A high-order solver for unsteady incompressible Navier-Stokes equations using the flux reconstruction method on unstructured grids with implicit dual time stepping

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Abstract

We report development of a high-order compact flux reconstruction method for solving unsteady incompressible flow on unstructured grids with implicit dual time stepping. The method falls under the class of methods now referred to as flux reconstruction/correction procedure via reconstruction. The governing equations employ Chorin's classic artificial compressibility formulation with dual time stepping to solve unsteady flow problems. An implicit non-linear lower-upper symmetric Gauss-Seidel scheme with backward Euler discretization is used to efficiently march the solution in pseudo time, while a second-order backward Euler discretization is used to march in physical time. We verify and validate implementation of the high-order method coupled with our implicit time stepping scheme using both steady and unsteady incompressible flow problems. The current implicit time stepping scheme is proven effective in satisfying the divergence-free constraint on the velocity field in the artificial compressibility formulation within the context of the high-order flux reconstruction method. This compact high-order method is very suitable for parallel computing and can easily be extended to moving and deforming grids.

Keywords: Navier-Stokes, Artificial compressibility, High-order, Flux reconstruction, Unstructured, Implicit LU-SGS

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1. Introduction

In computational fluid dynamics, unstructured high-order methods, i.e. those considered 3^{rd} order and above, are useful for the study of unsteady vortex dominated viscous flows in complex geometries. These methods can provide high accuracy for similar cost as low-order methods [1]. Furthermore, solution acceleration can be achieved with p -adaptivity and p -multigrid methods. However, high-order methods are less robust and more complicated to implement than low-order methods, especially when treating irregular geometries.

Four popular methods have been developed to address the need for high-order accuracy - discontinuous Galerkin (DG), spectral difference (SD), spectral volume (SV) and flux reconstruction/correction procedure via reconstruction (FR/CPR). Discontinuous Galerkin was initially developed for the neutron transport equation by Reed and Hill [2]. The staggered grid spectral method was initially presented by Kopriva [3] and was modified and called spectral difference method by Liu, Vinokur and Wang [4]. The spectral volume method was introduced by Wang, Zhang and Liu [5], where each element is split into multiple control volumes. Flux reconstruction was initially developed by Huynh [6, 7] and has a close connection to lifting collocation penalty by Wang and Gao [8] (LCP). Consequently, those authors coined the name correction procedure via reconstruction. Further development was made on energy stable flux reconstruction schemes by Vincent, Castonguay and Jameson [9] also known as Vincent-Castonguay-Jameson-Huynh (VCJH) schemes. The FR/CPR methods represent significant development because they have the ability to recover DG, SD and SV for linear problems. Furthermore, they are attractive because of the fact that no surface or volume integrals are required. Also, solution and flux points are arranged in a staggered fashion in SD, while flux points only lie along element interfaces in FR/CPR. As such, the latter method does not require extra flux computations at locations other than interior solution points. Using this fact, Liang, Cox and Plesniak [10] have shown improved computational efficiency of FR/CPR over SD for quadrilateral elements. For a comprehensive review of these methods, see Huynh, Wang and Vincent [11] and Wang [12].

With the development of high-order unstructured methods comes the need to achieve faster convergence, especially for solving large-scale problems using parallel computers. This demand motivates the development of time stepping techniques for which the Courant-Friedrichs-Lewy (CFL) condition is less restrictive, which is hardly the case when explicit (e.g. multi-stage Runge-Kutta) schemes are combined with high-order methods and dual time stepping. In this paper, we present an implicit scheme that overcomes the time step restriction associated with explicit schemes used for solving the unsteady incompressible Navier-Stokes equations. Work done to improve convergence of unsteady incompressible flow can be seen in Liang, Chan

and Jameson [13], whereby they use a spectral difference method and Chorin’s original artificial compressibility formulation (AC) [14] as well as a p -multigrid method to accelerate the convergence rate of pseudo time stepping for a particular physical time step. However, the p -multigrid method marginally improves the stiffness introduced by the artificial compressibility approach, especially for flows that require high aspect ratio elements near solid walls. As computers become equipped with larger RAM, implicit time stepping schemes are seen as effective drivers to overcome this stiffness. With these implicit schemes much larger time steps can be taken in comparison to explicit schemes, delivering the potential to improve the rate of convergence significantly. Application of the DG method to the incompressible Navier-Stokes equations was performed by Bassi et al. [15], where artificial compressibility was introduced only at the interface flux level. Shahbazi, Fischer and Ethier [16] and Nguyen, Peraire and Cockburn [17] applied DG to these equations as well, using triangular and tetrahedral grids. However, incompressible solvers involving a Poisson solver cannot be easily parallelized according to domain decomposition of the grid. One advantage of the approach taken in our current work lies in the fact that the method is discontinuous and local; as a result, there is no global matrix to split.

In recent years, the lower-upper symmetric Gauss-Seidel (LU-SGS) scheme that was originally developed by Jameson and Yoon [18] with multiple grids for solving the unsteady Euler equations has been used within the high-order CFD community for solving compressible flow problems on unstructured grids using SD [19, 20, 21] and SV [22] methods. However, when solving incompressible flows using artificial compressibility, the LU-SGS scheme is more economical because it requires the solution of only three equations in two dimensions as opposed to the four needed for compressible flow. Furthermore, with the introduction of artificial compressibility, pressure and velocity are loosely coupled and the Navier-Stokes equations take on a mixed hyperbolic/parabolic mathematical nature. This loose coupling lends itself to parallel computing as both pressure and velocity are state variables in pseudo time. As such, this paper aims to bring a popular high-order method and time stepping technique for producing high-order accurate solutions for compressible flow to the incompressible flow regime. In this regard the current method is novel, especially if it can be applied to moving and deforming grids needed to solve problems involving fluid-structure interaction (FSI) on massively parallel computers.

2. Governing equations with artificial compressibility

Numerical computation of incompressible flow is challenging because the continuity equation lacks a time-dependent term. To handle this difficulty, consider the two-dimensional unsteady incompressible

62 Navier-Stokes equations with artificial compressibility written in conservation form

$$\frac{\partial \mathbf{U}}{\partial \tau} + \mathbf{I}_D \frac{\partial \mathbf{U}}{\partial t} + \nabla \cdot \mathbf{F}(\mathbf{U}, \nabla \mathbf{U}) = 0 \quad (1)$$

63 where terms involving τ and t represent pseudo and physical time derivatives, respectively. The vector of
64 state variables $\mathbf{U}(x, y, t) \in \Omega$, where $\Omega \subset \mathbb{R}^2$ and $t \geq 0$, and the vector of fluxes $\mathbf{F}(\mathbf{U}, \nabla \mathbf{U})$ are

$$\mathbf{U} = \begin{bmatrix} p \\ u \\ v \end{bmatrix}, \quad \mathbf{F}(\mathbf{U}, \nabla \mathbf{U}) = \begin{bmatrix} f \\ g \end{bmatrix} \quad (2)$$

65 where $\mathbf{I}_D = \text{diag}(0, 1, 1)$. The flux vector contains both inviscid and viscous terms in x and y , where
66 $\mathbf{f} = \mathbf{f}_e - \mathbf{f}_v$ and $\mathbf{g} = \mathbf{g}_e - \mathbf{g}_v$. The inviscid fluxes for the artificial compressibility formulation are

$$\mathbf{f}_e = \begin{bmatrix} \beta u \\ u^2 + p \\ uv \end{bmatrix}, \quad \mathbf{g}_e = \begin{bmatrix} \beta v \\ uv \\ v^2 + p \end{bmatrix} \quad (3)$$

67 and the viscous fluxes are

$$\mathbf{f}_v = \begin{bmatrix} 0 \\ \nu \frac{\partial u}{\partial x} \\ \nu \frac{\partial v}{\partial x} \end{bmatrix}, \quad \mathbf{g}_v = \begin{bmatrix} 0 \\ \nu \frac{\partial u}{\partial y} \\ \nu \frac{\partial v}{\partial y} \end{bmatrix}. \quad (4)$$

68 In the above formulation, ν is the kinematic viscosity, $u = u(x, y, t)$ and $v = v(x, y, t)$ are the velocity
69 components, β is the artificial compressibility parameter, and $p = p(x, y, t) = P(x, y, t)/\rho$ is static pressure P
70 divided by density ρ .

