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Partitioned Algorithms using Vortex Particle Methods for Fluid–Structure Interaction of Thin-walled Flexible Structures

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Weimar, 24. März 2021

To
my mother Hena
my wife Sharmistha
my daughter Aishani and my son Ishaan

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Abstract

Fluid–structure interaction (FSI) is a multiphysics study of mutual interaction between deformable structure and surrounding or internal fluid flow. Proper understanding of FSI phenomena is crucial in many engineering fields. The increasing trend of extremely flexible and lightweight structures, such as long-span cable-supported bridges, super-tall towers and chimneys, large membrane roofs, requires accurate prediction of wind–structure interaction in the design process to avoid potential damage of important structures.

The grid-free Vortex Particle Method (VPM) has been established as an accurate and efficient computational fluid dynamic (CFD) simulation technique to model flow around complex geometries. Existing FSI models of VPM have been in the context of two-dimensional (2D) and pseudo-three-dimensional (pseudo-3D) multi-slice formulations. They are based on linear structural behaviour and limited to rigid cross-sections only. In this study, the VPM is extended with new developments to enhance its applicability for coupled FSI simulations of thin-walled flexible structures. The partitioned algorithms are employed to implement the coupling of flow solvers, 2D and pseudo-3D VPM, with advanced structural models.

Initially, the 2D VPM is coupled with corotational finite element formulation, which is to include geometric nonlinear effects for large-displacement FSI of thin plate systems. Fundamentally, at each simulation step, the fluid forces are projected from the surface panels to the FE nodes at the mid-surface of the thin body. The nodal displacements are projected as feedback to the surface panels to update the required boundary conditions. The coupled solver is validated on benchmark large-displacement FSI problems such as the flag-type flapping of cantilever plates in axial flow and Kármán vortex street. The validated extension of 2D VPM is successfully employed for analysing diverse and complex aeroelastic interactions of different thin-walled systems such as a) inverted and T-shaped cantilevers with/without tip mass, b) flexible membrane systems, and c) umbrella-type structures.

Secondly, the pseudo-3D VPM is extended similarly according to the procedure of 2D VPM, however, in a slice-wise manner. Importantly, the pseudo-3D VPM is proposed for FSI analysis of linear shell structures. Modal superposition technique is applied because of its computational efficiency. The novelty is the inclusion of 3D natural vibration modes in the structural analysis. The validated method is utilised for the aeroelastic interaction of shell-type structures such as large membrane roof and solar chimneys.

Furthermore, two new extensions of 2D VPM are developed for modelling of inflow fluctuations that can be used as inflow condition in FSI analysis. While the first extension allows modelling of low-frequency pulsating incoming flow, the second extension reproduces turbulent wakes from bluff bodies. Finally, the FSI model of 2D VPM is applied exclusively to a distinct application field: small-scale aeroelastic energy harvesting. The aero-electro-mechanically coupled behaviour is modelled for different thin and flexible prototype harvesters. An analysis framework is shown useful for optimisation of harvester performance for different inflow conditions. This work indicates that the developed numerical techniques are beneficial not only for fundamental investigations but also for aeroelastic interaction of large-scale thin-walled mega structures.

Kurzfassung

Die Fluid–Struktur-Kopplung, FSK (oder FSI im internationalen Kontext) ist ein multiphysikalischer Effekt der gegenseitigen Wechselwirkung zwischen verformbarer Struktur und umgebender oder interner Fluidströmung. Das richtige Verständnis der FSI-Phänomene ist in vielen technischen Bereichen von entscheidender Bedeutung. Der zunehmende Trend zu extrem flexiblen und leichten Strukturen, wie z.B. weitgespannte seilunterstützte Brücken, superhohe Türme und Schornsteine, große Membrandächer, erfordert eine genaue Vorhersage der Wind–Struktur-Kopplung (WSK) im Entwurfsprozess, um potenzielle Schäden an wichtigen Strukturen zu vermeiden.

