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Hydrodynamics of Vibrating Perforated Plates

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HYDRODYNAMICS OF VIBRATING PERFORATED PLATES

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Abstract

The objective of this Ph.D. project is to study the hydrodynamic response of oscillating perforated plates by utilizing analytical and numerical methods. Specifically, we will examine whether the permeable plates offer superior hydrodynamic stability than their impermeable equivalents. First, we will computationally investigate the linear hydrodynamic response of vibrating perforated plates in an unbounded domain in the asymptotic limit of small Keulegan-Carpenter number, i.e., KC $\to 0$. We will simulate various porosities and aspect ratios for a wide range of oscillatory Reynolds numbers (denoted by β) and seek to draw a comparison between our findings and the analytical works. Next, we will study the confinement effects on the hydrodynamic performance of permeable plates, again in the linear regime. To this end, we will analytically derive the expressions for the added mass coefficient C_a and damping coefficient C_d for two types of bounding surfaces: liquid-gas interface and solid wall. We will also corroborate our analytical work with follow up numerical simulations. Finally, we will develop a theoretical-computational framework to study the effects of finite KC. We will summarize our findings in the form of performance regime charts.

Chapter 1: Introduction

The central goal of this Ph.D. research is to examine the hydrodynamic performance of oscillating perforated disks (see Fig. 1.1). The proposed study is motivated by the fundamental premise that permeable objects can significantly outperform their impermeable counterparts when used as dampers to attenuate undesirable external perturbations. We predict that modest adjustments in the permeability of solid dampers can lead to considerable improvements in their hydrodynamic characteristics, without compromising their structural integrity. To test this hypothesis, we propose a combined theoretical and computational study of the interaction of fluid flows with periodically moving permeable plates.

Deep-water floating structures such as offshore platforms are susceptible to resonant oscillations induced by incident waves. These violent vibrations can cause structural damages and often lead to excessive downtime and poor overall performance. A common approach to mitigate these adverse oscillations is using drag-augmenting surfaces known as heave plates. Additional damping (and also added mass) provided by the plates enhances the dynamic stability of the floating structures. This project is dedicated to uncovering the true potential of permeable objects as hydrodynamic stabilizers when subject to broadside oscillations. In subsequent paragraphs, we will discuss the salient features of the problem in hand.

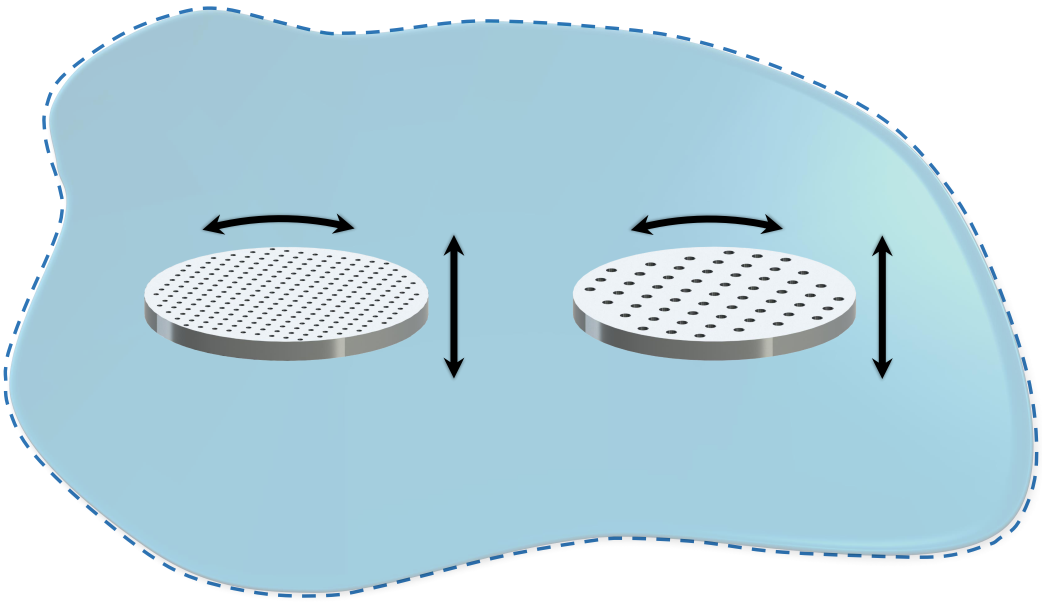

Figure 1.1: Perforated disks of identical porosity (but different pore size) separately undergoing periodic oscillations in an unbounded fluid domain.

