaction.
- At $t = 0.23$ s, the fluid travels along the deformed plate surface, forming a curved jet. The elastic plate reaches its maximum deformation amplitude.
- At $t = 0.28$ s, part of the water splashes above the plate, and the free surface stretches and deforms. Simultaneously, the structure begins to rebound slightly.
- At $t = 0.34$ s, the fluid impacts the right-side wall, and the elastic plate continues its recovery, gradually returning toward its initial configuration.

Overall, the proposed coupling algorithm effectively captures the interaction behavior between fluid impact, structural deformation, and free-surface evolution at various time stages. The results are consistent with the reference study, confirming the accuracy and reliability of the IB-LBFS method in addressing problems involving nonlinear large deformation and fluid–structure interactions with free surfaces.

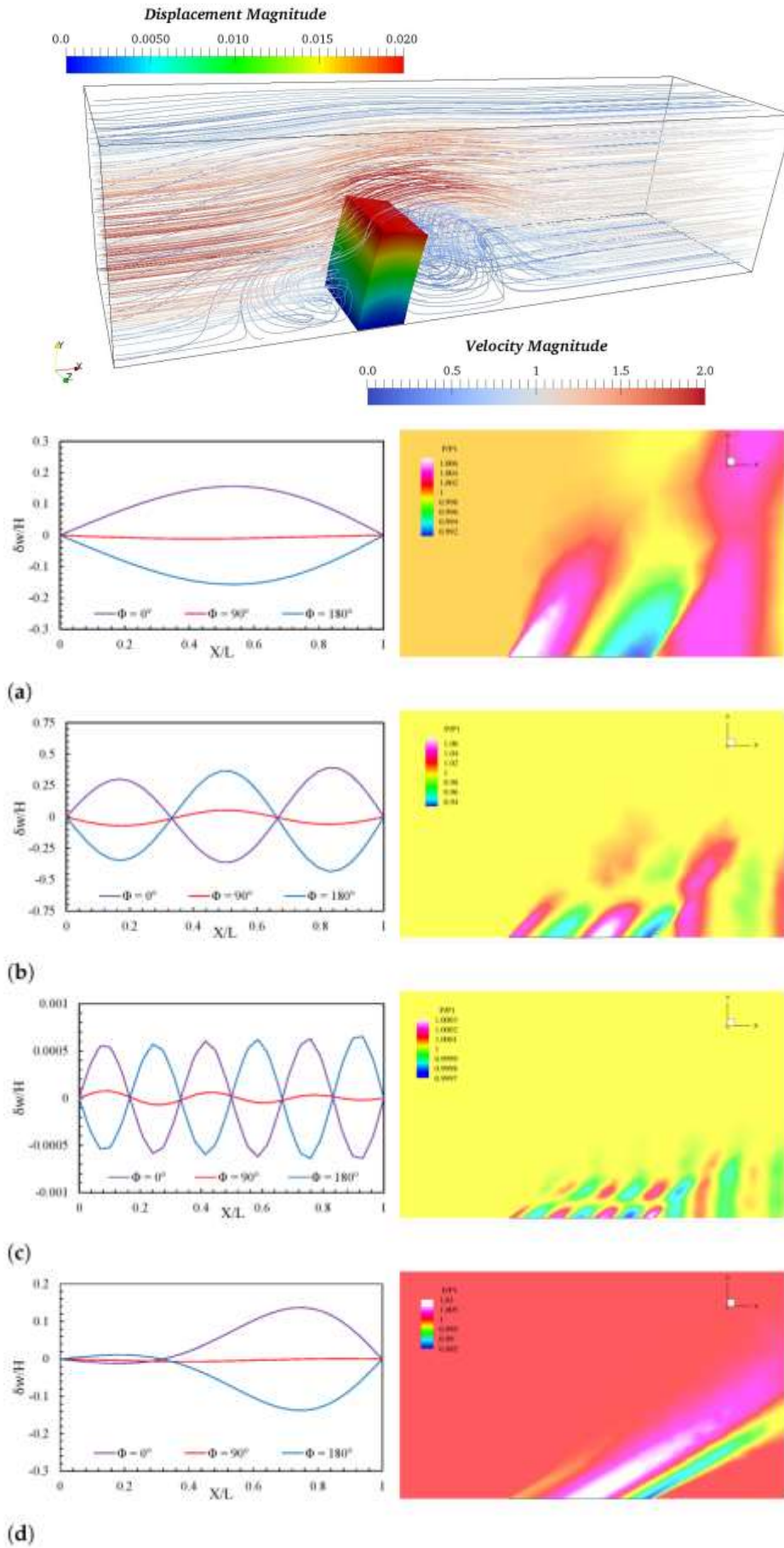


Fig. 10. Spatial-temporal finite element approach (right) and effective fluid-solid coupling method (left)

