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An experimental study on axial-flow-induced vibration of confined flexible rods with sequenced transverse rib roughness

Y. Perets[a,c,*], E. Sher[b], R. Harari[c]

[a] Department of Mechanical Engineering, Ben-Gurion University of the Negev, Beer-Sheva, Israel
[b] Faculty of Aerospace Engineering, Technion – Israel Institute of Technology, Haifa, Israel
[c] Nuclear Research Center-Negev (NRCN), Beer-Sheva, Israel

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ABSTRACT

Experiments were conducted with the aim of studying the dynamic behavior of vertical flexible silicon rods with clamped ends and different sequenced transverse rib roughness along their length. The rods were subjected to confined axial flow. In general, the rods have similar characteristics regarding their spatial oscillation with varying dimensionless flow velocities. Dynamic instability via high-mode flutter developed at a high flow velocity, which is characterized as a clockwise whirling motion of the first to the fourth modes. The transition from lower flutter mode to higher flutter mode was accompanied by a wave that traveled along the rods. Finally, high flow velocities led to a chaotic motion in all the rods. In this article, the onset of rod instability for the rib-roughness rods is considered the beginning of the first-mode clockwise whirling motion, unlike the onset divergence that appears on a smooth- surfaced rod with no ribs. The experimental results revealed that there is a non-negligible dependence between the ribs' pitch ratio and the critical flow velocity value at the onset of rod instability, which the rod destabilizes by increasing the friction factor according to the rib optimum pitch geometric at $p/e \cong 8$.

1. Introduction

Vibrations induced by axial fluid flow occur in many industrial applications, for example, in pipes that convey fluids and heat exchangers in chemical industries, the drill string in oil industry, and in nuclear power plant industries such as fuel rod assembly. Awareness of axial-flow-induced vibrations (FIV) has gradually increased in the last six decades through the experience accumulated in nuclear power plant industries. Axial-flow-induced vibration causes malfunctions in long-term service that arise from small-amplitude vibrations, which generate a periodic impact between adjacent structure components and can induce failures such as fatigue and fretting wear [7]. In nuclear power plants, failures due to FIV can result in serious consequences for critical components, such as fuel rods and heat exchangers, often involving extended shutdowns and high repair costs [20,18]. An additional reason for the increased interest in axial-flow-induced vibration is that designers stretch structure limits, causing structures to become progressively lighter and more slender because of the requirement to increase fuel efficiency; subsequently, the fuel rods become more flexible and can eventually overwhelm the structure's stiffness due to fluid elastic instability.

The dynamic characteristics of cylinders subjected to axial flow have been studied both theoretically and experimentally. Early on, theoretical models were developed using linear techniques [13,15] and later, a nonlinear model was suggested by Lopes et al. [8]. Both models were accompanied by experimental studies [14,19] in order to validate the results for each of them. A series of experiments [14] was conducted using a closed-loop water system with a horizontal test section. Different cylinders made of silicon rubber were placed inside the test section according to the boundary conditions for examination – simply supported and clamp-free (cantilevered) ends. The cylinders' oscillations occurred in a planar motion because metal strips were attached to it along its length. The dynamics of these cylinders were studied by increasing the axial flow velocity and methodically examining the effects of variations in the various system parameters on the cylinders' dynamics. The parameters included mass ratios, slenderness, surface roughness, and shape of the free-end cantilevered cylinder. For both boundary conditions, the main results show that with small-flow velocity, vibrations induced by small random flow fluctuation were damped. At a certain flow velocity, the onset of divergence (buckling around the cylinder's static equilibrium) occurred and when the flow velocity was increased further, a second-mode flutter developed

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[*] Corresponding author at: Department of Mechanical Engineering, Ben-Gurion University of the Negev, Beer-Sheva, Israel.
E-mail addresses: yaronprts@gmail.com, peretsya@post.bgu.ac.il (Y. Perets).

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Nomenclature

A	cross section
b	rib width
C_D	drag coefficient
C_N	normal viscous force coefficients
C_f	skin friction coefficient
C_T	tangential viscous force coefficients
D	test section inner diameter
d	rod diameter
d_{in}	inner rod diameter
d_{out}	outer rod diameter, $d_{out} = d_{in} + 2 \cdot e$
E	Young's modulus
e	rib height
f	frequency
f_i	eigenfrequency of the i mode (i = 1, 2, …n)
f_{0i}	natural frequency of the rod in still water (i = 1, 2, …n)
I	moment of inertia
L	length of test section
L_r	rod length
M	rod mass per unit length
P	rib pitch
Re	Reynolds number
U	dimensional flow velocity
U	non-dimensional flow velocity
X_{rms}	RMS amplitude
x	axial coordinate
y	transverse displacement
μ	dynamic viscosity
ρ	water density
ρ_r	rod density
$\dot{()}$	differentiation with respect to time

(oscillatory instability). Païdoussis's [14] experiments showed a slight effect of surface roughness on the cylinders' dynamics, which is reflected in the small effect on the stabilization of flutter. According to Païdoussis [14,17], with slenderness ratios $\varepsilon = L_r/d$ (length to diameter ratio) above 24, divergence did not arise, and with ε above 40, no flutter occurred.