The hydrodynamic response of oscillating bodies is governed by two independent non-dimensional parameters: Keulegan-Carpenter number KC which characterizes the amplitude of oscillations, and oscillatory Reynolds number β which effectively represents the frequency of oscillations. For a disk of radius a oscillating with amplitude A at frequency ω in a fluid with density ρ and viscosity μ, we have

$$\mathrm{KC} = \frac{\pi A}{a} \qquad \text{and} \qquad \beta = \frac{\rho a^2 \omega}{\mu}.$$

Product of these two dimensionless quantities is the Reynolds number$\mathrm{Re} = \beta \mathrm{KC}$. In physical terms, Keulegan-Carpenter number is a major contributor to the advective transport of momentum, while β acts as a knob for switching between viscous to inertial regimes.

Generally, the hydrodynamic force acting on a vibrating object, if harmonic, can be decomposed into two components. The component of the force in phase with the acceleration

is denoted as the added mass coefficient C_a, whereas the component in phase with the velocity is called the damping coefficient C_d. Average power required to sustain the vibration of the object is proportional to the damping coefficient only and hence determine its hydrodynamic stabilizing capability. When the hydrodynamic force signal is under the influence of multiple harmonics, a linear combination of C_a and C_d no longer represents the total force, in which case, the average power determines the damping potential of the vibrating body.

Under similar KC and β, hydrodynamic coefficients, C_a and C_d, also depend on the porosity, distribution and shape of the pores, and thickness of the permeable object. In this Ph.D. research, we will analytically and computationally investigate the effects of KC and β on the hydrodynamic coefficients of vibrating perforated plates. We will cover a wide range of β and low to moderate values of KC. We will also examine the influences of porosity, pore geometry and distribution as well as the aspect ratio of the plates on the hydrodynamic response of the plates. Both unbounded and confined domains will be considered in our analyses. Overall, the results of our studies will provide a fundamental understanding of the hydrodynamics of oscillating permeable objects, which is critically needed for unlocking the untapped potential of porous heave dampers. The knowledge gained upon successful completion of this project will pave the way for designing more effective stabilizers for deep-water floating devices including wave energy converters (WECs) [1] and floating offshore wind turbines [2].

Chapter 2: Prior Studies and Knowledge Gaps

Hydrodynamics of oscillating impermeable objects has been an important research domain over a century or so. For instance, in the mid-19$^{\text{th}}$ century, Stokes [3] theoretically solved the problem of an impermeable sphere oscillating in an unbounded fluid domain. Later, more studies followed [4–20] that developed the theoretical framework for different basic geometries. On the experimental front, plenty of resources were dedicated to investigate the hydrodynamic interactions during the oscillation of blunt bodies. A few noteworthy examples are Refs. [21–26]. The evolution of studies focused on the hydrodynamics of impermeable oscillating objects is well summarised in Refs. [27–29].

While the fluid-submerged oscillating impermeable objects were given due academic attention, their permeable counterparts were largely remained unexplored, despite their relevance in applications ranging from the design of hydrodynamic stabilizers [30], aerodynamics of insects flight [31], and bio-inspired robots [32] to oscillatory rheology of porous-particle suspensions [33], energy management of heat exchangers [34], and vortex induced vibrations [35]. Few theoretical and experimental studies were carried out in recent years seeking to understand the hydrodynamics of permeable objects in broadside oscillations. A closer inspection of the literature reveals an astonishing outcome which is the core motivation of

this project: permeable objects can outperform their impermeable counterparts as hydrodynamic dampers. However, very little is known about the underlying mechanisms for the hydrodynamic performance of permeable objects. Below, we summarize the literature and will pinpoint the unanswered questions.

Analytical investigations [30,33,36–44] are mainly focused on the limits of infinitesimally small amplitude and thickness for basic shapes. The derivations are made possible through the use of the concept of permeability instead of the more realistic parameter of porosity. Numerical studies, on the other hand, rely primarily on the potential flow theory as a leading-order approximation but they do resolve the flow through pores. However, in both analytical and numerical settings, the effects of flow separation from edges and vortex shedding are either ignored or accounted for empirically.