71 Since the governing form of the incompressible equations has been modified to take on a mixed hyper-
72 bolic/parabolic nature due to the introduction of artificial compressibility, there exist three characteristics in
73 2D that can be obtained from the eigensystem of the convective flux Jacobians $\mathbf{A}$ and $\mathbf{B}$

$$\mathbf{A} = \frac{\partial \mathbf{f}_e}{\partial \mathbf{U}} = \begin{bmatrix} 0 & \beta & 0 \\ 1 & 2u & 0 \\ 0 & v & u \end{bmatrix}, \quad \mathbf{B} = \frac{\partial \mathbf{g}_e}{\partial \mathbf{U}} = \begin{bmatrix} 0 & 0 & \beta \\ 0 & v & u \\ 1 & 0 & 2v \end{bmatrix}. \quad (5)$$

74 The eigenvalues of $\mathbf{A}$ and $\mathbf{B}$ are $\lambda_A = \{u - c_x, u, u + c_x\}$ and $\lambda_B = \{v - c_y, v, v + c_y\}$, where $c_x = \sqrt{u^2 + \beta}$
 75 and $c_y = \sqrt{v^2 + \beta}$ are now termed the *pseudo* speed of sound in each direction. This means that pressure
 76 waves having finite speed are introduced into the fluid. However, these pressure waves die out as the solution
 77 approaches the divergence-free velocity state - this is termed the *pseudo* steady state. Note that the pseudo
 78 speed of sound is a function of both the velocity and the artificial compressibility parameter. Furthermore,
 79 the pseudo Mach number $M_p = u/c_x$ is always less than 1 for $\beta > 0$. This is a necessary condition in order
 80 for pressure waves to travel upstream and affect the entire flow field. [More details on the eigenstructure of](#)
 81 [the incompressible equations can be found in Elsworth and Toro \[23\].](#)

82 2.1. A short note on the artificial compressibility parameter, β

83 In true incompressible flow, the pressure field is affected instantaneously throughout the domain by any
 84 flow disturbances. However, in Chorin's modified formulation, the artificial compressibility parameter β ,
 85 which is not a function of space or time in these simulations, introduces waves with finite speed into the
 86 fluid as a means to distribute the pressure. Consequently, the non-physical effect on the pressure field by any
 87 disturbance is delayed by some amount of time. Ideally, the value of β should be chosen as high as possible
 88 for a given algorithm such that incompressibility is recovered quickly without degradation of the solution.
 89 For steady flow, the artificial compressibility formulation can be very efficient because the divergence-free
 90 constraint for the velocity field does not have to be satisfied at each iteration. Only at the steady state does the
 91 solution take physical meaning and $\nabla \cdot \mathbf{V} = 0$. Also, computational efficiency is generally better than that for
 92 compressible flow solvers at the incompressible limit. However, unsteady computations of incompressible
 93 flows are time-consuming because any change in the flow must be propagated throughout the entire flow
 94 field. The classic formulation of Chorin has been rather well studied for transient flows, particularly by
 95 Rogers and Kwak [24], Rogers, Kwak and Kiris [25], Merkle and Athavale [26] and Soh and Goodrich [27].
 96 Also, application of exact and approximate Riemann solvers to Chorin's formulation has been conducted by
 97 Elsworth and Toro [23, 28].

98 In viscous flows, the formation of the boundary layer is sensitive to the streamwise pressure gradient,

99 especially in an environment where an adverse pressure gradient can cause flow separation. If separation
 100 occurs, a pressure wave with finite speed will modify the local pressure gradient, which will ultimately
 101 affect the position of separation. This phenomenon can have a feedback effect on the pressure field. Thus,
 102 convergence issues arise if the wave does not propagate sufficiently fast. For internal flows in particular,
 103 the distribution characteristics of pressure waves within a viscous flow become rather important. To achieve
 104 good convergence in this solver, β is typically chosen between 1 and 4. For the simulations discussed here
 105 $\beta = 1.25$, unless specified otherwise.

106 2.2. Mapping to reference element

107 An arbitrary solution domain Ω is partitioned into N_q non-overlapping, conforming, linear quadrilateral
 108 elements, each denoted by Ω_q such that

$$\Omega = \bigcup_{q=1}^{N_q} \Omega_q, \quad \bigcap_{q=1}^{N_q} \Omega_q = \emptyset. \quad (6)$$

109 In considering non-uniformity of the solution domain, one is motivated to transform each physical element
 110 Ω_q into a reference element $\Omega_r = \{\xi, \eta | 0 \leq \xi, \eta \leq 1\}$. The transformation from a physical domain to compu-
 111 tational domain can be achieved through an iso-parametric mapping

$$\begin{bmatrix} x \\ y \end{bmatrix} = \sum_{k=1}^K \Psi_k(\xi, \eta) \begin{bmatrix} x_k \\ y_k \end{bmatrix} \quad (7)$$

112 where K is the number of nodes per element Ω_q , (x_k, y_k) are nodal cartesian coordinates, and $\Psi_k(\xi, \eta)$ are
 113 shape functions. For the case where Ω_q is a linear quadrilateral element, $K = 4$ and node 1 is located at
 114 $(\xi, \eta) = (0, 0)$. After transformation into the computational domain, the governing equations in Eq. (1) can be
 115 re-written in the form

$$\frac{\partial \hat{U}}{\partial \tau} + \mathbf{I}_D \frac{\partial \hat{U}}{\partial t} + \hat{\nabla} \cdot \hat{\mathbf{F}} = 0 \quad (8)$$

116 where

$$\hat{U} = |J|U, \quad \begin{bmatrix} \hat{f} \\ \hat{g} \end{bmatrix} = |J|J^{-1} \begin{bmatrix} f \\ g \end{bmatrix}. \quad (9)$$

117 In this form, $(\hat{\cdot})$ represents values in transformed, computational space. For example, the operator $(\hat{\nabla})$ repre-
 118 sents a gradient in the reference element Ω_r , whereas previously (∇) was a gradient in the physical element
 119 Ω_q . For a stationary grid, the metric Jacobian J is independent of time and can be computed for each 2D
 120 reference element as

$$J = \begin{bmatrix} \frac{\partial x}{\partial \xi} & \frac{\partial x}{\partial \eta} \\ \frac{\partial y}{\partial \xi} & \frac{\partial y}{\partial \eta} \end{bmatrix} \quad (10)$$

121 where the metrics of the Jacobian are obtained from the relationship between the non-uniform physical
 122 element and the reference element. However, to simplify notation used throughout the remaining sections,
 123 we re-write Eq. (8) as

$$\frac{\partial \hat{U}}{\partial \tau} + \hat{S} + \hat{R} = 0 \quad (11)$$

124 where $\hat{S}$ represents the physical time derivative and $\hat{R}$ is the divergence of the flux vector, also known as the
 125 residual. These two terms combined can be called the *pseudo* residual $\hat{R}_\tau = \hat{S} + \hat{R}$.

126 2.2.1. High-order curved boundaries

127 In the current solver, general curvature of boundaries in complex geometries is represented through
 128 implementation of Bezier curves, similar to those used in Gao, Wang and Liu [29]. The Bezier curve
 129 implementation here uses the two end points of a boundary face along with two interior control points
 130 whose locations are defined based upon the geometry of neighboring boundary faces. Thus, these Bezier
 131 curves are designed to be cubic.

132 2.3. Compact flux reconstruction

133 The compact high-order method presented here falls under the umbrella of FR/CPR. In this type of
 134 method, the flux points are only required at element interfaces. This avoids the two-grid system and subse-
 135 quent computational work associated with a staggered solution point/flux point framework. Figure 1 shows

136 the distribution of solution and flux points for a 4th order flux reconstruction method inside a reference
 137 element. In this arrangement, the number of solution points in each coordinate direction is $N_p = 4$.

Figure 1: Distribution of solution points (SP $\bullet$) and flux points (FP $\square$) for a 4th order FR method inside a reference element Ω_r .

138 Along each direction, the solution points are located at the Legendre-Gauss points and the flux points
 139 are the two end points, 0 and 1, located along the interfaces. Choosing $P_{-1}(\xi) = 0$ and $P_0(\xi) = 1$, the
 140 higher-degree Legendre polynomials can be determined by

$$P_{N_p}(\xi) = \frac{2N_p - 1}{N_p}(2\xi - 1)P_{N_p-1}(\xi) - \frac{N_p - 1}{N_p}P_{N_p-2}(\xi). \quad (12)$$

141 The locations of these Legendre-Gauss quadrature points are the roots of the equation $P_{N_p}(\xi) = 0$. Using the
 142 solution at N_p solution points, a $N_p - 1$ degree polynomial can be built using the Lagrange basis

$$l_i(\xi) = \prod_{s=1, s \neq i}^{N_p} \left(\frac{\xi - \xi_s}{\xi_i - \xi_s} \right) \quad \forall \quad i = 1, \dots, N_p \quad (13)$$

143 and the reconstructed solution and flux vectors in Ω_r are tensor products of the two one-dimensional poly-
 144 nomials

$$\hat{\mathbf{U}}_r(\xi, \eta) = \sum_{j=1}^{N_p} \sum_{i=1}^{N_p} \hat{\mathbf{U}}_{r[i,j]} l_i(\xi) \cdot l_j(\eta) \quad (14)$$

$$\hat{\mathbf{f}}_r^D(\xi, \eta) = \sum_{j=1}^{N_p} \sum_{i=1}^{N_p} \hat{\mathbf{f}}_{r[i,j]}^D l_i(\xi) \cdot l_j(\eta). \quad (15)$$

145

146 According to Huynh [7], reconstruction for each element involves the jump in flux at each interface.
 147 Using this disparity, corrections need to be made to the discontinuous flux function given by Eq. (15) in
 148 order to define a flux function that is continuous. Following the initial 1D formulation presented by Huynh,
 149 let the polynomial $\hat{f}_r$ represent a continuous flux function in Ω_r that accounts for data interaction among
 150 adjacent elements by taking on common flux values at the two interfaces. The discontinuous flux function
 151 $\hat{f}_r^D$ is then corrected in the following manner

$$\hat{f}_r(\xi) = \hat{f}_r^D(\xi) + [\hat{f}_{r-\frac{1}{2}}^{com} - \hat{f}_r^D(0)]g_r^{LB}(\xi) + [\hat{f}_{r+\frac{1}{2}}^{com} - \hat{f}_r^D(1)]g_r^{RB}(\xi). \quad (16)$$