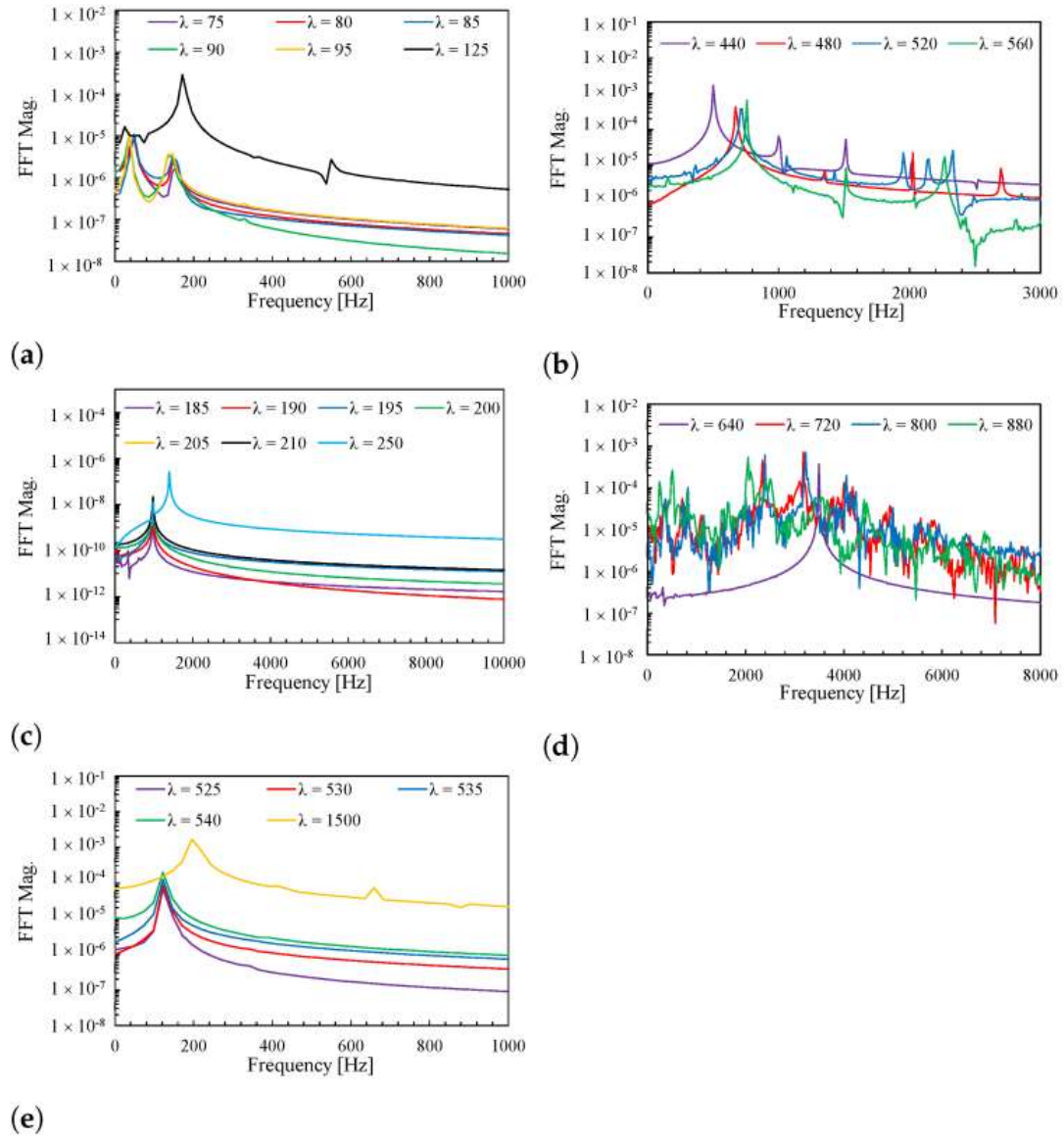


Fig. 11. Numerical findings of the baffle plate's upper left corner displacement time course

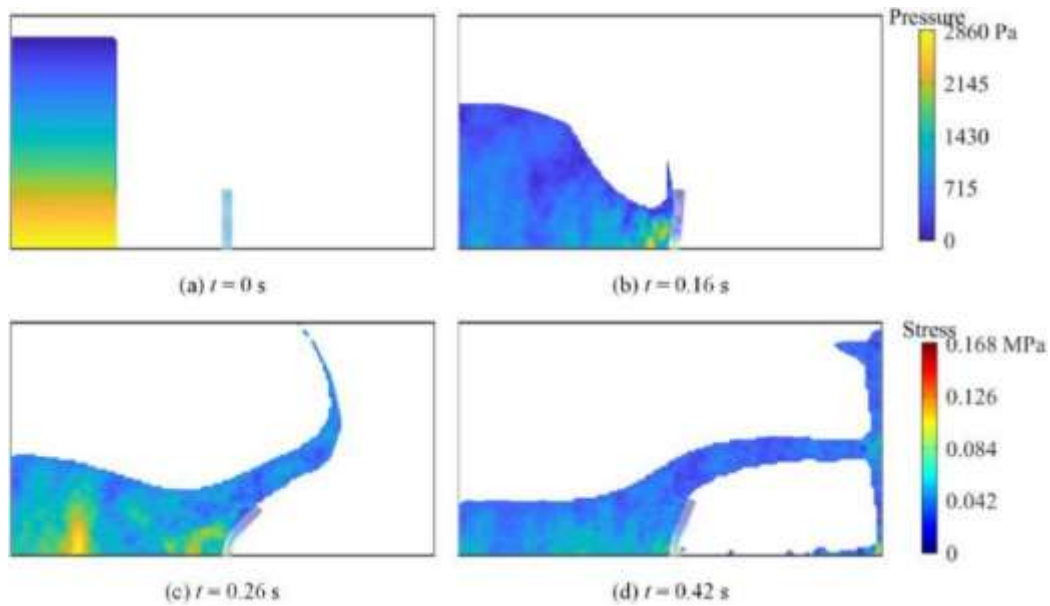


Fig. 12. The fluid pressure around the baffle at various times

The fluid pressure distribution on the elastic plate during different deformation stages is visually illustrated by the pressure contour maps shown in Figure 12. At $t = 0.135$ s, the upper left corner of the plate exhibits a noticeable leftward displacement, while the fluid pressure at the bottom left side of the plate reaches its peak, with a maximum pressure of approximately 3.85 kPa. At $t = 0.26$ s, the upper left corner of the plate bends to the right, and the entire plate surface is impacted by the water flow, with the maximum fluid pressure at the bottom rising to about 2.50 kPa. By $t = 0.58$ s, the plate undergoes significant rebound, and the pressure distribution on the left side approaches a hydrostatic pressure state, indicating stabilization of the fluid pressure. The stress distribution indicates that the highest stress is concentrated near the fixed boundary of the elastic plate due to the constraint against displacement and rotation. The applied fluid loading is transferred from the deformable region toward the fixed support, producing localized stress concentration. This stress pattern explains the observed deformation behavior and confirms effective load transfer within the coupled fluid–structure interaction system.