Experimental studies [37,39,45–54] are cheifly concerned with porous plates (square and circular) of small aspect ratios. Most of the works deal with porosities below 20% with the exception of Ref. [50], where porosities up to 62% were considered. These studies are carried out for small to moderate amplitudes of oscillations, with KC ranging from 0.1 to 1.2. The only exception is, again, Ref. [50], where KC values as high as 17 were tested. The oscillatory Reynolds number β in the above-referenced studies is found to be in the range of $10^4 - 10^5$. To the best of our knowledge, the effects of pore distribution and shape, aspect ratio, and confinement on the hydrodynamics of oscillating for porous plates have been reported only in a couple of studies [39,55], where very limited scenarios were examined. Despite being extremely valuable, experiments have been noted to suffer from some drawbacks including

(i) data corruption at small amplitudes due to the vibrations of the driving mechanism for the vibrations, (ii) unwanted confinement effects due to the finite size of the test environment, and (ii) extraneous fluid-structure interactions stemming from the submerged components of the experimental setups (see e.g. [21,22,46]).

Overall, a review of the existing literature suggests that porous permeable objects offer greater hydrodynamic damping than their solid impermeable equivalents. However, there is no consensus as to what porosity offers the greatest increase in damping coefficient C_d. Hence, there is a need to analyze this problem systematically, considering the effects of porosity, pore radius, pore distribution, aspect ratio and confinement. This holistic approach can reveal the true potential of porous plates as superior heave dampers.

Chapter 3: Research Objectives

The overarching goal of this PhD project is to examine the hydrodynamics of broadside oscillating permeable plates by using analytical and computational methods. The following interrelated tasks articulate how this objective will be achieved. Table 3.1 shows the proposed timeline for the specific tasks listed below.

Task 1: ***Characterize the linear response of porous disks vibrating in unbounded domains***

This task is a realistic extension of the analytical works that dealt with the small amplitude oscillations of permeable objects in unbounded domain. Here, we will use finite-volume-based numerical simulations to solve for the flow inside the pores of oscillating circular disks. The computational domain will be selected such that the boundary effects are negligible. The amplitude of oscillations will be kept very small compared to the radius of the disk such that

Research tasks	2021–2022	2022–2023	2023–2024
Task 1	■		
Task 2		■	
Task 3			■
Task 4		■	■

Table 3.1: Timeline for the proposed studies.

the hydrodynamic fluid-structure interaction follows the linearized Navier-Stokes equations. The radius of the disk will be chosen such that it is much greater than the radius of the pores. Having fixed these parameters, we will vary the frequency of oscillations and calculate the added mass C_a and damping coefficient C_d of porous disks. We will also consider porous disks of different aspect ratios to probe the effect of thickness on the hydrodynamic coefficients. Another milestone of this task will be to understand the effect of pore radius and pore distribution on C_a and C_d. Our efforts towards achieving the goals of this task has already begun and the results obtained so far are presented in the next chapter.

Task 2: ***Linear response of vibrating porous disks subject to confinements***

Building on to the foundation set by the results of Task 1, the aim of this task is to fundamentally understand the effect of confinement on the hydrodynamic performance of oscillating

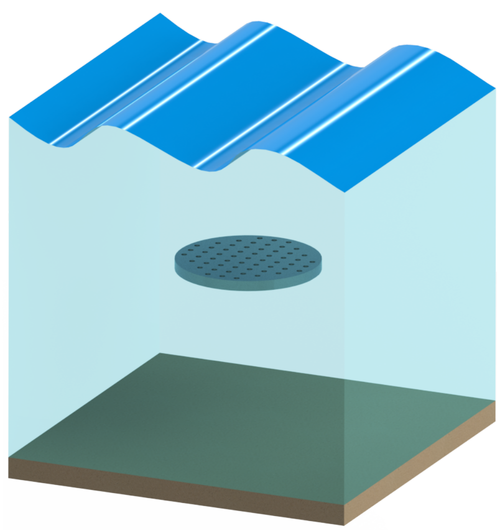

Figure 3.1: A liquid-submerged porous disk confined by a liquid-gas interface from above and a solid wall from below.

perforated plates. We will consider two types of bounding surfaces: liquid-gas interface and solid wall (see Fig. 3.1), again in the limit of small oscillation amplitude. The analyses will be carried out using analytical calculations and numerical computations. For the former, we will apply the image approach [56] and the method of reflections [57]. As for the latter, we will utilize the Volume of fluid (VOF) method as implemented in OpenFoam.