Die gitterfreie Vortex-Partikel-Methode (VPM) wurde als genaue und effiziente numerischen Strömungsmechanik (CFD im internationalen Kontext) Simulationstechnik zur Modellierung der Strömung um komplexe Geometrien herum etabliert. Bestehende FSI-Modelle der VPM wurden im Zusammenhang mit zweidimensionalen (2D) und pseudodreidimensionalen (Pseudo-3D) Mehrschichtformulierungen erstellt. Sie basieren auf linearem Strukturverhalten und sind nur auf starre Querschnitte beschränkt. In dieser Studie wird das VPM um neue Entwicklungen erweitert, um seine Anwendbarkeit für gekoppelte FSI-Simulationen von dünnwandigen flexiblen Strukturen zu verbessern. Die partitionierten Algorithmen werden eingesetzt, um die Kopplung von Strömungslösern, 2D und Pseudo-3D VPM, mit fortschrittlichen Strukturmodellen zu implementieren.

Zunächst wird der 2D VPM mit einer korotationalen Finite-Elemente-Formulierung gekoppelt, die geometrisch nichtlineare Effekte für FSI mit großer Verschiebung von dünnen Plattensystemen beinhalten soll. Grundsätzlich werden bei jedem Simulationsschritt die Fluidkräfte von den Oberflächenplatten auf die FE-Knoten in der Mittelfläche des dünnen Körpers projiziert. Die Knotenverschiebungen werden als Rückkopplung auf die Oberflächenplatten projiziert, um die erforderlichen Randbedingungen zu aktualisieren. Der gekoppelte Solver wird anhand von FSK-Benchmark-Problemen mit großen Verschiebungen validiert, wie z.B. das fahnenartige Flattern von Cantilever-Platten in axialer Strömung und Kármán Wirbelstraße. Die validierte Erweiterung von 2D VPM wird erfolgreich zur Analyse vielfältiger und komplexer aeroelastischer Wechselwirkungen verschiedener dünnwandiger Systeme eingesetzt, wie z.B. a) invertierte und T-förmige Cantilever mit/ohne Spitzenmasse, b) flexible Membransysteme und c) schirmartige Strukturen.

Zweitens wird die Pseudo-3D-VPM nach dem Verfahren der 2D-VPM in ähnlicher Weise erweitert, jedoch scheibenweise. Wichtig ist, dass die Pseudo-3D VPM für die FSI-Analyse von linearen Schalenstrukturen vorgeschlagen wird. Die modale Überlagerungstechnik wird wegen ihrer rechnerischen Effizienz angewendet. Das Novum ist die Einbeziehung von 3D-Eigenschwingungsmoden in die Strukturanalyse. Die validierte Methode wird für die aeroelastische Wechselwirkung von schalenartigen Strukturen wie großen Membrandächern und Solarkaminen eingesetzt.

Darüber hinaus werden zwei neue Erweiterungen von 2D VPM zur Modellierung von Einströmschwankungen entwickelt, die als Einströmbedingung in der FSK-Analyse verwendet werden können. Während die erste Erweiterung die Modellierung von niederfrequent pulsierender Einströmung ermöglicht, reproduziert die zweite Erweiterung turbulente Nachläufe von Steilkörpern. Schließlich wird das FSI-Modell der 2D-VPM ausschließlich auf ein bestimmtes Anwendungsgebiet angewandt: die kleinräumige aeroelastische Energiegewinnung. Das aero-elektro-mechanisch gekoppelte Verhalten wird für verschiedene dünne und flexible

Prototyp-Harvester modelliert. Es wird ein Analyserahmen gezeigt, der für die Optimierung der Harvesterleistung für verschiedene Einströmbedingungen nützlich ist. Diese Arbeit zeigt, dass die entwickelten numerischen Techniken nicht nur für grundlegende Untersuchungen, sondern auch für die aeroelastische Wechselwirkung großflächiger dünnwandiger Megastrukturen von Nutzen sind.

