A direct forcing immersed boundary method for flow through the blades of Savonius rotor in a static state

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Abstract

The method used to identify the immersed boundary nodes for different types of bodies determines the accuracy of numerical simulation of rigid body using the Immersed Boundary Method. The direct-forcing immersed boundary (DFIB) method was used to model fluid-solid interactions, and it successfully simulated problems involving the circular cylinder, airfoil, and spherical solid with considerable thickness. However, direct-forcing immersed boundary has not been extensively investigated for thin solid body problems.
To use this method, a new algorithm for identifying rigid solid boundary nodes in fluid and ensuring that the fluid cannot pass through the thin solid body required to develop. This study proposes a direct-forcing immersed boundary method for efficiently simulating thin solid boundaries in incompressible flows by developing a new algorithm that identifies solid boundary nodes from fluid and ensures that fluid cannot pass through the thin solid body when it is stationary or moving. The method's accuracy is demonstrated using 3D turbulent flow fields through the blades of a static Savonius rotor. The computational results showed the capability of the direct-forcing immersed boundary methods to solve thin body problems.
Key words: Direct forcing immersed boundary method, Fluid-solid interactions, Thin solid body, Savonius rotor

Problem description

The Savonius rotor is one of the classic type of the vertical-axis wind turbine (VAWT) which invented in 1922 by Finish engineer Sigurd J. Savonius [1]. The conventional type of Savonius rotor is composed of two or more semicircular blades with a slight overlap between them. The Savonoius wind turbine is a drag-driven VAWT with good starting torque with low speed, low noise, low construction costs, and a stronger structure that can withstand extreme wind that can destroy other types of wind turbines.
However, since complex flow dynamics around the Savonious rotor are inherently unsteady, their aerodynamic performance is difficult to predict or analyze. The complexity of the air around it, as well as the mutual interference of the buckets, makes theoretical prediction of Savonius rotor efficiency difficult, according to [2]. There are only two ways to investigate the for studying flow around Savonius wind rotors : experimental or Computational fluid dynamic (CFD) studies.
The Savonius rotor aerodynamic has been studied numerically using both DVM (Discrete Vortex Method) and Computational Fluid Dynamics (CFD) methods. DVM was used by Fujisawa [3] and Fernando and Modi to predict rotor performance [4]. This method does not yield a quantitatively accurate prediction of rotor performance when compared to measured data, but it does reproduce the main characteristics of the performance curves and flow field as described in [5]. Due to the recent advances in computational Fluid Dynamics (CFD) on complex structures assist in understanding the aerodynamic nature of the Savonius rotor. As a result, flow characteristics such as drag, lift, and torque coefficients, as well as aerodynamic efficiency, can be obtained without the need for complex and multiple experiments. The majority of studies concentrated solely on the explanation of dynamic properties; there is no information on static properties. Thus, to our knowledge, very little literature has given an adequate result for static torque, which is important for aerodynamic efficiency because the main characteristic of the Savonius rotor is to begin at low wind velocities regardless of wind direction. The numerical flow study on the Savonious rotor, on the other hand, was mainly carried out using body-fitted methods.

However, mesh generation would be difficult for objects with complex geometry, especially thin rigid bodies, since their volume is significantly too small, and the need to re-mesh the entire computational domain each time the object is displaced or deformed greatly increases the computation load.
The direct-forcing immersed boundary (DFIB) method, which is part of the immersed boundary method (IBM) family. The direct-forcing immersed boundary approach was used to successfully simulate problems involving rigid solid bodies of relatively large thickness [6]. However, simulating thin rigid body using a direct-forcing immersed boundary has not yet been studied.
The present study intends to demonstrate that the direct-forcing immersed boundary method can model thin bodies by developing a new algorithm that uses a volume of solid (VOS) to distinguish solid boundary nodes from fluid boundary nodes and ensures that fluid cannot pass through the thin solid body when stationary or moving. This approach was applied and tested on three-dimensional turbulent flow fields passing through the blades of a static Savonius rotor.