152 where $(\cdot)^{LB}$ and $(\cdot)^{RB}$ signify quantities at left and right boundary interfaces of Ω_r . This formulation provides
 153 two corrections to $\hat{f}_r^D$ in 1D - one correction due to a jump in flux at the left boundary and a second correction
 154 due to a jump in flux at the right boundary of Ω_r . The current choice of correction function for all Ω_r is
 155 $g_r = g_{GA}$ from Huynh [7]. This type of correction function is seen as a trade-off between stability and
 156 accuracy when considering other choices such as g_2 and g_{DG} . The reason for this trade-off lies in the relative
 157 steepness of the correction function g_{GA} - its steepness is greater than that of g_2 but less than g_{DG} . This
 158 corresponds to a correction strength between g_2 and g_{DG} , since ultimately we require derivatives of g_r to
 159 compute derivatives of the flux. As previously mentioned, the jump in flux at the interface results in a
 160 correction to $\hat{f}_r^D$ evaluated at all solution points. For the left boundary, the correction function in 1D is
 161 defined as

$$g_r^{LB}(\xi) = g_{GA}^{LB}(\xi) = \frac{N_p}{2N_p - 1}R_{R,N_p}(\xi) + \frac{N_p - 1}{2N_p - 1}R_{R,N_p-1}(\xi) \quad (17)$$

162 where $R_{R,N_p}(\xi)$ represents the right Radau polynomial

$$R_{R,N_p}(\xi) = \frac{(-1)^{N_p}}{2}(P_{N_p}(\xi) - P_{N_p-1}(\xi)). \quad (18)$$

163 The expression for a correction to the right boundary $g_r^{RB}(\xi)$ is obtained simply by reflection of $g_r^{LB}(\xi)$, so
 164 that $g_r^{RB}(\xi) = g_r^{LB}(1 - \xi)$ on the interval $\{\xi | 0 \leq \xi \leq 1\}$. The correction functions for left and right boundaries
 165 must take on the values

$$g_r^{LB}(0) = 1, \quad g_r^{LB}(1) = 0 \quad (19)$$

$$g_r^{RB}(0) = 0, \quad g_r^{RB}(1) = 1. \quad (20)$$

As stated before, the discontinuous flux function $\hat{f}_r^D$ is of degree $N_p - 1$. However, both g_r^{LB} and g_r^{RB} are of degree N_p . Therefore, the function $\hat{f}_r$ is of degree N_p and takes on the two common flux values at the interface

$$\hat{f}_r(0) = \hat{f}_{r-\frac{1}{2}}^{com} \quad (21)$$

$$\hat{f}_r(1) = \hat{f}_{r+\frac{1}{2}}^{com}. \quad (22)$$

This ultimately ensures flux continuity across interfaces. Once suitable correction functions for g_r^{LB} and g_r^{RB} have been defined for Ω_r , a derivative of the continuous flux function can be computed using

$$\frac{\partial \hat{f}_r}{\partial \xi} = \frac{\partial \hat{f}_r^D}{\partial \xi} + [\hat{f}_{r-\frac{1}{2}}^{com} - \hat{f}_r^D(0)] \frac{dg_r^{LB}}{d\xi} + [\hat{f}_{r+\frac{1}{2}}^{com} - \hat{f}_r^D(1)] \frac{dg_r^{RB}}{d\xi}. \quad (23)$$

A derivative of the discontinuous flux function $\partial \hat{f}_r^D / \partial \xi$ can be computed from a Lagrange polynomial or a chain-rule. In the current implementation, we use the former method.

Now, since the mathematical nature of the governing equations has been modified due to the introduction of artificial compressibility, common inviscid fluxes $\hat{f}^{com}$ at an interface can be computed using an approximate Riemann solver. Here, we employ the simple but robust local Lax-Friedrichs (LLF) flux [30]

$$\hat{f}^{com} = \frac{1}{2} [f_n^R + f_n^L - \lambda_{max}(\mathbf{U}^R - \mathbf{U}^L)] \quad (24)$$

where the convective flux normal to an interface is $\mathbf{f}_n = \mathbf{f}_e n_x + \mathbf{g}_e n_y$ and n_x and n_y are the interface normal components. Terms written as $(\cdot)^R$ and $(\cdot)^L$ denote right and left states of the interface. The maximum eigenvalue $\lambda_{max} = \max_k |\lambda^k| = |\mathbf{V}_n| + c_n$ falls out of an eigensystem analysis of the convective flux Jacobian $\mathbf{A}_n$, where

$$\mathbf{A}_n = \frac{\partial \mathbf{f}_n}{\partial \mathbf{U}} = \begin{bmatrix} 0 & \beta n_x & \beta n_y \\ n_x & 2un_x + vn_y & un_y \\ n_y & vn_x & 2vn_y + un_x \end{bmatrix}. \quad (25)$$

181 The velocity normal to the interface is defined as $V_n = u^* n_x + v^* n_y$, where $(\cdot)^*$ indicates quantities av-
 182 eraged from the right and left states. The pseudo speed of sound at the interface now takes the form
 183 $c_n = \sqrt{V_n^2 + \beta(n_x^2 + n_y^2)}$.

184 The common viscous fluxes at the interface can be computed using the first procedure of Bassi and Rebay
 185 (BR1) [31], Compact Discontinuous Galerkin (CDG) [32], Local Discontinuous Galerkin (LDG) [33], or
 186 the second procedure of Bassi and Rebay (BR2) [34]. In order to guarantee compactness of the stencil in
 187 multiple dimensions, the popular BR2 scheme is employed. To compute these terms, the derivative of $\hat{U}_r$ is
 188 needed to evaluate the derivative of the discontinuous flux function $\hat{f}_r^D$. Following the flux reconstruction
 189 concept in Huynh [7] and connecting it with the BR2 scheme, the gradient of the common solution is

$$\frac{\partial \hat{U}_{r+\frac{1}{2}}^{com}}{\partial \xi} = \frac{1}{2} \left[\frac{\partial \hat{U}_r^{RB}(1)}{\partial \xi} + \frac{\partial \hat{U}_{r+1}^{LB}(0)}{\partial \xi} \right] \quad (26)$$

190 where

$$\hat{U}_r^{RB}(\xi) = \hat{U}_r(\xi) + [\hat{U}_{r+\frac{1}{2}}^{com} - \hat{U}_r(1)] g_r^{RB}(\xi) \quad (27)$$

$$\hat{U}_{r+1}^{LB}(\xi) = \hat{U}_{r+1}(\xi) + [\hat{U}_{r+\frac{1}{2}}^{com} - \hat{U}_{r+1}(0)] g_{r+1}^{LB}(\xi) \quad (28)$$

$$\hat{U}_{r+\frac{1}{2}}^{com} = \frac{1}{2} [\hat{U}_r(1) + \hat{U}_{r+1}(0)]. \quad (29)$$

191 Therefore,

$$\frac{\partial \hat{U}_{r+\frac{1}{2}}^{com}}{\partial \xi} = \frac{1}{2} \left\{ \frac{\partial \hat{U}_r(1)}{\partial \xi} + \frac{\partial \hat{U}_{r+1}(0)}{\partial \xi} + [\hat{U}_{r+\frac{1}{2}}^{com} - \hat{U}_r(1)] \frac{dg_r^{RB}(1)}{d\xi} + [\hat{U}_{r+\frac{1}{2}}^{com} - \hat{U}_{r+1}(0)] \frac{dg_{r+1}^{LB}(0)}{d\xi} \right\}. \quad (30)$$

192 Note that Eq. (30) requires data from elements r and $r+1$ only. As a result, the computational stencil in 2D
 193 involves five elements. This compactness ultimately allows for a more economical integration of an implicit
 194 time stepping scheme. Furthermore, this stencil lends itself towards a more straightforward implementation
 195 on massively parallel computers.

196 2.3.1. High-order algorithm

197 In summary, the algorithm used to compute the residual $\hat{\mathbf{R}}$ for each reference element can be described
 198 in six major stages:

- 199 1. Construct the solution polynomial $\hat{U}_r$ using the solution at N_p points and a degree $N_p - 1$ polynomial
200 l_i built from a Lagrange basis.
- 201 2. Construct the discontinuous flux polynomial $\hat{f}_r^D$ of degree $N_p - 1$ from the solution at N_p points.
- 202 3. Reconstruct the solutions and discontinuous fluxes along the edges of Ω_r from Eqs. (14-15).
- 203 4. Use the results from stage 3 to form common values $\hat{U}_{r+1/2}^{com}$ and $\hat{V}_{r+1/2}^{com}$ needed to compute interface
204 fluxes.
- 205 5. Construct the continuous flux polynomial $\hat{f}_r$ of degree N_p by adding flux corrections based upon the
206 jump in flux along the the left and right edges of Ω_r by using correction functions g_r^{LB} and g_r^{RB} of
207 degree N_p . For these simulations, we utilize only one type of correction function; namely $g_r = g_{GA}$.
- 208 6. Evaluate the residual $\hat{V} \cdot \hat{F}$ at each solution point within Ω_r using Eq. (23).