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Nomenclature

Greek Letters

α	Section rotation
α_{rf}	Strength reduction factor
β	Magnetic flux density
$\boldsymbol{\mathcal{K}}$	Velocity kernel
$\boldsymbol{\omega}$	Vorticity
$\mathbf{\Phi}$	Mode shape matrix
$\mathbf{\Phi}_{num}$	Number of vibration modes
$\Delta s_{(slice)}$	Panel length in a flow analysis slice
Δt_{orig}	Original simulation time step
Δt_{rep}	Reproduction simulation time step
γ_0	Surface vorticity sheet strength
Γ_a	Approximated particle strength
Γ_m	Modified strength of vortex particle
κ	Non-dimensional flow velocity
λ	Wavelength of the periodic flow
μ	Mass ratio
ν	Poisson ratio
ν_f	Kinematic viscosity
Ω	Angular velocity
Ω_F	Fluid domain
Ω_S	Structure domain
ρ_f	Density of fluid
ρ_s	Density of solid
σ	Standard deviation
θ	Wind angle of attack
Θ	Electromechanical coupling coefficient of piezoelectric beam
ξ_{z_i}	Non-dimensional position of a flow simulation slice
ζ	Structural damping ratio
ζ_e	Electrical damping ratio
Δs	Panel length
Δt	Time step
Δt_f	Time step of flow solver
Δt_f^*	Non-dimensional time step of flow solver
Δt_r	Particle release time step
Δt_s	Time step of structure solver
Δt_s^*	Non-dimensional time step of structure solver
Γ_p	Vortex strength

Latin Letters

$\boldsymbol{n}$	Surface unit normal vector
$corr$	Correlation coefficient
cov	Covariance
h	Thickness of a plate
$\boldsymbol{b}$	Right hand side vector
$\ddot{\mathbf{d}}$	Vector of nodal acceleration
$\dot{\mathbf{d}}$	Vector of nodal velocity
$\mathbf{d}$	Vector of nodal displacement

$\mathbf{f_{ext}}$	VecExternal force vector
$\mathbf{f}_g$	Global force vector
$\mathbf{f}_l$	Local force vector
$\mathbf{q}$	Modal displacement vector
$\mathcal{B}$	Transformation matrix
$\mathcal{B}, \Sigma$	Interface between fluid and solid region
$\boldsymbol{u}$	Velocity
$\boldsymbol{x}_{c_i}$	Control point of surface panels
$\boldsymbol{x}_p$	Particle position
$\boldsymbol{b}^{s}_{(t_n)}$	Right hand side vector for slice s at time t_n
$\boldsymbol{b}_{(t_n)}$	Right hand side vector at time t_n
$\vec{e}$	Element vector
$\vec{p}$	Panel vector
d_x, d_y, α_z	Nodal displacements and rotation
d_y	Vertical displacement at a location
$d_{y,t}$	Vertical tip displacement
F	Total normal fluid force on panel
f, f_r	Response frequency
F_n	Normal fluid force on panel n
f_n	Natural frequency of nth vibration mode
f_s	Vortex shedding frequency
h_s	Distance between two seeding points
l_d	Length of the domain
l_{coil}	Total length of the coil
l_{elem}	Length of beam element
n_i	Node numbers
n_s	Number of step for sampling
p	Pressure
p_i	Velocity monitoring points
p_{ax}, p_{ay}	Panel accelerations
p_{vx}, p_{vy}	Panel velocities
s	Slice number
t	Time
t_h	Thickness of harvester plate
t_n	Time at nth step
u	Longitudinal fluctuating velocity
u_m	Peak longitudinal velocity fluctuation
v	Velocity of nodal displacement
w	Vertical fluctuating velocity
w_d	Width of the domain
X, Y, Z	Spatial coordinates
x, y, z	Spatial coordinates
x_{g_i}, y_{g_i}	Position of grid points
$\bar{U}$	Mean longitudinal velocity
$\boldsymbol{\mathcal{M}}$	Influence matrix
$\boldsymbol{\mathcal{M}}_{(t_n)}$	Influence matrix at time t_n
$\tilde{\mathbf{P}}$	Modal force vector
$\mathbf{K_t}$	Tangent stiffness matrix
$\mathcal{R}e$	Reynolds number
$\mathcal{S}c$	Scruton number
$\mathcal{S}t$	Strouhal number
$\mathbf{C}$	Damping matrix
$\mathbf{K}$	Stiffness matrix
$\mathbf{M}$	Mass matrix
C_e	Electrical damping of harvester
$C_{e(crit)}$	Critical electrical damping
E	Modulus of elasticity
H	Height of a system
I_u, I_w	Turbulence intensities
L	Length of a system
M	Mass of tip magnet
NT	Number of time steps
P_e	Electromagnetic power output
P_p	Piezoelectric power output
R_C	Electrical coil resistance
R_L	Electrical load resistance
RT	Run-time of a simulation
U	Resultant velocity field
U_∞	Free stream velocity
U_x	Longitudinal flow velocity
U_y	Vertical flow velocity