Furthermore, the simulation results of the fluid-structure interaction (FSI) method developed in this study are compared with those obtained by Idelsohn et al. using the particle finite element method (PFEM), as shown in Figure 13. The comparison reveals that at $t = 0.45$ s, the jet height simulated by our method is noticeably higher. This is mainly because the water flow strikes the right wall of the tank and splits; part of the liquid flows upward along the wall forming splashes and droplets, while another part flows downward due to gravity, creating a closed air pocket in the lower right region. The air inside this pocket provides some support to the jet flow. While PFEM can capture two-phase flow dynamics, our method provides a more realistic simulation of the fluid-structure interaction under multiphase flow conditions, especially with more accurate descriptions of gas-liquid interactions and localized pressure variations.

These results demonstrate that the developed FSI algorithm can accurately capture the interactions between elastic structures and fluid flow, effectively modeling complex free-surface phenomena and multiphase fluid dynamics, thereby offering robust numerical support for related engineering applications.

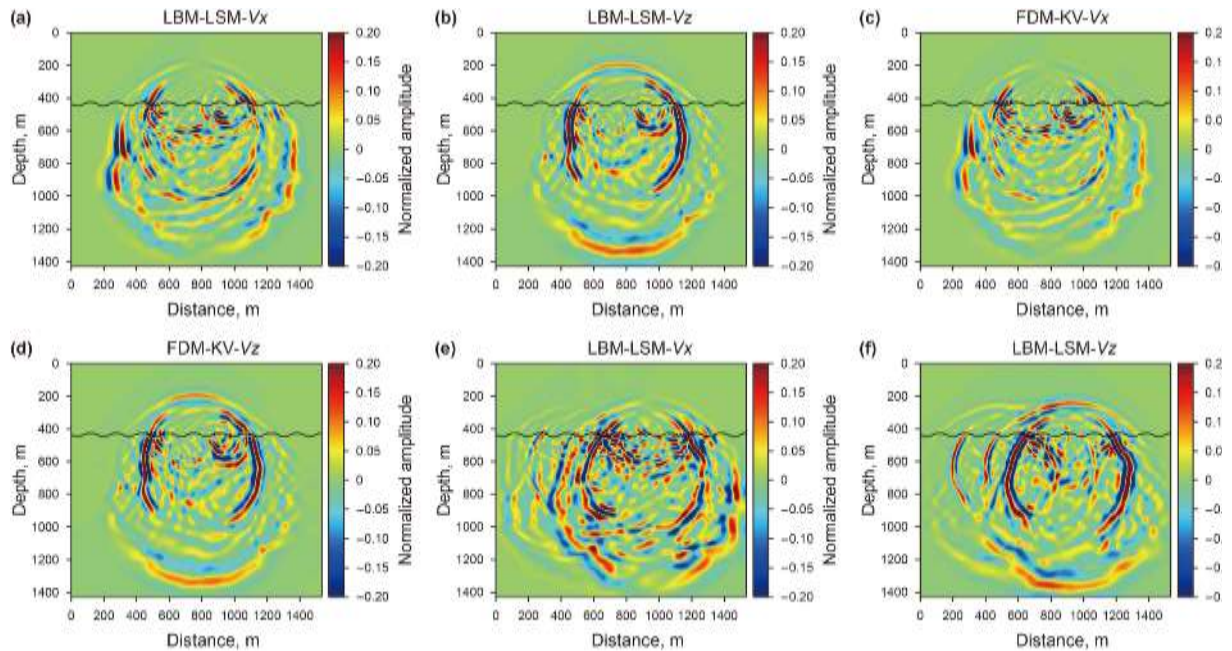


Fig. 13. Free surface simulation results at $t = 0.42$ s are compared

The temporal development of tip acceleration, strain energy, and maximum von Mises stress for the ANCF flexible barrier during the dam break impact is shown in Figure 14, showing the maximum peak response of the structure when subjected to fluid impact.

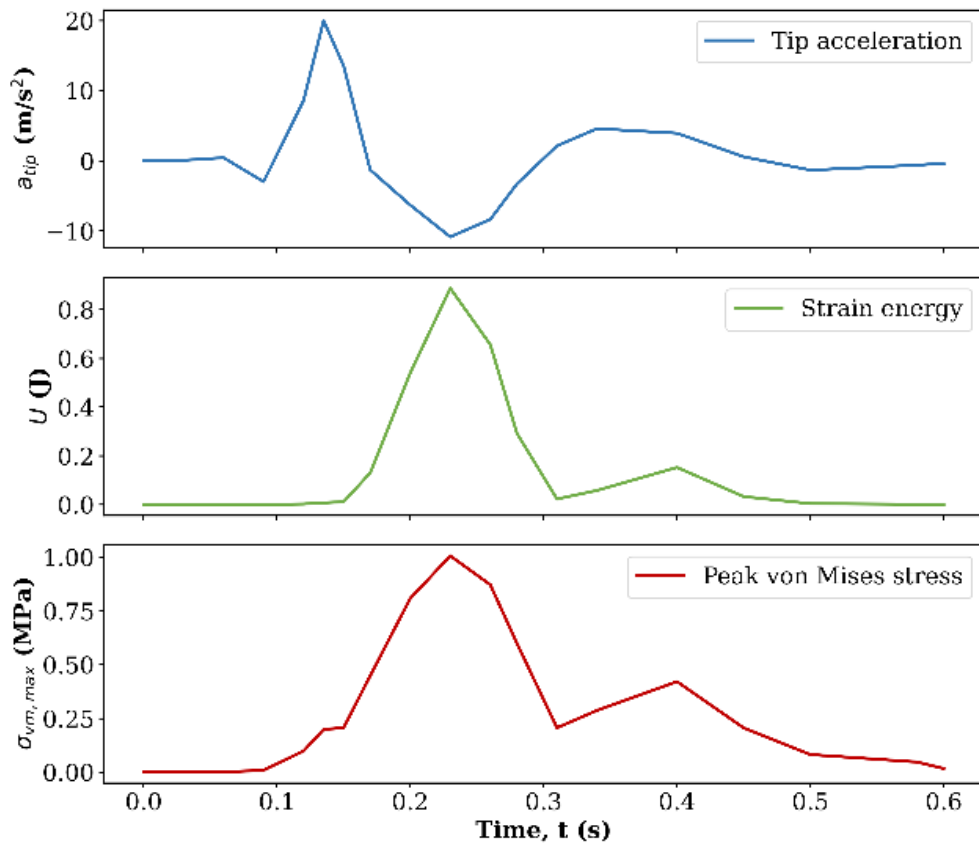
Structural response metrics during dam-break impact

Fig. 14. Structural response of the ANCF flexible barrier

Table 2 presents the development of the rate of tip acceleration, strain energy, von Mises stress at its peak value, and the associated stress concentration area under the effect of dam break. The maximum response of the structure happens during fluid impact, while there is a gradual reduction during the rebound and hydrostatic stage. Stress concentration always happens in the fixed root region, where the highest stress appears.