209 Once the above procedure is complete, a dual time stepping algorithm can be used to march the solution
210 forward in time. We use a second-order backward Euler scheme to discretize the physical time derivative.
211 Also, we implement an implicit backward Euler scheme with non-linear LU-SGS to march the solution in
212 pseudo time to drive the pseudo residual $\hat{R}_\tau$ to zero and evaluate its effectiveness in achieving a solenoidal
213 velocity field for each physical time step. Results are compared to those from pseudo time marching with an
214 explicit scheme such as Shu and Osher's total variation diminishing (TVD) three-stage third-order Runge-
215 Kutta scheme [35] (RK3). The implementation of explicit time marching in pseudo time follows the general
216 idea from the dual time stepping technique performed by Jameson [36].

217 2.4. Time stepping

218 2.4.1. Implicit

219 In order to relax the restriction on time step size and drive the pseudo residual $\hat{R}_\tau$ closer and faster to
220 zero to achieve steady state, we use an implicit time stepping scheme. The cost associated with the solution
221 of coupled non-linear equations at each time step motivates linearization of the residual in the governing
222 equations. This resulting linear system of equations is then solved *element-by-element* using an implicit
223 non-linear LU-SGS iterative smoother. For each element r , we can re-write Eq. (11) as

$$\frac{\partial \hat{U}_r}{\partial \tau} + \hat{S}_r + \hat{R}_r = 0. \quad (31)$$

224 The linearized set of equations is formulated below, where r and nb represent the current and neighboring
225 quadrilateral elements Ω_r and Ω_{nb} , respectively, and n and m represent physical and pseudo iteration indices,

226 respectively. The pseudo time derivative is discretized with a first-order backward Euler scheme

$$\frac{\hat{\mathcal{U}}_r^{n+1,m+1} - \hat{\mathcal{U}}_r^{n+1,m}}{\Delta\tau} + \hat{\mathcal{S}}_r^{n+1,m+1} + \hat{\mathcal{R}}_r^{n+1,m+1} = 0. \quad (32)$$

227 We can re-write Eq. (32) as

$$\frac{\hat{\mathcal{U}}_r^{n+1,m+1} - \hat{\mathcal{U}}_r^{n+1,m}}{\Delta\tau} + \hat{\mathcal{S}}_r^{n+1,m+1} - \hat{\mathcal{S}}_r^{n+1,m} + \hat{\mathcal{R}}_r^{n+1,m+1} - \hat{\mathcal{R}}_r^{n+1,m} = -\hat{\mathcal{R}}_r^{n+1,m} - \hat{\mathcal{S}}_r^{n+1,m} \quad (33)$$

228 where a second-order backward difference scheme (BDF2) is used for the physical time derivative,

$$\hat{\mathcal{S}}_r^{n+1,m+1} = \frac{\mathbf{I}_D}{2\Delta t} (3\hat{\mathcal{U}}_r^{n+1,m+1} - 4\hat{\mathcal{U}}_r^n + \hat{\mathcal{U}}_r^{n-1}). \quad (34)$$

229 Correspondingly, for pseudo time level m the discretization is

$$\hat{\mathcal{S}}_r^{n+1,m} = \frac{\mathbf{I}_D}{2\Delta t} (3\hat{\mathcal{U}}_r^{n+1,m} - 4\hat{\mathcal{U}}_r^n + \hat{\mathcal{U}}_r^{n-1}). \quad (35)$$

230 Gathering terms

$$\left(\frac{\mathbf{I}}{\Delta\tau} + \frac{3\mathbf{I}_D}{2\Delta t} \right) (\hat{\mathcal{U}}_r^{n+1,m+1} - \hat{\mathcal{U}}_r^{n+1,m}) + \hat{\mathcal{R}}_r^{n+1,m+1} - \hat{\mathcal{R}}_r^{n+1,m} = -\hat{\mathcal{R}}_r^{n+1,m} - \hat{\mathcal{S}}_r^{n+1,m} \quad (36)$$

231 and then linearizing the residual while dropping the $n + 1$ index for convenience

$$\hat{\mathcal{R}}_r^{m+1} - \hat{\mathcal{R}}_r^m \approx \frac{\partial \hat{\mathcal{R}}_r}{\partial \hat{\mathcal{U}}_r} \Delta \hat{\mathcal{U}}_r + \sum_{nb \neq r} \frac{\partial \hat{\mathcal{R}}_r}{\partial \hat{\mathcal{U}}_{nb}} \Delta \hat{\mathcal{U}}_{nb} \quad (37)$$

232 the following expression is obtained

$$\left(\frac{\mathbf{I}}{\Delta\tau} + \frac{3\mathbf{I}_D}{2\Delta t} + \frac{\partial \hat{\mathcal{R}}_r}{\partial \hat{\mathcal{U}}_r} \right) \Delta \hat{\mathcal{U}}_r^{m+1} = -\hat{\mathcal{R}}_r^m - \hat{\mathcal{S}}_r^m - \sum_{nb \neq r} \frac{\partial \hat{\mathcal{R}}_r}{\partial \hat{\mathcal{U}}_{nb}} \Delta \hat{\mathcal{U}}_{nb}. \quad (38)$$

233 To avoid computation and storage of $\partial \hat{\mathcal{R}}_r / \partial \hat{\mathcal{U}}_{nb}$ we can perform another linearization similar to the one done

234 in Kannan [37] and apply the LU-SGS algorithm by replacing m with k on the left hand side of Eq. (38),

235 where k represents one forward/backward sweep through the grid, and introducing $(\star)$ to signify the most

236 recently computed solution. With this modification, Eq. (38) becomes

$$\left(\frac{\mathbf{I}}{\Delta\tau} + \frac{3\mathbf{I}_D}{2\Delta t} + \frac{\partial \hat{\mathcal{R}}_r}{\partial \hat{\mathcal{U}}_r} \right) \Delta \hat{\mathcal{U}}_r^{k+1} = -\hat{\mathcal{R}}_r^m - \hat{\mathcal{S}}_r^m - \sum_{nb \neq r} \frac{\partial \hat{\mathcal{R}}_r}{\partial \hat{\mathcal{U}}_{nb}} \Delta \hat{\mathcal{U}}_{nb}^{\star}. \quad (39)$$

237 and $\partial \hat{\mathbf{R}}_r / \partial \hat{\mathbf{U}}_{nb}$ is eliminated in the following manner:

$$\hat{\mathbf{R}}_r^m + \sum_{nb \neq r} \frac{\partial \hat{\mathbf{R}}_r}{\partial \hat{\mathbf{U}}_{nb}} \Delta \hat{\mathbf{U}}_{nb}^* = \hat{\mathbf{R}}_r(\hat{\mathbf{U}}_c^m, \hat{\mathbf{U}}_{nb}^m) + \sum_{nb \neq r} \frac{\partial \hat{\mathbf{R}}_r}{\partial \hat{\mathbf{U}}_{nb}} \Delta \hat{\mathbf{U}}_{nb}^* \quad (40)$$

$$\approx \hat{\mathbf{R}}_r(\hat{\mathbf{U}}_c^m, \hat{\mathbf{U}}_{nb}^*) \quad (41)$$

$$\approx \hat{\mathbf{R}}_r(\hat{\mathbf{U}}_c^*, \hat{\mathbf{U}}_{nb}^*) - \frac{\partial \hat{\mathbf{R}}_r}{\partial \hat{\mathbf{U}}_r} \Delta \hat{\mathbf{U}}_r^* \quad (42)$$

238 Substituting Eq. (42) into Eq. (39), we can obtain the final form

$$\left(\frac{\mathbf{I}}{\Delta \tau} + \frac{3\mathbf{I}_D}{2\Delta t} + \frac{\partial \hat{\mathbf{R}}_r}{\partial \hat{\mathbf{U}}_r} \right) \delta \hat{\mathbf{U}}_r^{k+1} = -\hat{\mathbf{R}}_r(\hat{\mathbf{U}}_r^*, \hat{\mathbf{U}}_{nb}^*) - \hat{\mathbf{S}}_r(\hat{\mathbf{U}}_r^m, \hat{\mathbf{U}}_r^n, \hat{\mathbf{U}}_r^{n-1}) - \left(\frac{\mathbf{I}}{\Delta \tau} + \frac{3\mathbf{I}_D}{2\Delta t} \right) \Delta \hat{\mathbf{U}}_r^* \quad (43)$$

239 where

$$\delta \hat{\mathbf{U}}_r^{k+1} = \Delta \hat{\mathbf{U}}_r^{k+1} - \Delta \hat{\mathbf{U}}_r^* \quad (44)$$

240 and

$$\Delta \hat{\mathbf{U}}_r^{k+1} = \hat{\mathbf{U}}_r^{k+1} - \hat{\mathbf{U}}_r^m, \quad \Delta \hat{\mathbf{U}}_r^* = \hat{\mathbf{U}}_r^* - \hat{\mathbf{U}}_r^m. \quad (45)$$

241 The above linear system is solved element-by-element with direct LU decomposition and the solution is
242 updated with

$$\hat{\mathbf{U}}_r^{k+1} = \hat{\mathbf{U}}_r^* + \delta \hat{\mathbf{U}}_r^{k+1}. \quad (46)$$

243 After a maximum number of sweeps k_{max} through the grid, the solution reaches pseudo time level $m + 1$, and
244 after a maximum number of pseudo iterations m_{max} the solution reaches physical time level $n + 1$; at this time
245 the fictitious pressure waves introduced into the fluid by artificial compressibility disappear and the solution
246 $\hat{\mathbf{U}}_r$ takes physical meaning. It is important to note the size of the element matrix $\mathbf{M}_r$, which consists of terms
247 inside the brackets on the left-hand side of Eq. (43). The size of this matrix is shown in Eq. (47) and is a
248 function of the number of equations to solve N_{eq} , number of solution points N_p per Ω_r in 1D, and dimension

249 D of Ω

$$\text{Size of } \mathbf{M}_r = [N_{eq} \cdot N_p^D] \times [N_{eq} \cdot N_p^D]. \quad (47)$$

250 Table 1 shows the size of $\mathbf{M}_r$ as a function of N_p , where $N_{eq} = 3$ and $D = 2$. For increasingly higher orders
 251 of accuracy, the size of this matrix produces a higher memory requirement and increases the total number of
 252 operations, rendering the system more computationally expensive to solve.

