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Edge clearance effects on the added mass and damping of beams submerged in viscous fluids

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A B S T R A C T

Submerged structures that vibrate with a free boundary in close proximity to a comparatively rigid wall are commonly found in engineered systems. The confinement of the fluid in the gap can strongly influence the fluid added mass and damping associated with the structural vibration. Here, this influence is studied for submerged slender beams vibrating parallel to a wall, with small clearance between a lengthwise edge of the beam and the wall. The fluid–structure system is modeled using the Fourier transformed Stokes equations in two dimensions for incompressible viscous fluids. Added mass and damping are calculated with the use of a hydrodynamic function across a large range of Reynolds numbers and edge clearances. Relative to a previously studied case in which beams vibrate transversely to a rigid wall, the effects of the clearance gap in the present configuration — while significantly milder — are also more complicated. The results indicate that for a given Reynolds number, there is often a discrete gap height that maximizes fluid added mass or damping. This is in contrast to many other configurations where added mass and damping increase monotonically for fixed Reynolds number and increasing fluid confinement. A high-order polynomial is fit to the numerical results to facilitate their practical use. Experiments conducted in both water and vegetable oil validate the theoretical results across a wide parameter space.

1. Introduction

Natural frequencies of structures vibrating in fluids are lower than corresponding *in vacuo* natural frequencies due to the entrainment of fluid mass. Fluid-loaded natural frequencies are typically predicted by including a fluid added mass component in the representation of the system's mass. If the fluid is assumed to be inviscid and incompressible, potential flow theory can be used to calculate the fluid added mass for a variety of common structural cross-sections (Blevins, 2016; Naudasher and Rockwell, 2012). When a submerged structure vibrates in close proximity to a rigid surface, the entrained fluid is forced to assume high velocities in the confined domain. This leads to larger fluid kinetic energies, which translate to higher fluid added mass. Potential flow theory has also been used to predict confinement effects for a number of configurations of practical interest (Blevins, 2016; Naudasher and Rockwell, 2012). Confinement effects can also be modeled via structural-acoustic analyses that treat the fluid as inviscid and compressible (Valentín et al., 2014a, b; Bossio et al., 2017; Davis, 2017).

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Nomenclature

A	Fluid added mass
b^*	Beam width
C, C_b, C_w	Integral contours: general, along beam, along wall
E	Young's modulus
F	Non-dimensional hydrodynamic force
f	Beam natural frequency
G	Green's function for the Laplace equation
h^*	Beam thickness
K	Modified Bessel function of the third kind
l^*	Beam length
l_w	Extent of the wall
m	Order of the Gauss–Legendre quadrature
N	Number of integral segments
n	Differentiation normal to the fluid boundary
P^*, p	Dimensional, non-dimensional pressure
Δp^b, p^w	Pressure across the beam, at the wall
$\Delta \bar{p}^b$, $\bar{p}^w$	Numerical integral elements of the pressure across the beam, at the wall
R	Non-dimensional distance between two points
Re	Reynolds number
t	Differentiation tangential to the fluid boundary
$\mathbf{u^*}$	Velocity field
u, v, u^*, v^*	Dimensional, non-dimensional velocity of the fluid
V_b	Non-dimensional velocity amplitude of the beam
$\dot{w}$	Transverse velocity of the beam
y_j	Uniformly spaced segment boundaries
z_j	Non-uniformly spaced segment boundaries
α	Added mass correction factor
Γ	Hydrodynamic function
γ^*, γ	Dimensional, non-dimensional vorticity of fluid
$\Delta\gamma^b$, γ^w	Vorticity over the beam, at the wall
$\Delta\bar{\gamma}^b$, $\bar{\gamma}^w$	Numerical integral elements of the vorticity across the beam, at the wall
δ^*, δ, δ_{cr}	Edge clearance: dimensional, non-dimensional, non-dimensional clearance gap that maximizes the real or imaginary part of the hydrodynamic function
ζ	Viscous damping
η^*	Viscosity of the fluid
Θ	Green's function for transformed unsteady Stokes equations
ν	Poisson's ratio
ρ_f^*, ρ_s^*	Density: fluid, structure
ψ	Fluid stream function
Ω	Green's function for the Helmholtz equation
ω^*	Oscillating frequency of the beam

Subscripts

$_a$	Value in air
$_g$	Value with edge clearance
$_i$	Imaginary pert
$_l$	Value in fluid
$_r$	Real part
$_v$	Value *in vacuo*

Superscript

^{exp}	Experimental value

Classical fluid added mass solutions typically assume inviscid fluid. Accounting for the effects of viscosity complicates the analysis, but including viscosity is essential to predicting fluid added damping and can be important when calculating fluid added mass in confined and/or low-to-moderate Reynolds number configurations. One such configuration that has yet to be studied in detail involves submerged beams oriented edgewise near rigid walls. This configuration is relevant to the