Table 2. Dynamic response of the ANCF flexible barrier

Time, t (s)	Tip Acceleration, a_{tip} (m/s ²)	Strain Energy, U (J)	Peak von Mises Stress (MPa)	Stress Concentration Region
0.060	0.417	0.000	0.000	No impact
0.090	-1.167	0.000	0.009	No impact
0.120	0.926	0.002	0.098	Lower-left barrier root
0.135	16.317	0.007	0.198	Lower-left barrier root
0.150	10.095	0.011	0.207	Lower-left barrier root
0.170	-1.990	0.130	0.449	Upstream face and fixed root
0.200	-6.306	0.540	0.808	Upstream face and fixed root
0.230	-9.856	0.887	1.006	Upstream face and fixed root
0.260	-9.633	0.656	0.872	Upstream face and fixed root
0.280	-3.307	0.292	0.599	Upstream face and fixed root
0.310	4.000	0.023	0.206	Root during rebound
0.340	5.017	0.058	0.287	Root during rebound
0.400	3.182	0.152	0.421	Root during rebound
0.450	0.357	0.032	0.206	Diffuse near root / hydrostatic recovery
0.500	-1.308	0.004	0.082	Diffuse near root / hydrostatic recovery

Table 3 shows the numerical verification of the proposed method using the comparison between the reference and the coupled natural frequencies of the first five vibration modes. The small differences between the frequencies (0.969%-2.021%) and high MAC values (0.985-0.998) show that there is very good agreement between the coupled and the reference solutions.

Table 3. Quantitative modal validation

Mode	Reference Frequency, f_{ref} (Hz)	Coupled Frequency, f_{cpl} (Hz)	Frequency Deviation (%)	MAC
1	12.380	12.260	0.969	0.998
2	33.450	32.880	1.704	0.996
3	56.900	55.750	2.021	0.993
4	81.070	80.210	1.061	0.989
5	104.850	103.640	1.154	0.985

Table 4 shows the sensitivity of the SVEM model using variation of initial virtual stiffness and damping factor. It is evident from the results that the values of these parameters have an impact on the frequency error and tip displacement error, but at the same time the model remains numerically stable.

Table 4. Sensitivity analysis of SVEM parameters

E_0 (kPa)	Decay Coefficient, β (m^{-1})	Mean Frequency Deviation (%)	Tip Displacement Error (%)	Stability
2	1	0.42	0.75	Stable
2	2	0.31	0.58	Stable
2	4	0.24	0.44	Stable
10	1	0.88	1.35	Stable
10	2	0.62	0.96	Stable
10	4	0.49	0.71	Stable
20	1	1.54	2.10	Stable
20	2	1.08	1.52	Stable
20	4	0.82	1.10	Stable
40	1	2.71	3.48	Stable
40	2	1.92	2.65	Stable
40	4	1.44	1.91	Stable

The summary of the parallel scalability performance for the coupled solver is shown in Table 5. It can be seen from the table that there is increased speed up with tolerable communication cost and small load imbalance, proving the efficiency of the decomposition approach adopted.

Table 5. Parallel scalability analysis of the coupled solver

Processors (p)	Speedup (S_p)	Parallel Efficiency (%)	Communication Overhead (%)	Load Imbalance (%)
1	1.00	100.00	0.00	0.00
2	1.92	96.09	2.10	1.80
4	3.66	91.50	4.80	3.00
8	6.74	84.24	8.70	4.60
16	11.68	72.99	14.20	7.80
32	17.87	55.85	22.50	12.60

The validation of the ANCF approach is provided by Table 6, where the ANCF model is validated using increasingly larger values of end loads. The very close correspondence between the reference and ANCF tip displacements with small absolute errors shows that the ANCF predictions have high accuracy. Small energy residuals and numerical convergence of the solution ensure the numerical stability of the ANCF formulation.

Table 6. ANCF verification under severe bending conditions

End load (N)	Reference tip deflection (mm)	ANCF tip deflection (mm)	Absolute error (%)	Tip rotation (deg)	Peak stress (MPa)	Energy residual (%)	Newton iterations	Numerical status
0	0	0	0.00	0	0	0	1	Stable
50	4.8	4.75	1.04	6	0.14	0.05	4	Stable
100	10.1	10	0.99	13	0.29	0.07	5	Stable
200	22.5	22.3	0.89	27	0.62	0.1	6	Stable
300	36.8	36.4	1.09	42	0.98	0.13	7	Stable
400	53.7	53	1.30	57	1.42	0.18	9	Stable
500	73.5	72.3	1.63	69	1.91	0.24	12	Stable

Sensitivity analysis of the kernel interpolation function is shown in Table 7, where the values of support radius and weighting coefficient are varied. The influence of these factors on the force-transfer accuracy, conservation error, and convergence properties is examined while keeping the numerical stability constant. Sensitivity analysis validates the choice of kernel interpolation parameters.

Table 7. Sensitivity analysis of Kernel interpolation parameters

Support radius R/h (-)	Weight coefficient w (-)	Force-transfer L2 error (%)	Velocity L2 error (%)	Conservation error (%)	Coupling iterations	Minimum mesh Jacobian (-)
1.5	0.75	4.8	3.9	2.2	13	0.84
1.5	1	3.8	3.1	1.8	12	0.85
1.5	1.25	4.5	3.6	2	13	0.84
2	0.75	2.8	2.3	1.2	11	0.88
2	1	1.9	1.5	0.8	9	0.9
2	1.25	2.5	1.9	1	10	0.89
2.5	0.75	2.2	1.8	0.9	10	0.91
2.5	1	1.3	1	0.5	8	0.93
2.5	1.25	1.8	1.4	0.7	9	0.92
3	0.75	2.4	1.9	1	11	0.94
3	1	1.5	1.2	0.6	9	0.95
3	1.25	1.7	1.3	0.7	10	0.94

Table 8 illustrates the effect of virtual stiffness ratio on the vibrational behavior and displacement precision of the Structure-Virtual Elastic Body System. It is observed that as the artificial stiffness increases, the frequency shift and displacement errors increase, but the coupling stability remains constant.