Numerical Method

The incompressible flows governed by the dimensional Naiver-Stokes equations, including the body force term are given by:

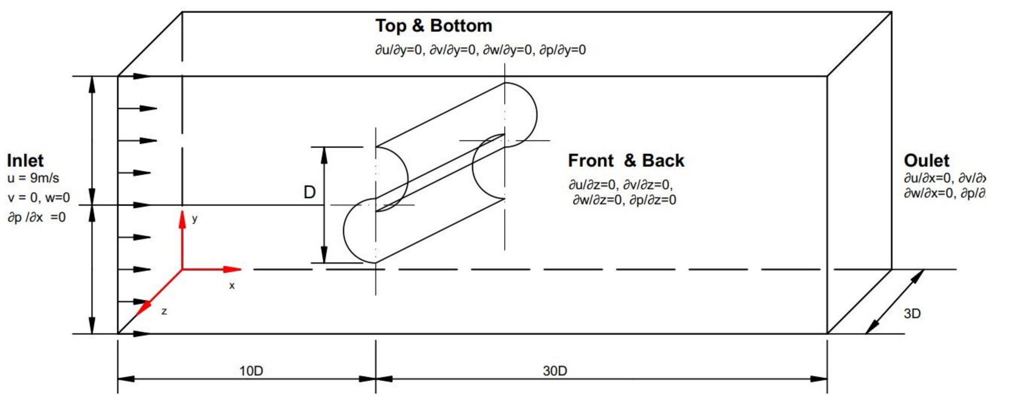
$$\frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{uu}) = -\frac{1}{\rho}\nabla p + \nu \nabla^2 \mathbf{u} + \eta \mathbf{f} \qquad \nabla \cdot \mathbf{u} = 0$$

The resultant force exerted on the blades and the resultant static torque produced by the Savonius rotor were calculated using the Simpson's rule as follows.

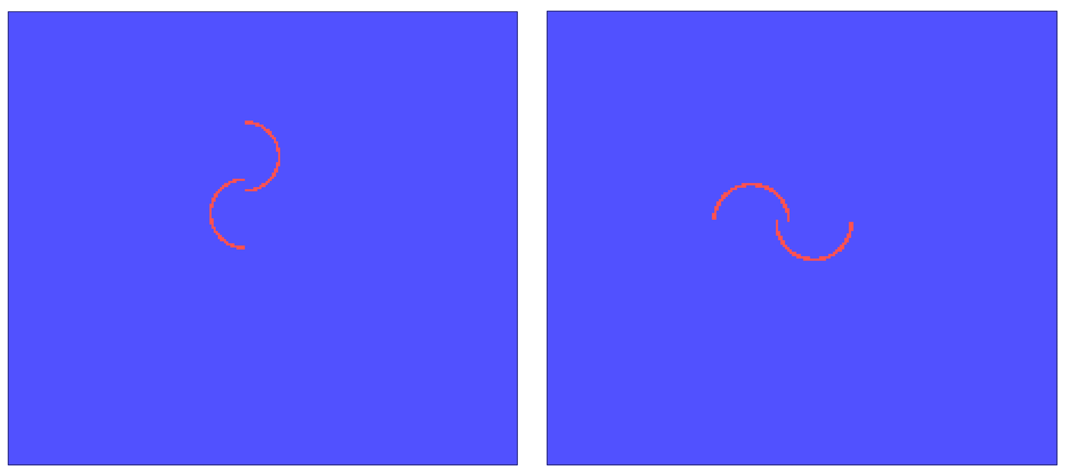
$$\mathbf{F} = \iiint_{\Omega_s} \mathbf{f} \rho \mathrm{dV} \qquad \mathbf{T} = \iiint_{\Omega_s} (\mathbf{f} D) \rho \mathrm{dV}$$