For the sake of completeness, we will consider three scenarios. The first two will involve either a free surface or a solid wall, whereas the third one involves both types of boundaries (see Fig. 3.1). We will systematically change the location of the disk relative to the boundaries and compare the results with the trends predicted by the theory. It is challenging to speculate as to what the results will reveal, but it will be certainly curious to know if porous plates can outperform their impermeable counterparts even under confinement. Either way, our findings will be of great practical use as confinements are usually unavoidable in real systems.

Task 3: *Investigate the non-linear response of oscillating permeable disks*

Having studied the linear response of perforated plates oscillating in unbounded and bounded domains, in this task, we will concentrate on the effect of finite oscillation amplitude, where non-linearities arise due to more vigorous vortex shedding from the edge of the disk and due to the advective transport of momentum that no longer can be ignored. On the theoretical front, we will use a regular perturbation expansion in terms of the dimensionless amplitude to obtain the leading-order correction to the hydrodynamic force on the vibrating porous disks

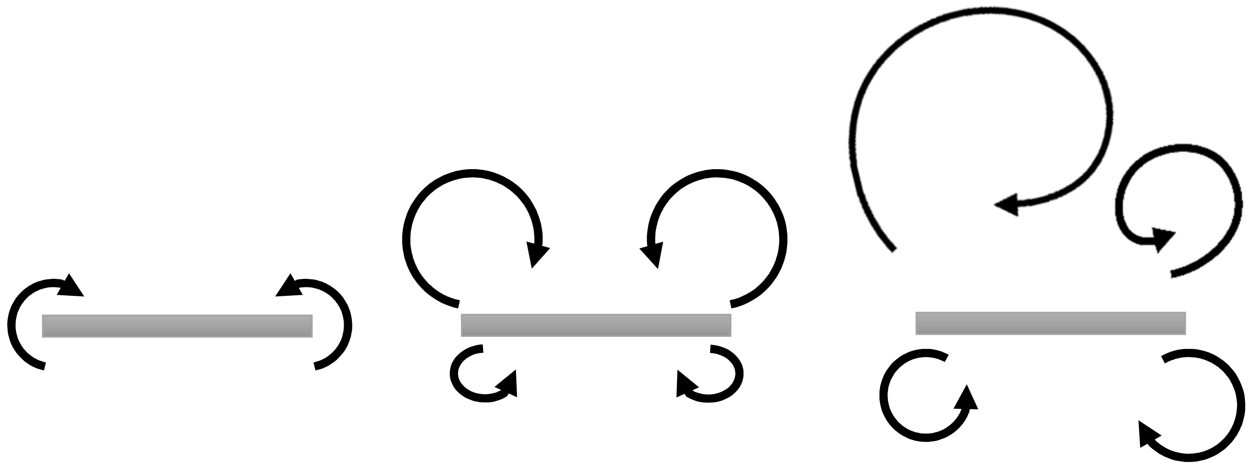

Figure 3.2: Schematic depicting the expected evolution of the vortical structures around the disk (gray rectangle) as the oscillation amplitude increases from the left to the right.

of the previous section. The theoretical results are predicted to be valid for low to moderate amplitudes. We will also perform simulations, where various oscillation amplitudes ranging from the small value all the way up to the radius of the disk will be tested.

At low to moderate amplitudes, we anticipate the force response to remain fairly harmonic. This means that, while being non-linearly dependent on the amplitude, the definitions of the damping and added mass coefficients, in this regime, will still follow the in-phase/out-of-phase decomposition used in Tasks 1 and 2. As the amplitude increases more, however, multiple harmonics are expected to emerge. Symmetry breakings and chaotic dynamic behaviors are also likely to occur following a further rise in the amplitude (see Fig. 3.2). We will identify under what conditions the transition between these distinctly different regimes takes place. In addition, when the force response is no longer harmonic, we will monitor the average power consumption to evaluate the damping performance of the plates.