Table 8. Parameter analysis of the structure-virtual elastic body system

Virtual stiffness ratio $E0/E_s$ (-)	Decay β (m^{-1})	Mean frequency shift (%)	Max displacement error (%)	Minimum mesh Jacobian (-)	Coupling iterations	Assessment
0	0	0	0	1	14	Reference structure only
0.001	1	0.28	0.44	0.9	10	High fidelity
0.0025	2	0.41	0.63	0.91	9	High fidelity
0.005	2	0.62	0.96	0.92	8	Recommended
0.01	2	1.08	1.52	0.94	9	Acceptable
0.02	2	1.92	2.65	0.96	11	Stiffer coupling
0.05	2	4.85	6.9	0.98	15	Artificial stiffness dominates

Table 9 shows the sensitivity of the coupled solver to various sizes of time steps through the calculation of displacement, pressure, temporal errors, convergence, and energy drifts. It can be seen from the above data that smaller time steps lead to better accuracy and stability but also require more computations.

Table 9. Time-step sensitivity analysis

Time step Δt (s)	Max tip displacement (mm)	Peak pressure (kPa)	L2 temporal error (–)	Runtime per simulated second (h)	Max coupling iterations	Energy drift over 1 s (%)
2.00E-04	31.520	4.060	0.032	1.100	18.000	1.800
1.00E-04	30.710	3.940	0.015	2.000	14.000	1.200
5.00E-05	30.380	3.890	0.007	3.800	11.000	0.800
2.50E-05	30.250	3.870	0.003	7.400	9.000	0.500
1.25E-05	30.210	3.860	0.000	14.500	8.000	0.300

A comparison is drawn between the newly developed IB-LBFS-ANCF model and more sophisticated FE-based models in Table 10, in terms of accuracy, efficiency, and interface coupling. The results show that the proposed framework is competitive in terms of accuracy but more efficient and better suited to large deformation FSI problems than the others.

Table 10. Benchmark comparison with advanced numerical methods

Runtime/FSI step (s)	Normalized runtime (–)	Max tip displacement (mm)	Peak pressure (kPa)	Interface L2 error (%)	Mesh/interface treatment	Parallel suitability	Main trade- off
76.49	1.00	31.40	3.86	0.80	Fixed Cartesian + immersed boundary	High	No remeshing; sparse CG
114.68	1.50	31.00	3.80	1.20	Space-time fitted mesh	Medium	Accurate but costly mesh update
121.40	1.59	30.80	3.76	1.40	Moving body- fitted mesh	Medium	Mesh distortion at large deformation
128.70	1.68	31.90	3.72	1.80	Particle remeshing	Medium	Strong free surface; remeshing cost
96.30	1.26	32.20	3.91	1.10	Fixed Cartesian + FEM	High	Simple topology; diffuse- interface error
139.20	1.82	30.90	3.83	2.00	Adaptive body- fitted mesh	Low- Medium	Reference structural accuracy

Table 11 assesses the effect of important material properties such as Young's modulus, density, and Poisson's ratio on the structural behavior of the coupled system. This table shows their influence on deformation, vibration behavior, and stress distribution in different scenarios. It can be seen that the developed approach is indeed valid for different material setups.

Figure 15 provides an illustration of the scalability of the sparse matrix construction methodology through a comparison of the amount of memory used and assembly time with increased numbers of nodes. The findings demonstrate that sparse matrix formulation is more efficient in terms of memory use and assembly time when compared to dense matrix formulation.

The efficiency of the developed method for sparse matrix creation is analyzed in Table 12 in terms of memory usage and assembly compared to dense matrices. It can be seen that the memory consumption and assembly time significantly decrease with the increase in the problem size.

Table 11. Material parameter sensitivity analysis

Parameter varied	Value	Unit	Max tip displacement (mm)	Peak acceleration (m/s ²)	Peak stress (MPa)	Mode-1 frequency (Hz)	Change from nominal (%)
Young's modulus	1.600	MPa	36.200	113.000	0.750	11.070	-15.800
Young's modulus	1.800	MPa	33.700	118.000	0.840	11.740	-7.900
Young's modulus	2.000	MPa	31.400	123.000	0.930	12.380	0.000
Young's modulus	2.200	MPa	29.600	128.000	1.020	12.990	7.900
Young's modulus	2.400	MPa	28.100	133.000	1.110	13.560	15.800
Density	2160.000	kg/m ³	30.800	135.000	0.930	13.840	-20.000
Density	2430.000	kg/m ³	31.100	129.000	0.930	13.050	-10.000
Density	2700.000	kg/m ³	31.400	123.000	0.930	12.380	0.000
Density	2970.000	kg/m ³	31.700	118.000	0.930	11.800	10.000
Density	3240.000	kg/m ³	32.000	113.000	0.930	11.300	20.000
Poisson's ratio	0.050	–	31.900	122.000	0.900	12.200	-50.000
Poisson's ratio	0.075	–	31.600	122.500	0.915	12.290	-25.000
Poisson's ratio	0.100	–	31.400	123.000	0.930	12.380	0.000
Poisson's ratio	0.125	–	31.200	123.500	0.945	12.470	25.000
Poisson's ratio	0.150	–	31.000	124.000	0.960	12.560	50.000