Results and discussion

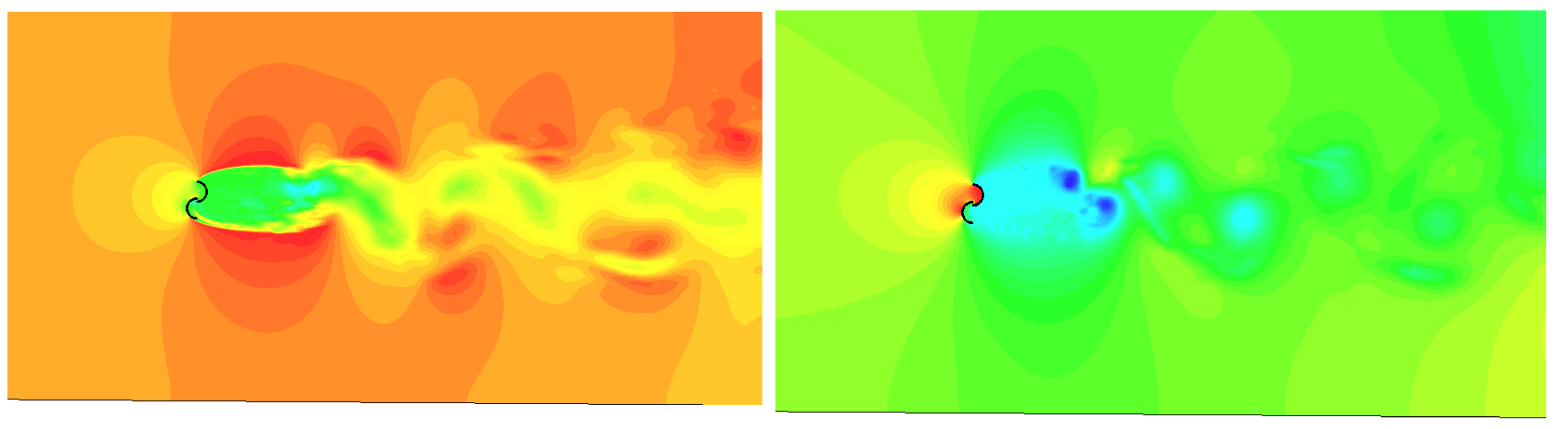
Schematic of computational domain and boundary conditions for a flow through a Savonius rotor.



Profile of Savonius rotor blades generated by VOS algorithm at η =1 at angular position of 90° and 180° respectively.



Velocity and pressure contour of at angular position of 90° from side view.



The dimensional and shape characteristics of the Savonius rotor.

Authors	Rotor Height H	Rotor Diameter D	Overlap Ratio β	Aspect Ratio As	Blade Arc Angle Ψ	Twist Angle α	End Plate	Number of Blades
Irabu and Roy [6] Experimental	160mm	89.89mm	0.14	1.78	180°	0°	Yes	Two
Irabu and Roy [7] Experimental	220mm	115.20mm	0.14	1.91	180°	0°	Yes	Two
Mirambell [8] Experimental	140mm	180.82mm	0.15	0.77	124°	12.5°	Yes	Two
Martorell [9] Numerical	140mm	180.82mm	0.15	0.77	124 °	12.5°	no	Two
Present study	**140mm**	**180.82mm**	**0.15**	**0.77**	**180°**	**0°**	**no**	**Two**

Comparison of the drag, lift and torque coefficients of stationary Savonius rotor in 3D flow at an angular position of (a) 30°, (b) 60°, and (c) 90°.

(a)

	Wind speed	Cd	Cl	Ct	Remark
Irabu and Roy [6]	9m/s	0.591	0.561	-	Experimental
Irabu and Roy [7]	9m/s	-	-	**0.356**	Experimental
Mirambell [8]	9m/s	1.008	0.878	**0.671**	Experimental
Martorell [9]	9m/s	0.42	0.37	**0.42**	Numerical (RANS)
Present study	9m/s	1.047	0.407	**0.395**	Numerical (LES)

(b)

