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The effect of flexural stiffness on the sound of a hanging filament: From a membrane to a rigid body

M. Weidenfeld, A. Manela*

Faculty of Aerospace Engineering, Technion - Israel Institute of Technology, Haifa 32000, Israel

A R T I C L E I N F O

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A B S T R A C T

We consider the acoustic field of a thin flexible filament subject to uniform mean flow and a ‘hanging chain’ tension force parallel to its unperturbed state. The filament is actuated via harmonic heaving motion at its upstream edge with prescribed frequency and small amplitude. To investigate the effect of filament flexural rigidity, we analyze the system acoustic radiation in the entire range of body structural stiffnesses. Assuming two-dimensional high Reynolds and low Mach number flow, we apply a near-field description based on potential thin airfoil theory. The near-field model is then used to formulate the source term in the Powell-Howe acoustic analogy. The far field sound is calculated applying a compact Green’s function approach, yielding the leading order acoustic dipole field. In the limit of small flexural stiffness, we find that the acoustic field of a highly-elastic filament converges to the far field of a hanging membrane, dominated by the wake dipole sound. The wake sound component also dominates the system radiation in the limit of small actuation frequencies, where the filament deflects as a rigid body regardless of its structural stiffness. Sufficient increase in heaving frequency intensifies the relative contribution of filament motion dipole, resulting in significant differences between systems with different rigidities. Reflecting the impact of filament elasticity, these differences manifest the system’s natural frequency response, leading to increased levels of sound for actuations at the system’s eigenstates. In cases where the trailing edge wake and motion dipoles acquire similar amplitudes and opposite phases, significant sound reduction is found.

1. Introduction

The acoustics of fluid-structure interactions, coupling the near-field fluid-structure dynamics of a body with its far acoustic signature, is a topic of extensive studies owing to its relevance in a large variety of engineering and natural applications [1]. These include, among others, the modeling of palatal snoring and its control [2]; the production of “insect songs” and its social role in various species of flies [3,4]; the analysis and biomimicry of silent flight in birds [5,6]; and the study of turbomachinery aerodynamic noise, a key component in aviation sound pollution [7,8]. All of these have motivated ongoing progress in the field of vibroacoustics, where the far-field noise generated by mechanically- and flow-induced body motions is considered. Existing studies are typically based on an acoustic analogy technique, where the near-field calculation serves as an effective source term, and an appropriate analogy is applied to predict the far acoustic pressure. Such a scheme appears superior over a direct numerical calculation of the entire flow field, as the far radiated signal turns prohibitively small (and, at some point, of the order

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* Corresponding author.
E-mail address: amanela@technion.ac.il (A. Manela).

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of the numerical error of the pertinent computational solver) far enough from the source. A first step into application of this approach is therefore the determination of the near-field fluid-structure dynamics of the configuration of interest.

Focusing on the near-field interaction between elastic bodies and a surrounding flow field, a large number of recent works have considered the model “flapping flag” problem, where a thin filament is immersed in uniform flow and exhibits either flow-induced or mechanically-imposed motions [9,10]. The associated setup has been shown relevant in a variety of applications, including the development of energy harvesting methodologies [11] and the optimization of propulsion efficiencies in single- and multi-body environments [12,13]. In the context of aeroacoustics, the flag model has been applied to evaluate the aerodynamic sound radiated during flapping flight [14,15].

In common to the above near- and far-field investigations, structural elasticity, modeled as a flexural stiffness term in the filament equation of motion, has a key effect in determining the system dynamics, in terms of both body motions and associated body-flow interactions. Yet, a detailed investigation of the gradual impact of rigidity on the system aeroacoustic properties is lacking. Such a study should rationalize the effect of body flexibility, at different magnitudes, on the system acoustic signature. In particular, the results may indicate on optimal conditions where the noise may be minimized, as a possible means for sound monitoring.