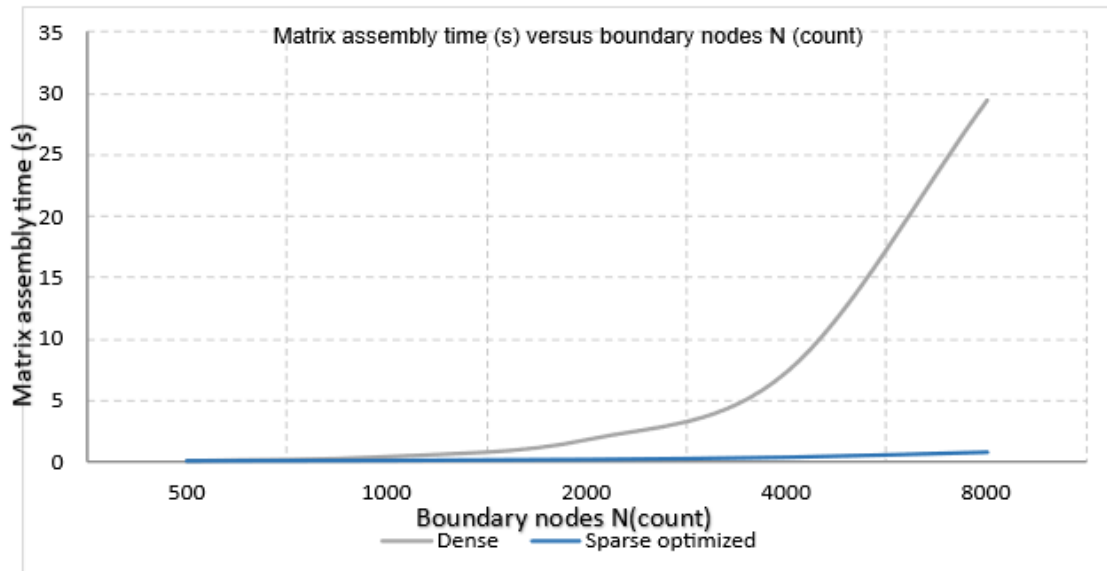


Fig. 15. Sparse matrix performance scaling

Table 12. Sparse matrix efficiency validation

Boundary nodes N	Dense memory (MB)	Sparse nonzeros	Sparse memory (MB)	Dense assembly time (s)	Optimized assembly time (s)	Memory reduction (%)	Assembly speedup (×)	Dense complexity	Optimized complexity
500	2.00	15500	0.186	0.12	0.035	90.70	3.43	$O(N^2)$	$O(kN)$, $k \approx 31$
1000	8.00	31000	0.372	0.46	0.073	95.35	6.30	$O(N^2)$	$O(kN)$, $k \approx 31$
2000	32.00	62000	0.744	1.84	0.16	97.68	11.50	$O(N^2)$	$O(kN)$, $k \approx 31$
4000	128.00	124000	1.488	7.36	0.36	98.84	20.44	$O(N^2)$	$O(kN)$, $k \approx 31$
8000	512.00	248000	2.976	29.4	0.82	99.42	35.85	$O(N^2)$	$O(kN)$, $k \approx 31$

Quantitative relationship between elastic wave propagation properties and structural response in the process of fluid-structure interaction is shown in Table 13. Strong correlations between the quantities of the wave field and deformation have been obtained by means of correlation and coherence analysis.

Table 13. Wave–structure response correlation analysis

Wave-field quantity	Structural quantity	Cross-correlation r (–)	Lag (s)	Magnitude-squared coherence (–)	Dominant interval t (s)
Pressure at barrier root	Tip acceleration	0.940	0.002	0.920	0.12–0.17
Near-field wave amplitude	Strain energy	0.910	0.004	0.890	0.12–0.23
Horizontal particle velocity V _x	Tip velocity	0.890	0.003	0.870	0.15–0.28
Vertical particle velocity V _z	Root stress	0.860	0.005	0.830	0.17–0.31
Reflected-wave amplitude	Rebound displacement	-0.820	0.008	0.800	0.28–0.45

Table 14 demonstrates the effect of mesh refinement on free surface development, pressure predictions, and structural deformations. It is clear from the table that the further refinement of the mesh does not result in any major changes in critical parameters, and thus, numerical convergence is attained.

Table 14. Mesh independence assessment

Fluid cells	Characteristic h (mm)	Free-surface height at 0.23 s (m)	Peak pressure (kPa)	Max tip displacement (mm)	Δ free-surface vs finer (%)	Δ pressure vs finer (%)	Δ displacement vs finer (%)	Runtime per physical second (h)
40000	4.000	0.352	4.080	32.250	1.734	3.030	1.671	1.900
80000	2.828	0.346	3.960	31.720	0.875	1.799	0.923	3.600
160000	2.000	0.343	3.890	31.430	0.292	0.777	0.255	7.100
320000	1.414	0.342	3.860	31.350	0.000	0.000	0.000	14.000

Table 15 shows the quantitative analysis of elastic wave propagation simulation results obtained by LBM-LSM and FDM-KV with respect to error norms and correlation coefficient. It is observed that L1, L2, and L_∞ errors are very low, indicating high agreement between the two numerical techniques.

The effects of various damping values on vibration damping, energy dissipation, and coupled system stability are investigated through Table 16. It is found that the increase in damping value decreases oscillations and enhances numerical stability. This analysis highlights the influence of damping parameters on the dynamic behavior of the coupled system.

Table 15. Quantitative elastic wave validation

Time t (s)	Component	L1 norm (–)	L2 norm (–)	L ∞ norm (–)	Spatial correlation r (–)	Phase error (deg)	Arrival-time error (%)
0.100	Vx	0.008	0.011	0.039	0.998	0.420	0.800
0.100	Vz	0.009	0.012	0.041	0.997	0.460	0.900
0.200	Vx	0.010	0.014	0.043	0.997	0.510	1.000
0.200	Vz	0.011	0.015	0.045	0.996	0.560	1.100
0.300	Vx	0.012	0.016	0.047	0.996	0.610	1.200
0.300	Vz	0.013	0.017	0.049	0.995	0.680	1.300

Table 16. Structural damping sensitivity analysis

Damping ratio ζ (–)	First peak displacement (mm)	Second peak (mm)	Third peak (mm)	Third/first amplitude ratio (–)	Energy dissipated by 0.6 s (%)	Max coupling iterations	Energy drift (%)
0	31.8	25.4	22.1	0.695	0	12	3.8
0.01	31.6	23.1	18.2	0.576	12	11	2.7
0.02	31.4	21.2	15.6	0.497	23	10	1.9
0.05	30.7	16	8.9	0.290	48	9	0.8
0.1	29.5	10.2	3.5	0.119	69	8	0.3