N_p	$\mathbf{M}_r$
2	12x12
3	27x27
4	48x48
5	75x75

Table 1: Size of element matrix $\mathbf{M}_r$ for LU decomposition as a function of N_p in 2D.

253 The element Jacobian $\partial \hat{\mathbf{R}}_r / \partial \hat{\mathbf{U}}_r$ is computed numerically [20] at every physical iteration n by applying a
 254 perturbation ϵ to each state variable,

$$\left. \frac{\partial \hat{\mathbf{R}}_r}{\partial \hat{\mathbf{U}}_r} \right|_n = \frac{\hat{\mathbf{R}}_r(\hat{\mathbf{U}}_r^n + \epsilon, \hat{\mathbf{U}}_{nb}^n) - \hat{\mathbf{R}}_r(\hat{\mathbf{U}}_r^n, \hat{\mathbf{U}}_{nb}^n)}{\epsilon} \quad (48)$$

255 where ϵ is typically $\sqrt{\epsilon_{machine}}$. To help improve convergence rates, however, the computation of $\partial \hat{\mathbf{R}}_r / \partial \hat{\mathbf{U}}_r$ can
 256 be frozen without degrading the solution. In other words, this term can be recomputed every 1-5 physical
 257 iterations, **depending on time step size**.

258 2.4.2. Explicit

259 The popular TVD RK3 scheme [35] when applied to pseudo time stepping can be written as

$$\begin{aligned} \hat{\mathbf{U}}_k^{n+1,m} &= a_k \hat{\mathbf{U}}_0^{n+1,m} + b_k \hat{\mathbf{U}}_{k-1}^{n+1,m} - c_k \Delta \tau \left[\hat{\mathbf{S}}_{k-1}^{n+1,m} + \hat{\mathbf{R}}_{k-1}^{n+1,m} \right] \\ \forall \quad k &= 1, \dots, 3, \quad m = 1, \dots, m_{max} \end{aligned} \quad (49)$$

260 where m represents the number of RK3 pseudo iterations. **At the start of each round of pseudo iterations,**
 261 **when $m = 1$, $\hat{\mathbf{U}}_0^{n+1,1}$ is the solution from the previous physical time step. However, for $m > 1$, $\hat{\mathbf{U}}_0^{n+1,m}$**
 262 **represents the solution from the previous pseudo time step.** The physical time discretization exists as a

263 source term and is given by

$$\hat{S}_{k-1}^{n+1,m} = \frac{I_D}{2\Delta t} (3\hat{U}_{k-1}^{n+1,m} - 4\hat{U}^n + \hat{U}^{n-1}) \quad (50)$$

264 The index k signifies different stages of the Runge-Kutta scheme for which the coefficients a_k , b_k and c_k are
265 defined as

$$\begin{aligned} \text{stage } k = 1 : \{a_1, b_1, c_1\} &= \{1, 0, 1\} \\ \text{stage } k = 2 : \{a_2, b_2, c_2\} &= \left\{\frac{3}{4}, \frac{1}{4}, \frac{1}{4}\right\} \\ \text{stage } k = 3 : \{a_3, b_3, c_3\} &= \left\{\frac{1}{3}, \frac{2}{3}, \frac{2}{3}\right\} \end{aligned}$$

266 3. Steady flow: Taylor-Couette flow with curved boundaries

267 Proper implementation of the numerical method is verified by comparing results to the exact solution for
268 steady incompressible Taylor-Couette flow [38]. The analytical expression for radial velocity $\tilde{V}(r)$ in this
269 problem is

$$\tilde{V}(r) = r_i \omega_i \frac{\frac{r_o}{r} - \frac{r}{r_o}}{\frac{r_o}{r_i} - \frac{r_i}{r_o}} + r_o \omega_o \frac{\frac{r}{r_i} - \frac{r_i}{r}}{\frac{r_o}{r_i} - \frac{r_i}{r_o}} \quad (51)$$

270 where $r_i=1$ and $r_o=2$ are the inner and outer radius and ω_i and ω_o are the inner and outer cylinder angular
271 speeds, respectively. The inner cylinder spins clockwise at a rate $\omega_i=1$ while the outer cylinder is stationary.
272 At $t = 0$, initial u and v velocity conditions are given based upon the analytical expression and cubic Bezier
273 curves are implemented for curved boundaries, where no-slip velocity conditions are satisfied through spec-
274 ification of exact flux. The Reynolds number $Re = r_i \omega_i d / \nu$ is 10, where $d = r_o - r_i$. Refinement is done
275 uniformly from the coarsest grid Ω^1 shown in Fig. 2a down to the finest grid Ω^4 . The L^p -norm of radial
276 velocity error $\|\epsilon\|_p$ for $N_p = \{2, 3, 4\}$ is computed by Eq. (52)

$$\|\epsilon\|_p = \left(\frac{\sum_{k=1}^{DOF} |\epsilon_k|^p}{DOF} \right)^{\frac{1}{p}} \quad (52)$$

277 where $\epsilon(r) = \tilde{V}(r) - V(r)$ and $V(r)$ is the radial velocity obtained numerically. Total degrees of freedom
278 are denoted by DOF , which represents the total number of solution points in Ω . The subsequent orders of

279 accuracy $\mathcal{P}$ achieved are computed by Eq. (53)

$$\mathcal{P}_{L^p} = \frac{\log \left[\frac{\|\epsilon\|_p(\Omega^d)}{\|\epsilon\|_p(\Omega^{d+1})} \right]}{\log \left[\frac{h(\Omega^d)}{h(\Omega^{d+1})} \right]} \quad (53)$$

280 where $p = \{1, 2\}$ to represent different norms and $h(\Omega^i) = 1 / \sqrt[d]{DOF}$ for $\Omega^i \subset \mathbb{R}^D$. For this benchmark test
 281 case, $i = \{1, 2, 3, 4\}$ to represent four uniformly refined domains with number of elements 48, 192, 768 and
 282 3072, respectively. For this two-dimensional benchmark test, $D = 2$.

283 The profile of radial velocity $V(r)$ obtained numerically with a 4th order method on Ω^3 is shown in
 284 Fig. 2b and reductions in L^1 -norm and L^2 -norm of the error are tabulated in Tab. 2. These order of accuracy
 285 results are obtained exactly using both explicit and implicit pseudo time stepping, with and without inclusion
 286 of the source term from physical time discretization $\hat{S}$. Convergence of the L^1 -norm of pseudo residuals
 287 $\mathbf{R}_\tau(\cdot) = \hat{\mathbf{R}}_\tau(\cdot)/|J|$ on Ω^3 from the continuity and momentum equations are plotted against physical time t in
 288 Fig. 3 using a 4th order FR method. The same physical and pseudo time step sizes are used for both RK3
 289 and LU-SGS time stepping schemes and $\|\mathbf{R}_\tau\|_1$ is required to decrease one order of magnitude within each
 290 physical iteration. As expected, the results from both schemes overlap each other and the level to which each
 291 residual drops is 10^{-13} . This analysis verifies that both RK3 and LU-SGS are implemented correctly under
 292 dual time stepping. Although both schemes perform well in computing this steady flow, the explicit scheme
 293 exhibits difficulty in addressing stiffness introduced by artificial compressibility in the modified continuity
 294 equation for unsteady flow. This fact is highlighted in Section 7, where we compare results between the
 295 explicit and implicit schemes for unsteady flow past a cylinder and show the latter scheme to be a promising
 296 choice.

Figure 2: Incompressible Taylor-Couette flow at $Re = 10$.

Domain	Elements	DOF	$\ \epsilon\ _1$	$\mathcal{P}_{L^1}$	$\ \epsilon\ _2$	$\mathcal{P}_{L^2}$
Ω^1	48	192	7.97E-2	-	9.55E-2	-
Ω^2	192	768	1.74E-2	2.20	2.16E-2	2.14
Ω^3	768	3072	3.98E-3	2.13	5.05E-3	2.10
Ω^4	3072	12288	9.26E-4	2.10	1.19E-3	2.08

(a) $N_p = 2$

Domain	Elements	DOF	$\ \epsilon\ _1$	$\mathcal{P}_{L^1}$	$\ \epsilon\ _2$	$\mathcal{P}_{L^2}$
Ω^1	48	432	6.94E-3	-	8.99E-3	-
Ω^2	192	1728	6.45E-4	3.42	8.81E-4	3.35
Ω^3	768	6912	8.45E-5	2.93	1.07E-4	3.04
Ω^4	3072	27648	2.01E-5	2.07	2.40E-5	2.16

(b) $N_p = 3$

Domain	Elements	DOF	$\ \epsilon\ _1$	$\mathcal{P}_{L^1}$	$\ \epsilon\ _2$	$\mathcal{P}_{L^2}$
Ω^1	48	768	1.64E-3	-	1.93E-3	-
Ω^2	192	3072	6.80E-5	4.59	8.16E-5	4.56
Ω^3	768	12288	3.71E-6	4.20	4.57E-6	4.16
Ω^4	3072	49152	2.22E-7	4.06	2.89E-7	3.98

(c) $N_p = 4$

Table 2: Taylor-Couette at $Re = 10$: order of accuracy obtained from L^1 -norm and L^2 -norm of errors during h -refinement.