The present work aims at studying the effect of body flexural stiffness, varying between vanishingly small (membrane) and exceedingly large (rigid body) values, on its far-field signature. In the small-stiffness limit, large body deformations develop unless the dampening effect of filament tension is taken into account. Indeed, inasmuch as bending rigidity exists for all elastic structures, tension forces always prevail to some extent. Such forces may originate from either structure-induced effects, viscous boundary layer loading, or other forms of external forcing acting parallel to the unperturbed body state. In the small-amplitude motion regime, it was shown that the effect of structure-induced tension is of higher order and may be neglected [16]. Additionally, the relatively small magnitude of drag-induced tension at high Reynolds numbers makes its impact relatively minor [17]. Small-amplitude motion at small stiffness rates may consequently occur in the presence of stronger tension forces.

To consider the effect of externally-induced tension at low-rigidity conditions, several works have examined the “hanging-filament” setup. Among others, Datta and Gottenberg [18] have studied the free vibrations developed in an infinitely long elastic strip hanging vertically in a downward stream, by using a simplified model for the fluid pressure loading. Lemaitre et al. [19] have applied a similar theoretical approach to analyze the flutter instability of a long ribbon hanging in axial flow, and validated their results experimentally. Several workers have later on suggested the hanging-filament setup as an efficient means for energy harvesting purposes [20–22]. The specific efficiency of a piezoelectric membrane hanging in axial flow was analyzed in detail [22,23]. In a recent contribution, the singular limit of small stiffness ratio has been examined for a “hanging flag” setup [24]. The convergence of a beam-type (having arbitrarily small rigidity) to a membrane-type description has been discussed, and the inevitable effect of body stiffness on the structure dynamics near its end points has been analyzed.

In view of the above investigations on the effect of small stiffness ratio on the motion of hanging elastic bodies, a study on their far-field properties is of interest. Apart from the fundamental significance of such a study, it may be useful for analyzing the acoustic field of the associated energy harvesting systems, generally known as a major concern in the design of industrial wind farms [25]. In common with Ref. [24], we consider a “hanging flag” setup. This permits investigation of the system far field sound in the entire range of body flexural rigidities, while maintaining the assumption of small-amplitude structural deflections even in the limit of vanishing rigidity. The two-dimensional configuration consists of a thin filament subject to leading-edge heaving actuation and a gravity force acting in parallel to the structure unperturbed state. Small body deflections are considered, so that the filament equation of motion may be linearized about its non-deflected state. Low-Mach and high-Reynolds number flow conditions are assumed, enabling application of a compact-body acoustic analogy for the prediction of the far field sound. In the subsequent section, the near- and far-field problems are formulated. Our results, analyzing the system response to harmonic actuation, are presented in Section 3, and concluding comments are given in Section 4.

2. Problem formulation

Schematic of the problem is shown in Fig. 1. Consider a two-dimensional setup of a thin elastic filament of chord $2a$ immersed in uniform flow of speed U in the x_1-direction. The filament is subject to a ‘hanging-chain’ gravity-induced tensile force [26]

$$T(x_1) = \rho_s g(a - x_1), \tag{1}$$

where ρ_s marks the structure mass per unit area, and g is the constant of gravitational acceleration. Mechanical loading is applied to the body, in the form of harmonic leading-edge heaving actuation

$$\xi(-a, t) = \overline{\varepsilon}_h a \sin\left(\omega_h t\right). \tag{2}$$

In Eq. (2), $\xi(x_1, t)$ denotes the filament displacement in the x_2-direction, $\overline{\varepsilon}_h \ll 1$ is the scaled heaving amplitude (with an overbar marking a non-dimensional quantity), and ω_h is the prescribed heaving frequency. In what follows, we investigate the acoustic far field generated by the fluid-structure interaction of the vibrating body with the flow. In a practical setup, the physical apparatus driving the filament actuation (2) should also contribute to the near- and far-field behaviors of the system. While such consideration is particularly important when conducting experimental measurements (see, e.g. Purohit et al. [27]), we regard this mechanism as “ideal” hereafter, so that its impact on the filament signature is not analyzed. High Reynolds and low Mach number conditions are assumed, thus considering the near field to be inviscid and incompressible. Compressibility effects are