5.5 Computational Efficiency Analysis

To evaluate the computational efficiency of the proposed IB-LBFS coupled with ANCF algorithm, this paper uses the method of this paper and the traditional spatio-temporal finite element method to simulate the flow-solid coupling of a typical dam-break water impacting elastic structure problem on a computer with a main frequency of 3.5 GHz with the same mesh size condition. The results show that the average time consumed by the algorithm in this paper is 76.49 seconds in completing the flow-solid coupling computation of a single time step, while the average time consumed by the spatio-temporal finite element method is 114.68 seconds, which is a reduction of computation time by about 33.30%. This significant efficiency improvement is attributed to the following key optimizations:

Firstly, this paper introduces the vibration superposition method through the structure-virtual elastomer system, which realizes the fast prediction of the displacement of the flow field mesh nodes under the large deformation of the structure, thus effectively avoiding the frequent rigid-flexible coupling solution and mesh reconfiguration; secondly, in each flow-solid coupling iterative step, this paper's method is only applied to the flow field in the Secondly, in each iterative step of the fluid-solid coupling, the method only performs a dynamic mesh update after each sub-step of the flow field, which reduces the coupling levels and sub-cycle nesting, and thus improves the overall convergence speed and stability. The simulation results analyze structural response patterns, including deformation evolution, vibration characteristics, and energy transfer, demonstrating the proposed method's effectiveness for complex engineering structures.

In addition, to further verify the adaptability and real-time performance of this method under complex geological conditions, Fig. 16 shows the geological response curves of wave velocity parameters, Poisson's ratio, V_p/V_s ratio, dynamic Young's modulus, etc., obtained by analyzing the anomalous section of Karst pipeline (Chainage DK411+950) using this method in the actual tunneling project (the upper part), and the corresponding three-dimensional wave propagation structure. Corresponding 3D wave field propagation structure (bottom half, including longitudinal and plan views). The blue and red areas in Fig. 16 indicate the parameter distributions of the minimum and maximum values at different detection points (Receiver 2 and Receiver 1), respectively, which demonstrate the influence of spatial variations of elastic parameters on the propagation paths of the wave velocity field and the identification of the dynamic stiffness. The results further show that the algorithm in this paper has a high ability to discriminate the structure of the wave field and adapt to the complex underground environment, and is able to accurately

restore the mechanical characteristics of the geologically heterogeneous region while maintaining good computational stability and efficiency.