Figure 3: L^1 -norm of continuity and momentum pseudo residuals, $\|R_\tau(\cdot)\|_1$, for a 4th order method on Ω^3 .

4. Steady flow: NACA0012 airfoil

In order to demonstrate performance of implicit dual time stepping on a highly non-uniform grid, numerical results were obtained for steady flow past a NACA0012 airfoil at zero angle of attack at $Re = 1850$ and unit chord length. The grid used for this simulation, shown in Fig. 4, contains a total of 8114 linear quadrilateral elements with 100 of these representing the profile of the airfoil, which exhibits a sharp trailing edge. Curvature of the airfoil is captured using our cubic Bezier curve implementation. The blockage in y caused by the presence of the airfoil in the 40×40 domain is 0.3%. Initial conditions are set to $[p, u, v]^T = [1, 1, 0]^T$. At the inlet boundary, freestream velocity conditions are given while at the outlet, only pressure is specified. Far field boundary conditions are applied to the top and bottom boundaries of the domain. The no-slip ve-

306 locity condition is applied to the airfoil surface. We run 2nd, 3rd and 4th order FR methods, which correspond
 307 to 32456, 73026 and 129824 degrees of freedom, respectively. Since we seek a steady state solution, we can
 308 remove dual time stepping and ignore the term $\hat{S}$ resulting from physical time discretization. To demonstrate
 309 the effectiveness of sweeping within the LU-SGS scheme in driving $\nabla \cdot V$ to zero and ultimately the residual
 310 $\hat{R}_\tau$ to zero, we run multiple scenarios for the sweep count k_{max} . The various sweep counts used in this study
 311 are $k_{max} = \{1, 3, 6, 10\}$, where one forward/backward movement through the grid constitutes one full sweep.

312 The implicit scheme offers increased stability and permits highly accelerated convergence to the steady
 313 state. We accomplish this by setting the initial maximum CFL at $m = 0$ to 0.5 and increasing it exponen-
 314 tially [22] at every pseudo iteration with $CFL|_m = CFL|_{m=0} \cdot a^m$, where the factor a is set to 1.2. Using this
 315 function and the definition for CFL , this equates to increasing $\Delta\tau$ exponentially towards ∞ .

Figure 4: NACA0012 mesh.

316 Figure 5 shows steady state pressure contours around the leading and sharp trailing edge for various
 317 orders of accuracy. As expected, improvements in contour shape can be seen with higher orders of accuracy.
 318 Contours for u -velocity and convergence rates of $\|\mathbf{R}_\tau\|_1$ are shown in Fig. 6 for all sweep count numbers.
 319 The fast reduction in residual using the LU-SGS scheme due to the increased pseudo time step can be seen in
 320 this figure. Maximum CFL numbers using RK3 for 2nd, 3rd and 4th order methods are 0.16, 0.14 and 0.07,
 321 respectively. This figure also shows the effectiveness of LU-SGS sweeping in dropping the steady state
 322 residual by an order of magnitude, from $k_{max} = 1$ to $k_{max} = 10$. Speedup factors for different values of N_p
 323 with the various sweep counts are tabulated in Tab. 3 and are computed at the point where $\|\mathbf{R}_\tau\|_1 = 1.0E - 5$.
 324 Results show that LU-SGS minimum wall clock times have been achieved for $k_{max} = 10$. For all LU-

325 SGS simulations in this test case, the element Jacobian $\partial \hat{\mathbf{R}}_r / \partial \hat{\mathbf{U}}_r$ is computed every five iterations. Slightly
326 faster convergence can be achieved through optimization of this incremental value. Convergence of the
327 drag coefficient obtained through polynomial order enrichment (p -refinement) is shown in Figure 7, with a
328 converged value of $C_D = 0.0867$.

Figure 5: NACA0012 at $Re = 1850$: pressure at LE (a,c,e) and TE (b,d,f) from LU-SGS pseudo time stepping with $k_{max} = 10$.

Figure 6: NACA0012 at $Re = 1850$: u -velocity from LU-SGS pseudo time stepping with $k_{max} = 10$ (a,c,e). L^1 -norm of pseudo residual, $\|R_\tau\|_1$, as a function of wall clock time for various sweep numbers (b,d,f).

	RK3						LU-SGS				
k_{max}	-	1	3	6	10		-	1	3	6	10
$Speedup$	1	9.0	10.1	10.9	14.4		1	19.8	25.6	28.4	28.8

(a) $N_p = 2$

	RK3						LU-SGS				
k_{max}	-	1	3	6	10		-	1	3	6	10
$Speedup$	1	19.8	25.6	28.4	28.8		1	10.5	13.9	14.6	16.7

(b) $N_p = 3$

	RK3						LU-SGS				
k_{max}	-	1	3	6	10		-	1	3	6	10
$Speedup$	1	10.5	13.9	14.6	16.7		1	10.5	13.9	14.6	16.7

(c) $N_p = 4$

Table 3: NACA0012 at $Re = 1850$: speedup

Figure 7: NACA0012 at $Re = 1850$: C_D convergence using order enrichment (p -refinement) and LU-SGS.

329 5. Unsteady flow: Taylor-Green decaying vortices

330 The Taylor-Green decaying vortex problem with periodic boundary conditions is commonly used to
331 verify a numerical method for simulation of unsteady incompressible flow. The periodic conditions help to
332 remove influence from boundaries of the domain on the accuracy of the method. We solve the unsteady
333 Navier-Stokes equations on a square domain $\{x, y | 0 < x, y < 2\pi\}$ at $Re = 10$. We set the initial condition to
334 the exact solution

$$p(x, y, t) = -\frac{\cos(2qx) + \cos(2qy)}{4} \exp\left(\frac{-4q^2 t}{Re}\right) \quad (54)$$

$$u(x, y, t) = -\cos(qx) \sin(qy) \exp\left(\frac{-2q^2 t}{Re}\right) \quad (55)$$

$$v(x, y, t) = \sin(qx) \cos(qy) \exp\left(\frac{-2q^2 t}{Re}\right) \quad (56)$$

335 at $t = 0$, where $q = 1$ is the Taylor array number. Similar to Section 3, h -refinement is done uniformly from
 336 the coarsest grid Ω^1 (4x4) down to the finest grid Ω^4 (32x32); however, to render the elements more irregular
 337 a perturbation of 10% is applied to the mesh nodes based on h . The L^p -norms are computed using u -velocity.
 338 A small constant time step of $\Delta t = 10^{-4}$ is chosen to ensure that spatial accuracy does not degrade due to
 339 errors resulting from time discretization. At this small time step, the maximum number of pseudo iterations
 340 is set at $m_{max} = 20$ and the sweep count at $k_{max} = 3$.

341 The vorticity field obtained numerically with a 4th order FR method using LU-SGS on Ω^3 is shown in
 342 Fig. 8, and the L^p -norm of the errors are tabulated in Tab. 4 at $t = 1s$. These results demonstrate the order
 343 of accuracy for 2nd, 3rd and 4th order methods. Comparing results in Tab. 4b for Ω^3 and Tab. 4c for Ω^2 , we
 344 can see that by increasing the order from 3 to 4 similar levels of $\|\epsilon\|_1$ and $\|\epsilon\|_2$ can be achieved with less than
 345 half the number of DOFs. Furthermore, order enrichment results gathered from Tab. 4 and plotted in Fig. 9
 346 demonstrate exponential rate of convergence.

Figure 8: Taylor-Green at $Re = 10$: 4th order FR method with LU-SGS pseudo time stepping on Ω^3 at $t = 1s$.

Domain	Elements	DOF	$\ \epsilon\ _1$	$\mathcal{P}_{L^1}$	$\ \epsilon\ _2$	$\mathcal{P}_{L^2}$
Ω^1	16	64	3.15E-1	-	3.91E-1	-
Ω^2	64	256	1.18E-1	1.42	1.48E-1	1.40
Ω^3	256	1024	1.90E-2	2.63	2.35E-2	2.66
Ω^4	1024	4096	2.68E-3	2.83	3.31E-3	2.83

(a) $N_p = 2$

Domain	Elements	DOF	$\ \epsilon\ _1$	$\mathcal{P}_{L^1}$	$\ \epsilon\ _2$	$\mathcal{P}_{L^2}$
Ω^1	16	144	3.27E-2	-	4.05E-2	-
Ω^2	64	576	3.21E-3	3.35	4.05E-3	3.32
Ω^3	256	2304	2.38E-4	3.75	2.95E-4	3.77
Ω^4	1024	9216	2.66E-5	3.16	3.31E-5	3.16

(b) $N_p = 3$

Domain	Elements	DOF	$\ \epsilon\ _1$	$\mathcal{P}_{L^1}$	$\ \epsilon\ _2$	$\mathcal{P}_{L^2}$
Ω^1	16	256	3.98E-3	-	4.96E-3	-
Ω^2	64	1024	2.28E-4	4.12	2.79E-4	4.15
Ω^3	256	4096	1.04E-5	4.46	1.30E-5	4.42
Ω^4	1024	16384	6.80E-7	3.93	8.59E-7	3.92

(c) $N_p = 4$

Table 4: Taylor-Green at $Re = 10$: order of accuracy obtained from L^1 -norm and L^2 -norm of errors during h -refinement, with LU-SGS pseudo time stepping.