Task 4: ***Develop performance regime maps***

With all of the results from the theoretical analyses and numerical simulations in Tasks 1-3, we envision organizing them in regime maps for the damping and added mass coefficients. The maps are intended to provide a distilled version of massive information gathered during the course of the project. We will report the results for C_d and C_a on two dimensional plots of porosity versus dimensionless frequency. Both coefficients will be normalized by their corresponding values for impermeable disks. The diagrams will be made for various aspect ratios, pore distributions and different ratios of the oscillation amplitude to the disk radius.

Chapter 4: Preliminary Results

In this chapter, we present our preliminary findings towards fulfilling the goals of Task 1. We begun our investigations by considering small amplitude broadside oscillations of permeable circular plates in an unbounded domain. The heaving velocity of the disk was set to $U = -A\,\omega\cos(\omega t)\,\boldsymbol{e}_z$, where $\boldsymbol{e}_z$ is the unit vector in the z direction of (x, y, z) coordinates. To avoid dynamic meshing in our simulations, we chose to express the Navier-Stokes equations in a non-inertial reference frame fixed to the disk as

$$\rho\left(\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u}\cdot\boldsymbol{\nabla}\boldsymbol{u}\right) = \mu\nabla^2\boldsymbol{u} - \boldsymbol{\nabla}p - \rho\,\frac{dU}{dt}\,\boldsymbol{e}_z \qquad \text{and} \qquad \boldsymbol{\nabla}\cdot\boldsymbol{u} = 0 \tag{4.1}$$

where $\boldsymbol{u}$ and t represent the fluid velocity field and time, respectively. Also, we assumed that the fluid is initially at rest, and that it obeys the no-slip condition on the disk. Furthermore, to effectively model an infinite fluid domain, the outer boundary of the computational domain was set to a large cylinder, symmetrically encompassing the disk. Proper inlet, outlet, and zero-gradient boundary conditions were applied to top, bottom, and side surfaces of the outer boundary.

Equation (4.1) was numerically solved using a second-order finite-volume method as implemented in *OpenFOAM* [58]. In our numerical calculations, the Laplacians and gradients were discretized via the second-order linear Gaussian integration, the corrected scheme (with

the number of corrections set to two) was used to calculate surface normal gradients, and the time derivatives were approximated by the second-order backward differentiation formula. Also, the PIMPLE algorithm was employed to treat the pressure-velocity coupling, the linear solver GAMG (Geometric-Algebraic Multi-Grid) with DIC (Diagonal Incomplete-Cholesky) preconditioner was used to solve for the pressure field, and the Gauss-Seidel method was utilized to calculate the velocity field. Moreover, the flow domain was discretized using tetrahedral elements, where the space in the vicinity of the disk was further resolved through a boundary layer mesh (adjusted for different values of β) to better capture the velocity gradients. Domain size, grid independence, and time step resolution tests were performed to ensure accurate results.

Specifically, we simulated flow through and around oscillating disks with porosities and aspect ratios ranging from 0% to 30% and 5% to 25%, respectively. The pore distribution and number of pores were kept the same for all porous plates, while the pore radius was altered to achieve the desired porosity. The amplitude of oscillations was set at $A = 10^{-3}a$ and the oscillatory Reynolds number β was varied from 10^{-2} to 10^{6}. Amplitude independence tests were performed to ensure the insignificance of non-linear effects. Lastly, cycle-averaged hydrodynamic force coefficients were extracted by the method of least squares once a periodic steady-state was reached.

The results of our simulations are presented in Figs. 4.1 and 4.2, where the added mass and damping coefficients of porous disks are normalized by their impermeable counterparts

and presented. In short, we learn from these figures that permeable disks behave as their impermeable counterparts at small and intermediate values of the oscillatory Reynolds number β, with the effect of thickness being relatively negligible. As β transitions to higher values ($\mathcal{O}(10^2)$ and beyond), the added mass coefficient decreases monotonically with increasing the porosity, whereas the damping coefficient initially rises with the porosity, then reaches a maximum, and finally declines with further increasing the degree of perforation. In this regime, we observe modest improvements of both added mass and damping coefficients for thicker disks. These findings provide new insights into the role of porosity in the dynamic response of perforated disks.