Later experiments [19] were performed in a vertical test section with vertical cantilevered cylinders and no metal strip, as in the earlier experiments, in order to allow spatial motion. In general, these experiments' results produced dynamic characteristics similar to those in the earlier experiments: a cantilevered cylinder with a well-streamlined free end loses stability by divergence, and when flow velocity is further increased, the cylinder loses stability by second-mode flutter and then by third-mode flutter, which are reflected in the power spectral density (PSD) spectrum by second-mode and third-mode dominance, respectively. Nevertheless, the flutter appeared as an orbital motion. With a blunt downstream free-end cylinder, instability did not arise.

Modarres-Sadeghi et al. [12] conducted experiments with vertically supported cylinders, clamped-end cylinders, and a clamped-sliding cylinder to accompany their nonlinear theoretical model [10–11]. The onset of divergence arose in all experiments. However, the loss of stability by flutter in its second mode was observed only for a very slender, hollow cylinder used in the third series of experiments and appeared only for a small range of flow velocities. The dimensionless flow-velocity values for onset divergence were extracted using three methods. One of these involved approximating the vanishing of the first-mode frequency value ($\omega_1 = 0$) with the increase in dimensionless flow velocities via extrapolation of the experiment point's trend with parabolic fit. The experiments revealed some differences from nonlinear theory. While nonlinear theory for a supported cylinder predicted flutter motion around a buckled state, the experiment showed that the flutter motion goes around the original static axis. Additionally, there was a non-negligible deviation of approximately 30% between the experimental thresholds for flutter instabilities and the theoretical results. Rinaldi and Païdoussis [22] experiment subjected a cantilevered flexible slender cylinder to axial flow of air from the free end toward the clamped end. First-mode oscillation, which could be considered flutter-like, was observed at low flow velocities. For higher flow velocities, the oscillation amplitude was reduced and a static divergence occurred, while the cylinder's deflection increased with an increase in flow velocity.

Other studies relate to the dynamics of a cylinder whose confined annular flow is directed through a very small gap. The pre- and post-instability of an axis-symmetric elastic cylinder in a small annular gap that is subjected to laminar axial flow, i.e., leakage flow, was studied numerically and experimentally by Fujita et al. [6]. The experimental results revealed the appearance of traveling waves accompanying the transition from lower flutter mode to higher flutter mode.

Linear and nonlinear theories show that fluid friction forces have a considerable effect on the appearance of flutter instability and its threshold. Recent numerical works that included experiments attempted to improve the understanding of fluid normal forces exerted on an inclined cylinder [5] and on an inclined and curved solid cylinder [3] in order to provide a better estimation of the linear fluid forces. The main insight of these works is the distinction between the two regimes of angle attack; for a small yaw angle ($< 5°$), the lift force varies linearly with the angle, and for a large yaw angle, it varies according to the quadratic relationship of the angle of attack [5]. More recent numerical studies [4,23] were performed on fuel rods subjected to axial turbulent flow. De Santis and Shams [4] conducted a numerical simulation of axial turbulent flow-induced vibration of confined single and double fuel rods. The effects of the varying flow velocity on the natural frequency and damping ratios of clamped ends and pinned-clamped rods were examined and compared to experimental results. Some discrepancies were demonstrated between the numeric and the experimental results due to variances between them.

Nevertheless, a systematic approach to investigating the effect of surface roughness on the dynamics of structures has not been addressed until now. With an understanding of the importance of the fluid-friction-forces effect on the rods' dynamics, this paper experimentally investigates the dynamic behavior of flexible cylindrical structures, emphasizing the effects of the different sequenced rectangular ribs. For example, pitch-to-height ratio (p/e) is used as a systematic surface roughness parameter of rods in confined flow. Previous experiments in the literature focused on unconfined flow (Moddarass, 2008; [14,19].

The objectives of this research are as follows: (1) to characterize the ribbed rods' dynamics given a wide range of flow velocities; (2) to verify onset instability; (3) to reveal the flutter instability of high modes; and (4) to provide insight into the effects of roughness and confinement flow on the flutter dynamics of high modes.

2. Experimental apparatus and setup

Several sets of experiments were carried out with four cast silicon rods, one with a smooth surface and the three others covered by repeated transverse ribs with different pitch-to-height ratios (p/e). The rods were mounted vertically inside the center of a vertical circular test section that was part of a circular water loop channel, as illustrated in Fig. 1.

A centrifugal pump with a maximum flow rate of $150\,\mathrm{m}^3/\mathrm{hr}$ was used to circulate water flow in the closed-loop pipe system. Table 1 summarizes the properties of the hydraulic water loop.

The test section was made of a transparent polyvinyl chloride (PVC) cylinder (pipe) to enable observation of the rod inside. The inner