Figure 9: Taylor-Green at $Re = 10$: p -convergence of $\|\epsilon\|_1$ (dashed) and $\|\epsilon\|_2$ (solid).

347 6. Unsteady flow: double periodic shear layers

348 The second unsteady test case presented is a double periodic pair of horizontal shear layers with a small
349 vertical perturbation in a square domain $\{x, y | 0 < x, y < 1\}$ with periodic boundary conditions. This problem
350 was introduced by Bell, Collela and Glaz [39] to test convergence properties of their projection method and

351 later studied by Minion and Brown [40] to assess the effect of grid resolution on the behavior of various
 352 difference approximations for the unsteady incompressible Navier-Stokes equations. This is considered a
 353 “thick” shear layer problem with initial conditions given by

$$u(x, y, 0) = \begin{cases} \tanh[(y - 0.25) / \rho], & \text{if } y \leq 0.5 \\ \tanh[(0.75 - y) / \rho], & \text{if } y > 0.5 \end{cases} \quad (57)$$

$$v(x, y, 0) = \delta \sin(2\pi x) \quad (58)$$

354 where $\rho = 1/30$ represents shear layer thickness (smaller ρ produces thinner shear layers) and $\delta = 0.05$
 355 the amplitude of the initial perturbation. The vorticity solution at various times can be seen in Fig. 10.
 356 Each shear layer evolves into a periodic arrangement of large symmetric vortices, with the shear layer being
 357 thinned by the large straining flow field. The thinning shear layers eventually roll up with the large vortices.
 358 To test the convergence of our solver, we compute the solution at $t = 1s$ using 32×32 , 64×64 and 128×128
 359 grids, similar to the grid shown in Fig. 8a. The Reynolds number is $Re = 500$ and physical and pseudo time
 360 steps are $1.0E - 4$. Max pseudo iterations were set to $m_{max} = 20$ and the sweep count to $k_{max} = 3$. The
 361 convergence rates for 2^{nd} , 3^{rd} and 4^{th} order FR methods are estimated in the same manner as Minion and
 362 Brown [40] using a procedure based on Richardson extrapolation and provided in Tab. 5.

363 To illustrate the performance of our high-order FR method with implicit pseudo time stepping in re-
 364 solving this shear layer at higher Reynolds number, we increase Re to 10,000 and march the solution to
 365 $t = 1.8s$ on 32×32 , 64×64 and 128×128 regular grids. As the larger physical vortices develop and the shear
 366 layer thins, non-physical vortices originate in the shear layer due to insufficient grid and/or order resolution.
 367 These vortices are further stretched as they wrap around the larger ones. The spurious nature of these vor-
 368 tices is confirmed by observing their elimination from the solution during h - and p -refinement. This fact can
 369 be seen in Fig. 11, which shows existence of spurious vortices using $N_p = \{2, 3, 4\}$ on a 32×32 grid and using
 370 $N_p = 2$ on a 64×64 grid. Furthermore, comparing results in Figs. 11b and 11g, which both use 128 DOFs in
 371 each direction, we can conclude that performance of a 4^{th} order scheme is greater than a 2^{nd} order scheme in
 372 attempting to remove the spurious vortices. If we refine these grids further to contain DOFs ≥ 256 we can
 373 appropriately resolve the flow field and eliminate any non-physical numerical artifact.

Figure 10: Double shear layer at $Re = 500$: vorticity for 4th order FR method with LU-SGS pseudo time stepping.

	$N_p = 2$	$N_p = 3$	$N_p = 4$
$\ u_{\Omega^1} - u_{\Omega^2}\ _2$	2.263E-2	2.569E-3	1.367E-4
$\ u_{\Omega^2} - u_{\Omega^3}\ _2$	6.374E-3	3.817E-4	1.053E-5
<i>Richardson Rate</i>	1.83	2.75	3.70

Table 5: Double Shear Layer at $Re = 500$: convergence rate obtained from L^2 -norm of errors using Richardson extrapolation at $t = 1s$.

Figure 11: Double shear layer at $Re = 10,000$: vorticity at $t = 1.8s$ for $N_p = 2$ (a-c), $N_p = 3$ (d-f) and $N_p = 4$ (g-i) order methods. DOFs along each coordinate direction are given in parenthesis.

7. Unsteady flow: cylinder

The novelty of this paper is the design of an implicit dual time stepping scheme for the high-order FR method to predict unsteady flow in complex geometries. In this section, we report numerical results for unsteady laminar flow at $Re = 100$ past a stationary cylinder with diameter $d = 1$. The grid used for this test case shown in Fig. 12 contains 4371 linear quadrilateral elements with 48 elements along the wall of the cylinder, which again is represented by our cubic Bezier curves. The blockage in y caused by the presence of the cylinder in the 50×40 domain is 2.5%. The initial and boundary conditions applied to the NACA0012 airfoil were also applied to this geometry. As before, we run 2^{nd} , 3^{rd} and 4^{th} order FR methods, which correspond to 17484, 39339 and 69936 degrees of freedom in Ω , respectively.

The pseudo time step to be taken by the implicit scheme is chosen to be $100x$ larger than that afforded by the explicit scheme. Furthermore, increased stability offered by the LU-SGS implementation can permit a $100x$ larger physical time step, while still capturing the transient process. The pseudo and physical time step size used by the explicit scheme is $\Delta\tau^{RK3} = \Delta t^{RK3} = 1.0E - 3$ for a 3^{rd} order method and $\Delta\tau^{RK3} = \Delta t^{RK3} = 6.0E - 4$ for a 4^{th} order method. Cost per physical iteration is higher for the implicit scheme and mainly depends upon four factors: (1) the frequency of computing the element Jacobian $\partial\mathbf{R}_r/\partial\mathbf{U}_r$, (2) size of the element matrix $\mathbf{M}_r$ (i.e. polynomial order), (3) number of pseudo iterations, and (4) number of sweeps through the mesh. For unsteady flow calculations, a criterion is used during each physical iteration, whereby the pseudo residual is evaluated at the end of each pseudo iteration to determine if the continuity equation has been satisfied. The criterion for pseudo steady state convergence per physical time step requires that $\|\mathbf{R}_\tau\|_1$ drop by a factor of 10^3 . If this value is not reached, the maximum number of pseudo iterations for explicit and implicit schemes is set to $m_{max}^{RK3} = 20$ and $m_{max}^{LU-SGS} = 200$. The value for m_{max}^{LU-SGS} is made larger by an order of magnitude to account for the increased time step size associated with this scheme. Larger $\Delta\tau$ and Δt cause the element matrix $\mathbf{M}_r$ to be less diagonally dominant and result in more pseudo iterations to achieve convergence to the pseudo steady state than smaller time step sizes. The LU-SGS sweep count number is set to $k_{max} = 3$. In this unsteady flow problem, $\partial\hat{\mathbf{R}}_r/\partial\hat{\mathbf{U}}_r$ is computed at every single physical iteration.

Figure 12: Cylinder grid.

Instantaneous vorticity contours at approximately $t = 360s$ for 2^{nd} , 3^{rd} and 4^{th} order methods can be seen in Fig. 13 for both RK3 and LU-SGS schemes. Figures 13a/13b demonstrate that the current grid is inadequate for a 2^{nd} order FR method to maintain the integrity of the vortex shedding downstream of the bluff body. Figures 13c/13d and 13e/13f demonstrate that higher order polynomials have the ability to capture the vortex shedding properly, with the latter set of figures from a 4^{th} order method displaying the smoothest contours of vorticity.

Plots of force coefficients C_L and C_D generated by a 3^{rd} order method are shown in Fig. 14 for roughly 32 vortex shedding cycles. These plots show a visual comparison between RK3 and LU-SGS, with the former exhibiting a slightly larger amplitude for C_L (1.6%) and larger mean value for C_D (0.15%). Values for Strouhal number and various force coefficients are tabulated in Tab. 6 using data collected from approximately 60 data points per shedding cycle over 50 cycles. A fast Fourier transform was performed to capture the shedding frequency f_s needed to compute the Strouhal number $St = f_s d / U_\infty$. Coefficients of lift and drag due to pressure ($C_{L,p}, C_{D,p}$) and viscosity ($C_{L,v}, C_{D,v}$) are shown and compared to data from Park, Kwon and Choi [41] and Sharman et al. [42]. The former authors employed the fractional step method of Choi and Moin [43] while the latter authors utilized the SIMPLE algorithm [44]. Results from Posdziech and Grundmann [45] are reported as well. Root mean square (RMS) values are indicated by $(\cdot)'$. For a 4^{th} order FR method with LU-SGS, the RMS of lift coefficient ($C'_L = 0.23$) exactly matches the values obtained by Park et al. and Sharman et al., while the RMS of drag coefficient ($C'_D = 0.0063$) is smaller by approximately 1.5% but exactly equal to the value reported by Posdziech et al. Additionally, amplitudes of C_L and C_D are provided in Tab. 7 along with results from different authors such as Chan et al. [46], Liu et al. [47], Ding et

al. [48], [49] and Williamson [50]. We compute C_L by taking an average of peak values and we compute C_D by averaging all values over the 50 shedding cycles. The uncertainty in drag is calculated by averaging the differences between all peak values and the mean value. Note that the current incompressible 4th order results using LU-SGS agree extremely well with the result from Chan, who used a low speed compressible flow solver with a 4th order spectral difference method. Values for Strouhal number $St = 0.164$ are consistent across the board of numerical results and match the experimental result from Williamson.