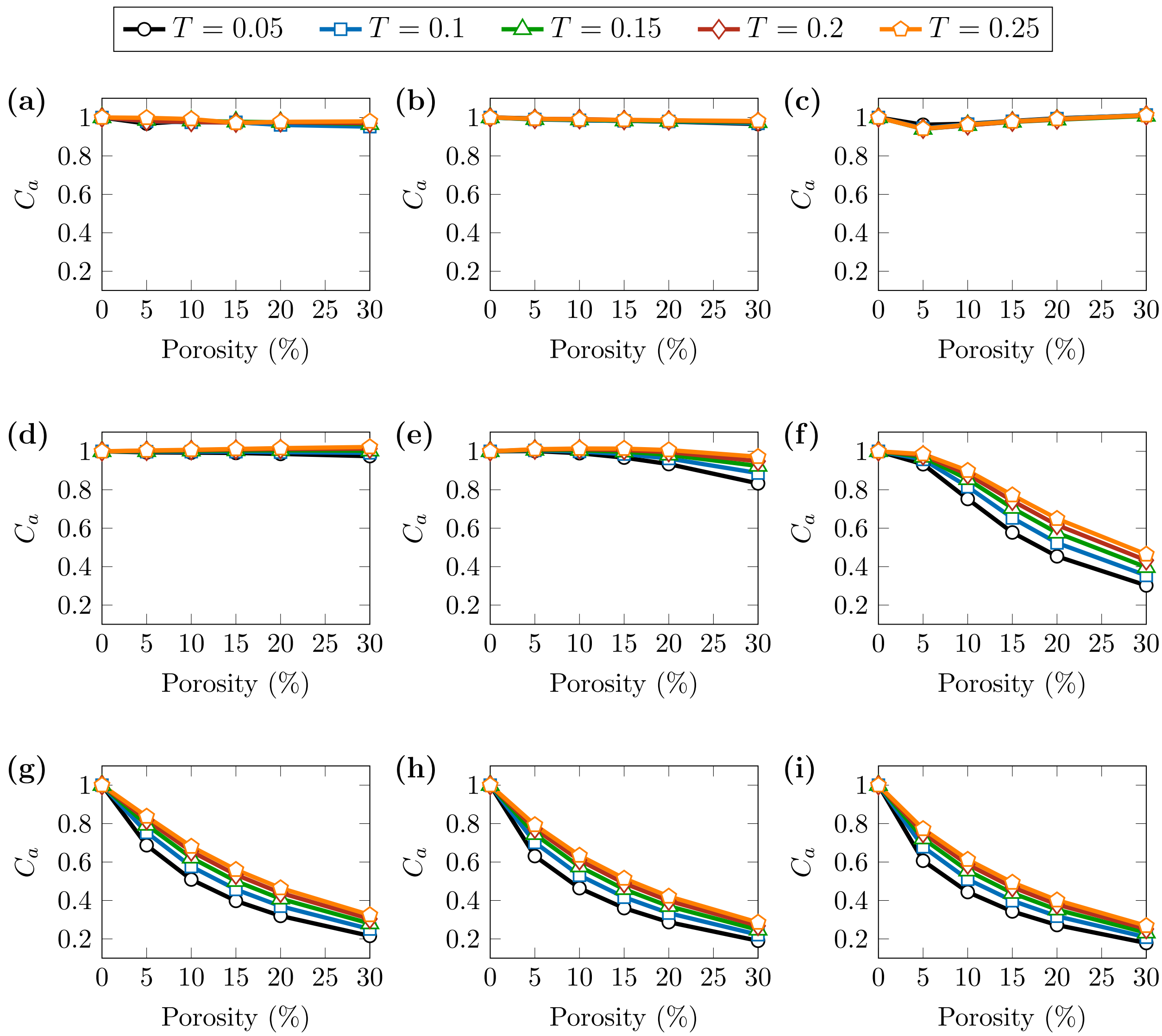

Figure 4.1: Normalized added mass coefficient C_a versus porosity for disks with various normalized thickness T. Subfigures (a) to (i) correspond, respectively, to oscillatory Reynolds number $\beta = 10^{-2}, 10^{-1}, \cdots, 10^{6}$.