$U_{\infty(cr)}$	Critical flow velocity
V_L	Voltage across load resistance
V_{oc}	Open-circuit voltage
W	Width of a system
$\boldsymbol{\mathcal{M}}^{s}_{(t_n)}$	Influence matrix for slice s at time t_n
$\boldsymbol{I}$	Induced velocity
$\tilde{\mathbf{C}}$	Modal damping matrix
$\tilde{\mathbf{K}}$	Modal stiffness matrix
$\tilde{\mathbf{M}}$	Modal mass matrix
A^{*}_{i}	Aerodynamic derivatives for aerodynamic moment
K_α	Rotational stiffness
M_α	Rotational mass
N_x, N_y	Number of grid nodes
N_{elem}	Number of beam elements
$N_{P_{cpl}}$	Calculated number of particles at each particle layer
$N_{pan(slice)}$	Number of panels per flow simulation slice
N_{panel}	Number of panels
$N_{particle}$	Number of particles
N_{slice}	Number of flow analysis slice
N_{rp}	Number of released particles

Acronyms

ALE	Arbitrary Lagrangian–Eulerian formulation
BEM	Boundary Element Method
CFD	Computational fluid dynamics
Eq.	Equation
FEM	Finite Element Method
Fig.	Figure
FRM	Flow reproduction method
FSI	Fluid–structure interaction
IB	Immersed boundary
LCO	Limit cycle oscillation
RMS	Root mean square
SCPP	Solar chimney power plant
SDOF	Single-degree-of-freedom
SHM	Structural health monitoring
VIV	Vortex-induced vibration
VPM	Vortex Particle Method
WSI	Wind–structure interaction
WSN	Wireless sensor networks

Chapter 1

Introduction

1.1 Background and motivation

Fluid–structure interaction (FSI) is a multiphysics study that focuses on the mutual dependence between deformable structure and surrounding or internal fluid flow. The flapping flag and the falling of a leaf are amongst the daily life FSI examples. FSI frequently encounters in many areas of civil, mechanical, aerospace and biomechanical engineering such as the aeroelastic phenomena in long-span bridges, tall towers, chimneys, and lightweight membrane systems, the motion of wind-turbine blades, the fluttering of aeroplane wings, the flow-induced vibration of marine risers, heat exchanger tubes, and the blood vessel dynamics, etc.

Structures under wind action can exhibit a variety of aerodynamic phenomena, which can lead to destructive and catastrophic events. Under specific wind–structure interaction (WSI) scenario, the aerodynamic forces can insert on a structure as a consequence of its motion, also known as self-excited forces, which cause aeroelastic instability. The incident that took attention of the bridge engineers worldwide is the historical Tacoma Narrows Bridge disaster (Fig. 1.1) in 1940, which was not entirely comprehended back at that time due to the lack of understanding of self-excited forces. Furthermore, three of a group of eight tall thin-walled cooling towers (375 ft high) collapsed in Ferrybridge/England in 1965 (c.f. Fig. 1.2), which

Figure 1.1: The Tacoma Narrows Bridge before (left) and after the collapse (right) (picture courtesy: University of Washington Libraries, Special Collections).

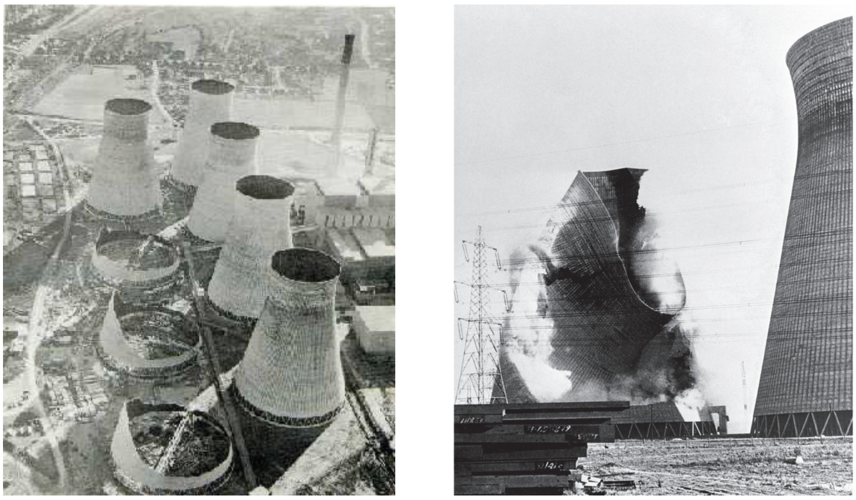

Figure 1.2: The collapse of three tall cooling towers in Ferrybridge/England (left), the moment of collapse of one tower (right) (picture courtesy: www.halinaking.co.uk).