Side-by-side comparisons of reduction in $\|\mathbf{R}_\tau(1)\|_1$, $\|\mathbf{R}_\tau(2)\|_1$ and $\|\mathbf{R}_\tau(3)\|_1$ between RK3 and LU-SGS are plotted in Figs. 15, 16 and 17, respectively, during the physical time interval $340 \leq t \leq 440$. These plots display the level of pseudo residuals for all three equations before pseudo iterations begin ($m = 0$) and after pseudo iterations end ($m = m_{max}$) per physical iteration over multiple shedding cycles. Also, the number of pseudo iterations required for convergence per physical time step for LU-SGS is shown in Fig. 18. The flat line for RK3 in this plot demonstrates that the criterion for $\|\mathbf{R}_\tau\|_1$ is consistently not satisfied due to the inability of the explicit scheme to further improve the divergence of velocity field through rather restricted pseudo time stepping, which is evident in the overlapping lines in Fig. 15a. This fact points to the stiffness associated with pressure. In Fig. 15b, however, we see that the LU-SGS scheme is capable of reducing $\|\mathbf{R}_\tau(1)\|_1$, which is required to more accurately satisfy the continuity equation. This reduction is attributed to the larger pseudo time step afforded by the implicit scheme. Though, at the same time, some accuracy in $\|\mathbf{R}_\tau(2)\|_1$ and $\|\mathbf{R}_\tau(3)\|_1$ is given up under the assigned criterion, as illustrated in Figs. 16 and 17. To assess the effect of time step size on the number of pseudo iterations when using LU-SGS, we reduce the time step by an order of magnitude from $\Delta\tau^{LUSGS} = \Delta t^{LUSGS} = 0.1$ to $\Delta\tau^{LUSGS} = \Delta t^{LUSGS} = 0.01$, and plot maximum pseudo iterations per physical time step in Fig. 19. These results demonstrate that we require approximately 2.5x more pseudo iterations to drop $\|\mathbf{R}_\tau\|_1$ by the same criterion of 10^3 using this smaller time step. So, to simulate the same amount of physical time, the smaller pseudo time stepping requires 25x more CPU time. Therefore, we can conclude that the increased stability offered by large implicit pseudo time stepping improves the convergence rate.

Analysis of this unsteady laminar flow problem highlights that the explicit scheme is not as effective in satisfying the divergence-free constraint on the velocity field as the implicit scheme. The implicit scheme for pseudo time stepping is well suited for accurately solving unsteady incompressible flow using the artificial compressibility method. Within the context of the present high-order FR framework, the restrictions on both pseudo and physical time step sizes experienced by the combination of RK3 and BDF2 for dual time stepping can be effectively alleviated by an implicit backward Euler scheme with non-linear LU-SGS.

	Current				Park et al. [41]	Sharman et al. [42]	Posdziech et al. [45]
	RK3	LU-SGS	RK3	LU-SGS			
Blockage	2.5%	2.5%	2.5%	2.5%	1.0%	2.0%	0.71%
Elements	4371	4371	4371	4371	~39000	14441	~19000
N_p	3	3	4	4	-	-	-
St	0.164	0.164	0.164	0.164	0.165	0.164	0.164
C_L	± 0.320	± 0.316	± 0.331	± 0.325	± 0.332	± 0.325	-
C'_L	0.227	0.223	0.234	0.230	0.23	0.23	0.23
$C'_{L,p}$	0.200	0.197	0.205	0.202	0.21	0.20	0.20
$C'_{L,v}$	0.031	0.030	0.031	0.031	0.030	0.030	0.031
C_D	1.344	1.342	1.342	1.339	1.33	1.33	1.33
$C_{D,p}$	1.002	1.000	1.000	0.997	0.99	0.99	0.99
$C_{D,v}$	0.342	0.342	0.342	0.342	0.34	0.34	0.34
C'_D	0.0066	0.0062	0.0068	0.0063	0.0064	0.0064	0.0063
$C'_{D,p}$	0.0060	0.0056	0.0064	0.0058	0.0058	0.0058	0.0058
$C'_{D,v}$	7.13E-4	6.50E-4	7.50E-4	6.58E-4	7.00E-4	4.00E-4	7.00E-4

Table 6: Cylinder at $Re = 100$: Strouhal numbers and force coefficients due to pressure $C_{(\cdot),p}$ and viscosity $C_{(\cdot),v}$ predicted by 3rd and 4th order methods. Root mean square values are signified by the superscript ($\cdot$)'.

	Method	St	C_L	C_D
Current (4 th order w/ LU-SGS)	Artificial Compressibility + Flux Reconstruction	0.164	± 0.325	1.339 ± 0.009
Park et al. [41]	Fractional Step	0.165	± 0.332	1.33 ± 0.009
Sharman et al. [42]	SIMPLE	0.164	± 0.325	1.33 ± 0.009
Chan et al. [46] (4 th order)	Compressible Spectral Difference	0.164	± 0.325	1.338 ± 0.009
Liu et al. [47]	Artificial Compressibility + RANS	0.165	± 0.339	1.350 ± 0.012
Ding et al. [48]	Hybrid Finite Difference	0.164	± 0.280	1.325 ± 0.008
Ding et al. [49]	Hybrid Finite Difference	0.166	± 0.287	1.356 ± 0.010
Williamson [50] (experiment)	-	0.164	-	-

Table 7: Cylinder at $Re = 100$: comparison of St , C_L and C_D with various incompressible solvers.

(a) RK3: $N_p = 2$

(b) LU-SGS: $N_p = 2$

(c) RK3: $N_p = 3$

(d) LU-SGS: $N_p = 3$

(e) RK3: $N_p = 4$

(f) LU-SGS: $N_p = 4$

Figure 13: Cylinder at $Re = 100$: vorticity.

Figure 14: Cylinder at $Re = 100$: C_L and C_D vs. physical time predicted by a 3rd order method.

Figure 15: Cylinder at $Re = 100$: L^1 -norm of continuity residual vs. physical time before pseudo iterations begin ($m = 0$) and after pseudo iterations end ($m = m_{max}$) predicted by a 3rd order method.

Figure 16: Cylinder at $Re = 100$: L^1 -norm of x -momentum residual vs. physical time before pseudo iterations begin ($m = 0$) and after pseudo iterations end ($m = m_{max}$) predicted by a 3rd order method.

Figure 17: Cylinder at $Re = 100$: L^1 -norm of y -momentum residual vs. physical time before pseudo iterations begin ($m = 0$) and after pseudo iterations end ($m = m_{max}$) predicted by a 3rd order method.

Figure 18: Cylinder at $Re = 100$: total pseudo iterations m_{max} per physical time step predicted by a 3rd order method.

Figure 19: Cylinder at $Re = 100$: total pseudo iterations m_{max} per physical time step using LU-SGS, highlighting increased iterations with order of magnitude reduction in time step size.

8. Conclusion

A high-order compact flux reconstruction method for solving unsteady incompressible flow on unstructured grids with implicit dual time stepping has been presented. The governing equations employ Chorin's classic artificial compressibility formulation such that advanced time stepping techniques developed for solving compressible flow can be used. We implement both a total variation diminishing Runge-Kutta scheme

456 and a backward Euler with non-linear LU-SGS smoothing scheme to handle pseudo time and a second-order
 457 backward Euler scheme for physical time. Viscous fluxes across each interface are computed using the pop-
 458 ular 2nd procedure of Bassi and Rebay. This method makes the computational stencil compact, requiring
 459 information from direct neighboring elements only and allowing for inversion of the implicit operator within
 460 the LU-SGS framework. Accuracy and convergence of this solver is shown by studying both steady and
 461 unsteady laminar flow problems. The current implicit dual time stepping scheme is proven effective in solv-
 462 ing the unsteady incompressible Navier-Stokes equations in pseudo time in the context of a discontinuous
 463 high-order spatial method, which is limited by time step size restrictions in explicit schemes. The class
 464 of discontinuous high-order methods (e.g. DG, SD and FR/CPR) that were designed to solve the unsteady
 465 compressible Navier-Stokes equations can be extended to solve incompressible flow using the artificial com-
 466 pressibility formulation with dual time stepping presented in this paper. Furthermore, our incompressible
 467 solver is very suitable for parallel computing that uses straightforward domain decomposition for partition-
 468 ing computational elements, which in turn is friendly towards iterative methods that can be used to update
 469 solutions within each element for higher order polynomials. Finally, this solver can be easily extended to
 470 handle moving and deforming grids, similar to the implementation in Cox et al. [51].

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