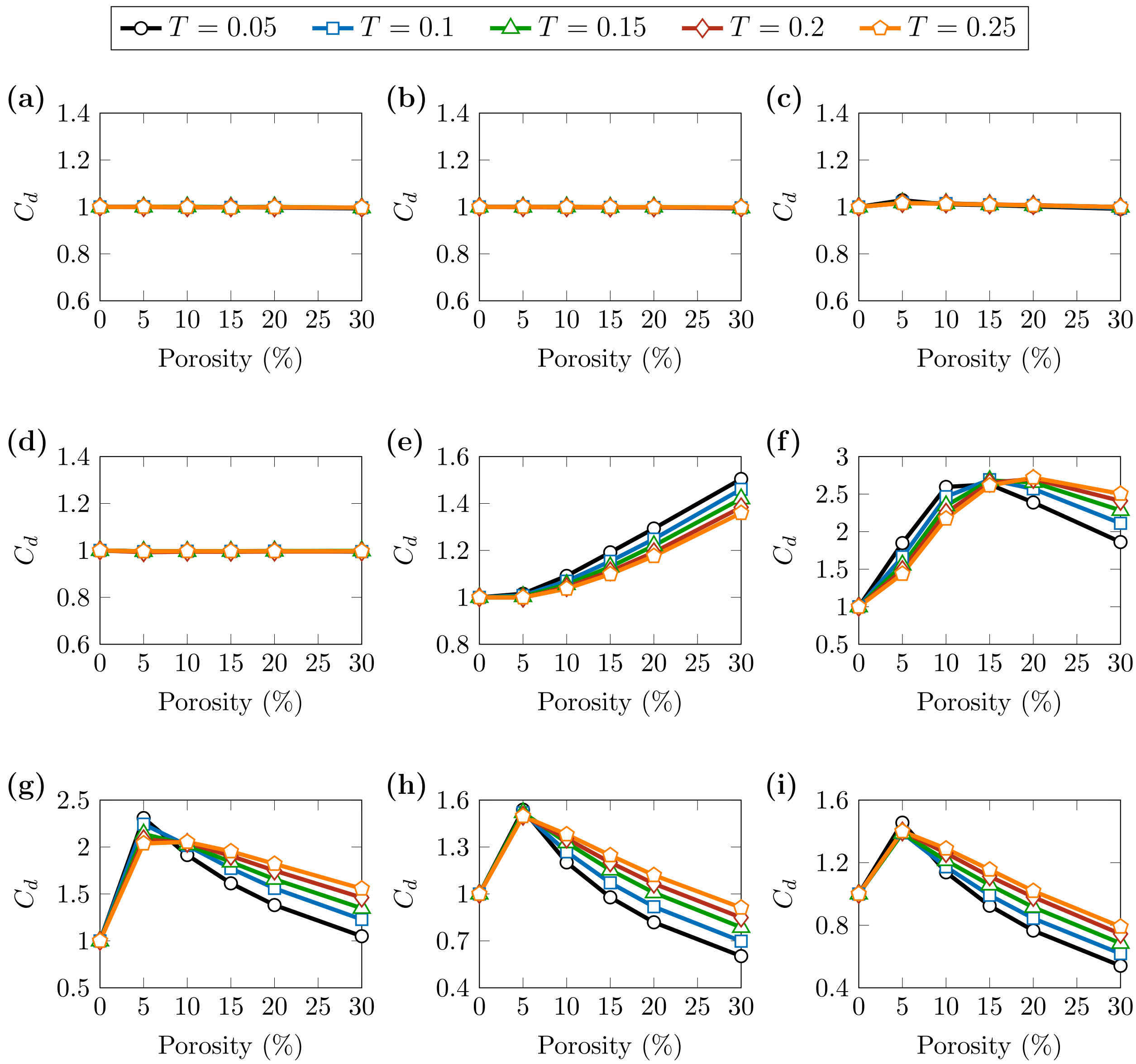

Figure 4.2: Normalized damping coefficient C_d versus porosity for disks with various normalized thickness T. Subfigures (a) to (i) correspond, respectively, to oscillatory Reynolds number $\beta = 10^{-2}, 10^{-1}, \cdots, 10^{6}$.

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