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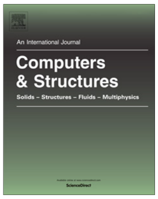

# Modeling of pulsating incoming flow using vortex particle methods to investigate the performance of flutter-based energy harvesters

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ABSTRACT

The paper presents a numerical technique within the framework of two-dimensional Vortex Particle Methods to simulate pulsating flow by seeding pre-calculated vortex particles into the free stream flow. The interest is to investigate the performance of small-scale flutter-based energy harvesters, particularly under low-frequency periodic incoming flows. The proposed numerical extension utilizes the natural convection of the particles, regularly seeded from two distant seeding points near the upstream boundary. The seeding mechanism and the orientation of the particles are handled such that they induce only horizontal velocity components around the domain center while the vertical components are nearly canceled out. The sinusoidal periodic flow is modeled by seeding the particles of varied strength and orientation, correspondingly. Convergence studies are performed to validate the scheme. The quality of the modeled periodic flows is assessed and quantified. Finally, the studies are carried out to investigate the dynamic motion of a reference T-shaped harvester under steady and periodic incoming flows. The initiation of unstable flutter response is observed earlier in case of periodic incoming flows. The response amplitude and the pattern of limit cycle oscillations are found to be depending on the combination of frequency and intensity of the periodic flow.

## 1. Introduction

The study of unsteady pulsating flow is of practical engineering importance especially in the field of turbo-machinery. The turbocharger turbine usually operates under heavy unsteady flow conditions due to the opening and closing of the engine valves. Therefore, the optimization of the engine performance, which is in terms of cost, fuel consumption, and $CO_2$ emissions, depends on accurate prediction of the compressor behavior under high-speed pulsating flow [1–5]. The importance of pulsating internal fluid motion in closed cylindrical channels have received widespread consideration to describe the dynamics of blood flow in the circulatory system [6–9]. Motivated by a new design of total artificial lung to provide better gas exchange, a fundamental study was performed in [10] to characterize the flow around an oscillating cylinder in a pulsatile flow environment. With an assumption of flow parallel to the pipe axis, Uchida [11] presented an exact solution of pulsating laminar flow superposed on the steady fluid motion in a circular pipe. The understanding of the characteristics of vibrations induced by the vortex shedding is of great importance in the design of marine risers [12,13] since they carry fluid flow in a pulsating manner. The flow around cylinders has always been a challenge, and it has been shown in the past that the pulsating flow has a significant influence on the vortex shedding and lock-on of cylindrical sections. Experimental studies were performed on a circular cylinder and blunt-faced flat plate in oscillatory flow, respectively, in [14,15]. The geometrical effects of the bluff-body in oscillatory flow was studied in [16]. The effects of the aspect ratio of a rectangular cylinder on lock-in characteristics in pulsating flow were studied in [17]. The effect of forcing amplitude on the locked-on wake of a circular cylinder in pulsating flow was studied in [18]. It was shown experimentally in [19] that the heat transfer from a square cylinder can be enhanced substantially by keeping the pulsating frequency within the lock-on regime.

This paper presents a numerical technique within the framework of two-dimensional (2-D) Vortex Particle Methods (VPMs) which allows the solver to model pulsating incoming flow by releasing pre-calculated vortex particles into the free stream flow. Fundamentally, the VPMs are based on the particle discretization of the vorticity field in a Lagrangian form of the governing Navier–Stokes equations. One of the major advantages that VPMs offer is the automatic adaptivity of the computational elements, i.e., the vortex particles. The proposed numerical scheme allows a regular release of the pre-calculated vortex particles, particularly

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near the upstream boundary from two seeding points which are separated by a particular distance across the flow direction. The particles convect downstream in the free stream flow, approximately in two parallel layers, and the imposed periodic variation of the seeded particle strength while convecting allows inducing the desired pulsating flow around the center of the simulation domain. The fact that facilitates the simulation of the pulsating flow is the seeding of a pair of particles, particularly at each release instant, in which the particles are of same absolute strength, however, of opposite rotational direction. It allows the cancellation of the velocity components across the flow direction whereas depending on the particle orientation the addition or the subtraction of velocity components along the flow direction, specifically around the center of the domain. The strength and the orientation of the particles are changed periodically to model the corresponding periodic variations in the horizontal velocity components. The time histories of the vortex particles, which are released from the particle seeding points, are calculated based on the target pulsating flow. The sinusoidal flow is modeled as a target flow to investigate the accuracy of the scheme. The modeled flow is monitored, and the quality of the flow field is assessed using statistical velocity profiles. The convergence studies are performed for the validation of the proposed method with respect to the number of seeded particles in the free stream to simulate the target signal. The sinusoidal flows of different frequency and intensity of flow fluctuation are modeled, and the critical conditions are identified for the limit of the scheme in application field.