	Wind speed	Cd	Cl	Ct	Remark
Irabu and Roy [6]	9m/s	1.05	0.095	-	Experimental
Irabu and Roy [7]	9m/s	-	-	**0.344**	Experimental
Mirambell [8]	9m/s	1.27	0.135	**0.584**	Experimental
Martorell [9]	9m/s	0.77	0.12	**0.42**	Numerical (RANS)
Present study	9m/s	1.45	0.123	**0.350**	Numerical (LES)

(c)

	Wind speed	Cd	Cl	Ct	Remark
Irabu and Roy [6]	9m/s	1.23	0.321	-	Experimental
Irabu and Roy [7]	9m/s	-	-	**0.166**	Experimental
Mirambell [8]	9m/s	1.569	0.289	**0.305**	Experimental
Martorell [9]	9m/s	1.180	0.29	**0.21**	Numerical (RANS)
Present study	9m/s	1.650	0.321	**0.201**	Numerical (LES)

Since all studies used very similar test conditions, such as an air velocity of 9m/s and rotor location in relation to the air flow, the variations in findings shown in the tables are obviously due to differences in:

- Geometrical features of the Savonius rotors, such as the aspect ratio, twist angle, and blade arc angle,
- Measurement devices and the wind tunnel's accuracy, which results in a non-uniform flow, and
- Numerical model accuracy.

Conclusions

The direct-forcing immersed boundary method has been developed to simulate flow with thin bodies, with a new algorithm that uses a volume of solid (VOS) to identify solid boundary nodes from fluid boundary nodes and ensures that fluid cannot pass through the thin solid body while stationary or moving. This method was applied and tested on three-dimensional turbulent flow fields flowing through the blades of a static Savonius rotor, and the results demonstrated the direct-forcing immersed boundary methods' ability to solve thin body problems.

References

[1]. M. Rahman, M. Ahmed, M. Bashar, A. Mitra, T. Salyers, Numerical and Experimental Investigations on Vertical Axis Wind Turbines of Different Models, OALib 04 (01) (2017) 1-37.
[2] M. F. V.J. Modi, Unsteady Aerodynamics And Wake Of The Savonius Wind Turbine : A Numerical Study, Journal of Wind Engineering and Industrial Aerodynamics 46 (47) (1993) 811-816.
[3] N. Fujisawa, On the torque mechanism of Savonius rotors, Journal of Wind Engineering and Industrial Aerodynamics 40 (3) (1992) 277-292.
[4] M. Fernando, V. Modi, A numerical analysis of the unsteady flow past a Savonius wind turbine, Journal of Wind Engineering and Industrial Aerodynamics 32 (3) (1989) 303-327.
[5] V. D'Alessandro, S. Montelpare, R. Ricci, A. Secchiaroli, Unsteady aerodynamics of a Savonius wind rotor: a new computational approach for the simulation of energy performance, Energy 35 (8) (2010) 3349-3363.
[6] Chern, Ming-Jyh, Yu-Hao Kuan, Giri Nugroho, Guan-Ting Lu, and Tzyy-Leng Horng, Direct-forcing immersed boundary modeling of vortex-induced vibration of a circular cylinder, Journal of Wind Engineering and Industrial Aerodynamics 134 (2014): 109-121.
[7] Irabu, Kunio, and Jitendro Nath Roy. "Characteristics of wind power on Savonius rotor using a guide-box tunnel." Experimental thermal and fluid science 32, no. 2 (2007): 580-586.
[8] Irabu, Kunio, and Jitendro Nath Roy. "Study of direct force measurement and characteristics on blades of Savonius rotor at static state." Experimental Thermal and Fluid Science 35, no. 4 (2011): 653-659.
[9] Masramon, Eloi Mirambell. "Experimental study of flow through a Savonius wind Turbine." PhD diss., Universitat Politècnica de Catalunya. Escola Superior d'Enginyeries Industrial, Aeroespacial i Audiovisual de Terrassa, 2015.
[10] Martorell Pol, Pere Antoni. "Numerical study of flow through a Savonius wind turbine." Bachelor's thesis, Universitat Politècnica de Catalunya, 2015.