was due to disregarding of wind action enhanced by powerful Kármán vortex street. Four towers which were on the windward side survived the wind action, but those behind were strongly affected by the vortices induced from the upstream bodies.

The design criteria of megastructures, such as long-span cable-supported bridges, super-tall buildings, towers and chimneys, large membrane roofs, are governed by the aeroelastic interaction phenomena. Advancement in computer-based numerical modelling as well as the improvement in the wind tunnel test aid to push the boundary limit of these structures. However, the desires to go beyond introduce explicit challenges for their safety and performances, mainly when they are in demand to be increasingly aesthetic and flexible. The vast majority of these structures are built in the atmospheric boundary layer, which implies that they are exposed to high turbulence flow and other effects of climate changes due to the surge of extreme events. Accurate prediction of WSI in the design process is crucial to avoid potential damage of important structures.

While the wind effects on civil engineering structures are of significant concern, the WSI has been used for large-scale wind power generation in many parts of the world. Due to the increasing demand for energy, Professor J. Schlaich of Stuttgart University proposed a solar chimney power plant (SCPP) in 1978 for solar-based electrical energy in the deserts. Conceptually, the efficiency of power generation depends largely on the chimney height and the enlargement of the heat collector area at the base. The feasibility studies on such large thin-walled chimneys proposed for different heights of 1000–1500 m and diameters of 120–170 m. Apart from several other critical design issues, such a tall vertical cantilever tower is strongly susceptible to aeroelastic buckling of thin shells. Accurate modelling and analysis of coupled behaviour have been a significant concern.

The application fields of WSI have not been limited to large-scale wind energy harvesting. In recent years, aeroelastic responses or limit cycle oscillation (LCO) of thin-plate systems have been converted to electrical energy. It has been an active research area of the last decade because of the boom in structural health monitoring, which is influenced further by the advancements in wireless sensor networks. The harvesters offer green power as an alternative to the traditional limited-life batteries, which can save maintenance costs, particularly for extensive network systems. However, the sustainable motion of aeroelastic energy harvesters is a prerequisite for energy extraction. Proper understanding of the aero-electro-mechanically coupled interaction of thin-walled harvesters is necessary for study on energy optimisation.

It is challenging to analyse FSI problems using analytical methods since they are intrinsically nonlinear and time-dependent. Experimental studies are always considered as a standard procedure; however, the advantages that make the numerical methods increasingly widespread are their ability to predict the full-scale aerodynamic behaviour, modelling of complex shapes, and detailed visualisation of interesting flow phenomena around bluff or moving flexible bodies. They hold further some preferred components, such as low cost and easy controlling of input parameters for fluid and structural models.

The numerical methods to solve FSI problems can broadly be classified as *monolithic* and *partitioned* based on the coupling algorithm. The monolithic algorithms solve the governing equations of fluid and structural dynamics simultaneously, and therefore, they are highly robust and stable. However, monolithic algorithms are computationally costly and require substantial expertise for code preservation. In contrast, partitioned algorithms are extensively used since they allow synthesizing independent computational schemes for the fluid and the structural dynamics subsystems. However, the stability of the coupled method requires special attention. With the advancements of the computational fluid dynamics (CFD) and computational structural mechanics, significant research on FSI has been performed. However, it is still challenging to answer many of the fundamental questions in FSI concerning appropriate coupling scheme, accuracy, robustness, performance, and applicability of the simulation techniques, which indicates the need for further developments.