The numerical analyses within this study have been carried out using a VPM based flow solver which has successfully been used for modeling and analyzing of flows past complex structural assemblies [20,21], and furthermore, the aerodynamics of long-span bridges [22–25]. The concept of seeding particles within the framework of VPM was introduced in [26,27] for modeling of 2-D unsteady wind. The particles were pre-calculated from statistically generated target wind field. The method was further employed in [28,29] for the simulation and estimation of the aerodynamic admittance in bridge aerodynamics. The particle seeding technique within the framework of the presented VPM based solver was shown in [30] for reproduction of a simulated flow field. The further extension of the solver in pseudo three-dimensional (3-D) context was shown in [31,32] for analyzing the aeroelastic response of bridges due to the turbulent wind. In contrast to the previous studies, in which the particles were seeded to model 2-D or 3-D turbulent flow field, the particles are seeded in this study to simulate periodic flow fluctuation, specifically along the flow direction.

The aim of the proposed numerical extension from an application point of view is to analyze the performance of small-scale flutter-based energy harvesters, especially under very low-frequency periodic incoming flows. Small-scale energy harvesting has been an active research area as the demand for renewable energy sources increases gradually. The recent advancement and the continuous reduction of the power requirement of wireless sensor networks (WSN) make them more attractive for structural health monitoring (SHM), and motivate the researchers to look for alternative energy sources to avoid the replacement of limited-life batteries. The conversion of mechanical vibration to electrical energy using an electromagnetic transducer or using piezoelectric patches are among the most studied cases, both experimentally and numerically [33–36]. Among different vibration sources, the use of wind-induced unstable vibrations of smart structural systems has gained significant attention in this application field. The instability phenomena such as galloping and flutter were shown for small-scale energy harvesting in many research using wind tunnel experiments and numerical analyses [37–43]. Flutter is a dynamic instability phenomenon of an elastic structure which is potentially destructive [44,45]. The sensitivity of T-shaped flexible cantilever beams to rotational flutter was exploited for extracting electrical power using an EM transducer in [46], and furthermore, the optimization of the harvester performance was shown in [47]. The efficiency of piezoelectric energy harvesting from the flutter-induced vibration of a T-shaped cantilever was shown in [48]. It is important to note that the instability-based harvesters are, most commonly, analyzed under steady incoming flows to estimate and optimize the harvester performance. However, the atmospheric wind field is turbulent in nature, and the structural systems immersed in such flow fields are supposed to face 3-D flow fluctuations of different frequencies. The fact is that the axial or the longitudinal flow generally governs the design of the instability based small-scale energy harvesters; the vertical flow fluctuations within limited turbulence intensity are often less sensitive to the onset flutter wind speed or the vibration system of a system based on flutter instabilities [49,50]. In different studies, the cases in which the vertical fluctuations and the angle of attack of the mean flow may influence the harvester response, the channelization of the incoming flow by using a funnel [51–53] was found to be helpful to enhance the harvester performance. However, the variation of the wind velocities along the flow direction is unavoidable. The periodic fluctuations along the flow direction, particularly of very low frequencies due to the large-scale eddies can influence the onset flutter wind speed as well as the amplitude of unstable vibration. The generation of very low-frequency periodic fluctuations in the wind tunnel is challenging. The numerical method is presented here, as an alternative solution, to simulate flow fluctuations along the flow direction to study the performance of flutter-based harvesters under pulsating incoming flow. The performance of a reference T-shaped flutter based harvester, which was studied in [46], has been investigated. The influence of the frequency and the intensity of velocity fluctuation on the harvester response has been analyzed, and the outcomes are compared with the responses under steady flows.

This article is organized as follows. A new numerical extension of VPM is proposed to simulate pulsating flow. At first, the mathematical background behind the proposed numerical scheme including the applied assumptions is discussed. The method is applied to simulate a target sinusoidal flow fluctuations. The quality of the modeled flow field is assessed and compared to the target flow. Furthermore, the convergence studies are performed to validate the method. This is followed by the analysis of a T-shaped flutter-based harvester under low-frequency periodic inflow condition. The performance of the harvester under pulsating inflow condition are compared against the steady inflow condition. Summary, final remarks, and scope for further works conclude this article.

## 2. A proposed numerical technique for simulation of synthetic pulsating flow

In the following the new extension of the 2-D Vortex Particle Method (VPM) has been presented for simulation of pulsating flow synthetically. The governing equations of the flow solver and different existing extensions are discussed briefly. Furthermore, the formulation of the proposed numerical scheme and the particle seeding mechanism behind the modeling of the flow pulsation are discussed.

### 2.1. Vortex Particle Method

The numerical method VPM is based on the simplified vorticity description of the fundamental Navier–Stokes (NS) equation. The vorticity $\boldsymbol{\omega}$ is the curl of velocity field $\boldsymbol{u}(\boldsymbol{x}, t)$ of a flow, such that

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