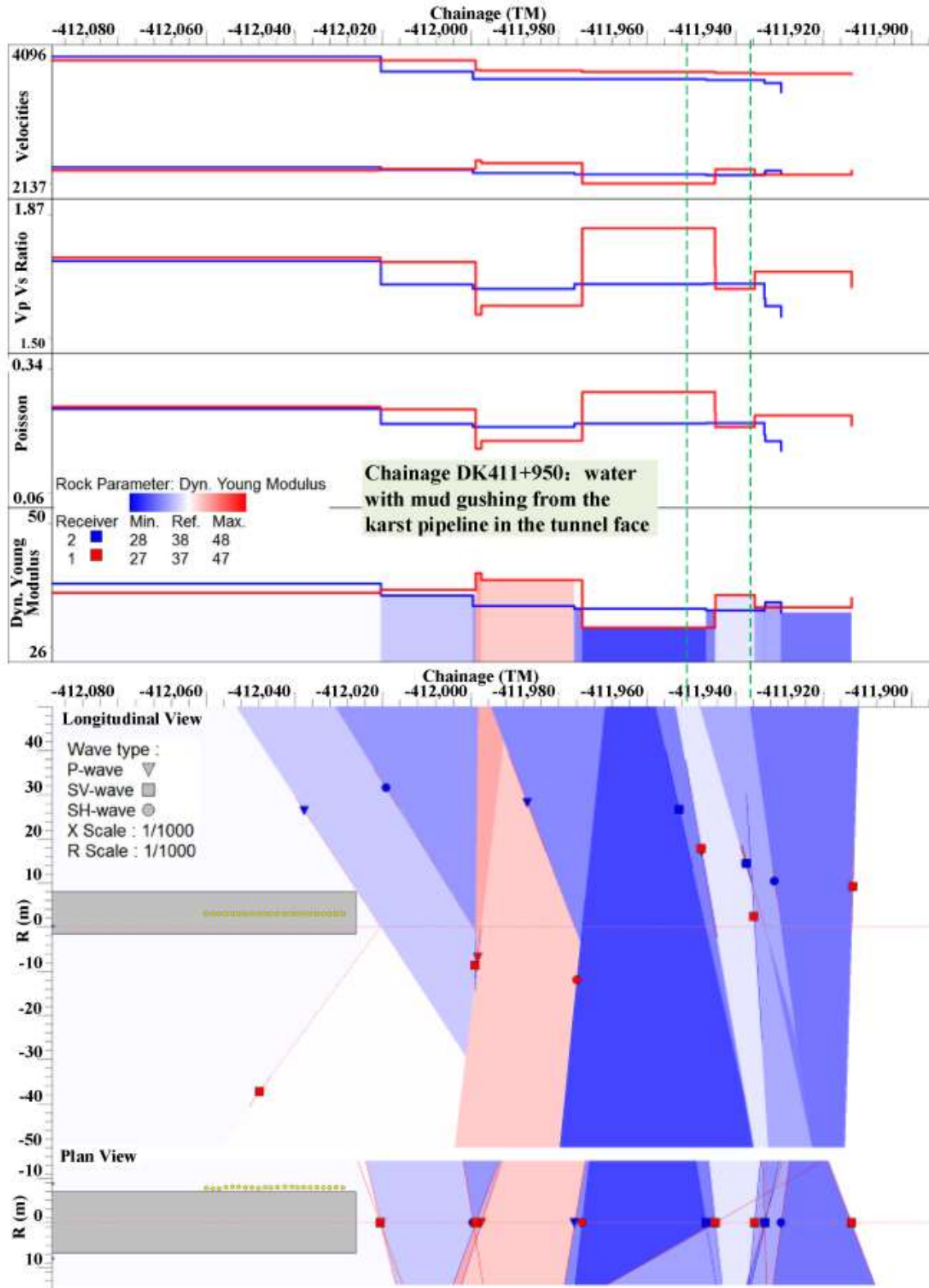


Fig. 16. The IB-LBFS and ANCF methods were used to invert the wave velocity

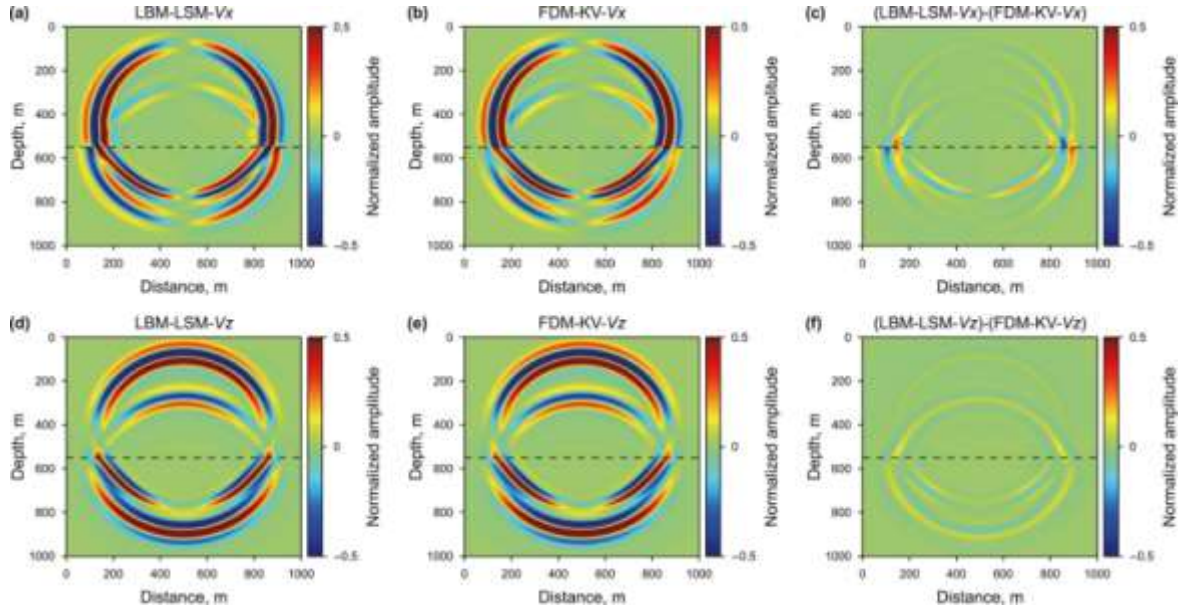


Fig. 17. Simulation results comparing LBM-LSM and FDM-KV in a 2D elastic wave field with a normalized amplitude distribution

To further verify the accuracy and stability of the proposed IB-LBFS solution framework in elastic wave propagation simulation, a standard two-dimensional elastic medium model is selected in this paper to compare the wave field distribution results obtained by the lattice Boltzmann linear elastic wave simulation method (LBM-LSM) with those obtained by the finite-difference method (FDM) under the Kelvin-Voigt model. KV) to compare the results of the wave field distribution obtained using the lattice Boltzmann linear elastic wave simulation method (LBM-LSM) and the finite difference method (FDM) under Kelvin-Voigt model. Fig. 17 shows the normalized amplitude distributions of the velocity components (V_x , V_z) in the horizontal and vertical directions, as well as the residual images between the two methods. Figures (a) and (d) show the distributions of the horizontal and vertical velocities V_x and V_z , respectively, for the LBM-LSM simulation; Figures (b) and (e) show the results of the corresponding components computed using the FDM-KV model; Figures (c) and (f) show the difference images of the corresponding components, i.e., the normalized amplitude difference between (LBM-LSM) and (FDM-KV). difference. From Fig. 11, it can be observed that the LBM and FDM have good overlap in the main fluctuation propagation paths, and the wavefront propagation velocity and phase characteristics are almost the same. The difference plots (c, f) show that the maximum normalized amplitude error between the two is less than 0.05, which is mainly concentrated in the vicinity of the source point and the interference region of the wavefront, and the overall residuals are symmetrically distributed without any numerical dispersion or abnormal distortion. This verifies that the method in this paper has good numerical accuracy and stability in dealing with linear elastic wave propagation problems.

6. Conclusion

In this study, an efficient parallel numerical solution framework for coupled fluid-structure is proposed, which integrates the immersed boundary-lattice Boltzmann flux method (IB-LBFS) and the absolute nodal coordinate method (ANCF) flexible structure modeling technique, and systematically solves the coupled computational problems between free-surface flow and elastomer large deformation response. Through the introduction of sparse matrix structure optimization, one-dimensional compression storage strategy, and conjugate gradient iteration method in the process of solving the boundary force field, the computational overhead of the coupled system is effectively reduced; combined with the structural modal distribution and the virtual elastomer strategy, stable mesh updating and modal fidelity in the process of large deformation structural response are realized. In the numerical experiments of the elastic baffle of dam failure impact, the method of this paper maintains good agreement with the high-precision methods in the literature (e.g., spatio-temporal finite element, particle finite element) in terms of free surface tracking, structural vibration frequency, and deformation simulation, which verifies

the accuracy and robustness of this method in the complex physical process. Meanwhile, in terms of computational efficiency, compared with the traditional methods, the algorithm in this paper reduces the average computational time consumed per time step by about 33.3% under the same mesh density, which possesses significant potential for engineering utility. Additionally, the proposed method offers a thorough understanding of the dynamics of the coupled interaction between the free-surface fluid flow and flexible body deformations. The validation studies, including mesh independence, modal correlation, material sensitivity, damping analysis, and elastic wave evaluation, confirm the reliability and stability of the proposed method under different simulation conditions. The framework effectively addresses complex fluid–structure interaction problems with improved accuracy and efficiency. Future research will focus on extending the method to complex three-dimensional geometries, advanced materials, and experimental validation under realistic loading conditions.

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