The Vortex Particle Method (VPM) has been established as an accurate and efficient CFD simulation technique to model flow around complex geometries. The particle-based VPM has been a viable alternative to grid-based schemes for its strength in preserving rotational flow features, which drive separation, reattachment and vortex shedding behaviour. The existing FSI implementations of VPM, which are mainly in the context of two-dimensional (2D) and pseudo-three-dimensional (pseudo-3D) formulations, have successfully been used for the analysis of aeroelastic interactions of line-like flexible structures such as long-span cable-supported bridges and towers. The existing 2D VPM can perform FSI simulation of rigid cross-sections with 3 degrees of freedom only. The pseudo-3D VPM, as the name suggests, uses multiple slices of 2D VPM simulations along the longitudinal direction of the structure to represent the full-scale 3D FSI phenomena. Even though vortex methods have successfully been used for bluff-bodies and in bridge aerodynamics; there exist no noticeable contributions in VPM for FSI analysis of deformable geometry that can be widely accepted in practical applications. The possibility of analysing flow around thin-walled flexible bodies would allow VPM to investigate a new class of FSI problems such as the flow-induced bending of a thin-plate or the deformation of thin-walled shell structures.

1.2 Objectives, methodologies and contributions

The main objective of this study is to extend the applicability of VPM for coupled FSI simulations of thin-walled flexible structures under steady and fluctuating incoming flows. The initial task is to extend the 2D VPM such that the flow-induced large motion of flexible thin bodies can be analysed. The subsequent task is to extend the pseudo-3D VPM for multi-slice FSI analysis of shell-type systems. In addition to validation of the extended FSI models, it is important to demonstrate their suitability to different FSI problems and application field of thin-walled structures. The final and compelling task is to investigate the interaction between fluid and structure influenced by inflow fluctuations.

In this context, the flow around deforming thin bodies is to be analysed using the 2D and pseudo-3D implementations of VPM. The structural behaviour is modelled and analysed using the Finite Element Method (FEM). The partitioned numerical approach is considered because of the flexibility of using different mathematical procedures for solving fluid and solid mechanics. The advantage of VPM is that the method is primarily grid-free; there is no need for conforming of mesh at the interface of fluid and structure. The structural equations are formulated and analysed at the mid-surface of the thin element because of its efficiency of handling large deformation. It is important to note that the coupled numerical extensions are based on non-conforming mesh since the interface of fluid and structure is separate. The accuracy of such models largely depends on the appropriate projection of information from one interface to another and satisfaction of the required boundary conditions.

The interest of this study includes applying the FSI models under both laminar and fluctuating incoming flows. The VPM allows including vorticity carrying particles in the free stream flow, which can create flow fluctuations in the simulation domain while convecting downstream. Prior knowledge about the characteristics of the vortex particles is necessary to achieve the desired flow fluctuations.

This thesis separates the existing FSI models of VPM from the new contributions that allow the extended coupled methods to analyse FSI of thin-walled flexible structures. The latest advancements of the VPM, the governing equations of structural analysis, and the coupling of the fluid and structural models are explained in the same chapter (Chapter 4). The validation of the coupled methods and their application are presented in the next chapters for different FSI problems. Finally, the thesis presents two further numerical extensions of VPM that allow the modelling of inflow fluctuations along with their application in FSI simulations.

The numerical extensions, the methodology, and the contribution of this research are summarized as follows:

- A partitioned algorithm of 2D VPM for large-displacement FSI simulation of thin-walled flexible systems.

  It is a newly developed partitioned FSI model using 2D VPM. The model is implemented mainly for large-displacement coupled interactions of thin-plate systems. The 2D VPM with immersed interface technique is utilised for analysis of flow around deformable bodies; the method ignores across-flow effects. The 2D corotational finite element formulation is used to analyse the geometric nonlinear motion of thin-plate systems.

- A partitioned algorithm using pseudo-3D VPM for FSI analysis of linear shell-type structures.

  It is another new extension of VPM in the context of pseudo-3D multi-slice FSI analysis. Here, the structural equations are solved using superposition of uncoupled natural vibration modes, and therefore, the method is for linear structures. The novel contribution is the inclusion of 3D vibration modes of shell structures in contrast to the existing line-like structural model based on beam elements. This new extension allows simulating FSI problems of thin-walled shell structures such as large membrane roofs, tubes, towers, and chimneys, etc.

- A simplified aeroelectromechanical coupled model within the framework of 2D coupled VPM.