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FEATURE ARTICLE

tutorials and items of special interest

DYNAMICS OF CABLES, TOWING CABLES AND MOORING SYSTEMS

M.S. Triantafyllou[1]

Abstract. This is the third in a series of reviews of the mechanics of cables. This review concentrates on the dynamics of towed cables and the drag of mooring systems and covers the general literature on cables that has appeared since the last review.

The subject of the mechanics of cables and chains attracts considerable attention, and the related literature is very extensive. The reasons are that cables find use in positioning or anchoring structures of a great variety of shape, in air or in the ocean, while their mechanics contain a rich variety of interesting or even intriguing properties, which are still being discovered. If one were to consider also the related subjects of fluid-structure interaction and hydrodynamically induced instability, a review would be too extensive. As a result the focus here is primarily on issues related to the basic mechanisms of cable response.

The linear and nonlinear dynamics of cables and chains were reviewed by the author in 1984 [1] and in 1987 [2]. Since then a number of studies have appeared, addressing primarily the behavior of cables and mooring lines in water and the nonlinear behavior of cables in air.

CABLES AND CHAINS IN WATER

The dynamic behavior of a cable in water is affected primarily by the presence of the nonlinear drag force. The basic developments have been outlined in the second review [2]. The drag force itself is the subject of extensive study both for its importance as a force resisting any imposed motion and for the complex phenomena that cause it. The concentration here is on some aspects germane to cable dynamics, since the subject of viscous fluid forces is very extensive and is covered elsewhere in the literature, for example, Sarpkaya's paper [3].

A horizontal hawser used in towing surface vessels has similar properties as mooring lines in that drag suppresses transverse motions causing the tether to stretch substantially. In fact, for higher frequency motions the cable employs almost exclusively its elastic rather than its catenary stiffness [4,5]. An additional phenomenon of particular importance to hawsers is snapping. Snapping occurs when the dynamic tension exceeds the static tension in amplitude, causing the cable to become slack for part of the cycle, and then to tighten suddenly, possibly causing extreme tensions and failure. The principal parameter controlling snapping was found to be the free-falling velocity of the hawser. When this velocity is small, the tether cannot achieve a sufficiently deep catenary when falling freely, and the subsequent tightening is accommodated by stretching and hence high tension. On the other hand, if the free falling velocity is increased (for example, by making the hawser heavier), the cable forms a deep catenary shape when it becomes slack. Then as it tightens, the cable absorbs the imposed motions through changes in the catenary, resulting in small dynamic tensions [6-8]. Milgram, et al. [7] explored these properties of towing hawsers and developed a methodology for predicting extreme forces in towing through a seaway.

The optimization of the dynamics of mooring lines with submerged attached buoys was addressed by Mavrakos, et al. [9,10]. It was shown that these moored buoys behave as inverted pendula, with the buoyancy acting as an equivalent gravity force. This, in turn, allows, through proper design of the natural frequencies, substantial reduction of the dynamic tension. If proper care is not taken, then buoys can cause the dynamic tension to increase substantially [11].

Modeling and testing of cables and mooring lines was addressed by Papazoglou, et al. [8]. It was shown analytically and experimentally that the principal parameter to model is the elastic stiffness of the cable, and this can be achieved in practice

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only through the insertion of a spring in series with the mooring line. For hawsers, the free falling velocity of the cable, as already described, must also be scaled properly. In a subsequent work, Papazoglou, et al. [12] consider model testing of a cable with attached buoys. It is shown that proper scale modeling requires the insertion of a properly designed spring in each cable span between buoys and in the span between the lower buoy and the anchor.

Cables towed in water. A large number of publications have appeared covering the subject of a cable towed in water, usually with a body attached at the lower end. Depending on the application, the cable may be nearly vertical (as in many applications involving remotely operated vehicles positioned through a surface vehicle) or nearly horizontal (as in the case of towed arrays). The hydrodynamic forces are completely different in these two cases. In the first case, there is a strong resistive in-line force and a vortex induced out-of-plane (lift) force, causing out-of-plane oscillations. In the second case, the force is primarily inviscid and acts under certain conditions to destabilize the motion of the cable. The basic mechanism of destabilization is described in a large number of related publications reviewed by Paidoussis [13]. A more recent, very elaborate analytical-numerical treatment of the dynamics of such cables can be found in Dowling's work [14,15].

Cables towed nearly horizontally are used for a variety of applications, such as geophysical exploration and vehicle detection. Paul and Soler [16] considered the two-dimensional dynamics of a towed cable-body system. They ignored inertia forces and used a finite link approximation, while they introduced some clever analytical manipulations to reduce the computational cost. Sanders [17] considered the three-dimensional dynamics of a towed system using finite differences, also ignoring inertia forces. Delmer, et al. [18] formulated the problem of the nonlinear three-dimensional motion of a multi-segmented cable subject fo fluid and weight forces using the finite element method (specifically, the method of lines) and allowing for cables whose length varies with time. They reported a 10% accuracy when they compared their results with experiments involving the deployment of a cable [19]. Ablow and Schechter [20] studied the same problem using the method of finite differences and local cable coordinate formulation (i.e. projecting the equations along the local tangential, normal, binormal directions), gaining in speed of execution over Sanders [17]. Further improvement in the methodology of Ablow and Schechter [20] was achieved by Milinazzo, et al [21] who employed an implicit, second order finite difference approximation of the governing equations. Comparison was made with the experimental results of Rispin [22]. An omission in these publications that should be pointed out is in not properly accounting for the hydrostatic force. This requires using the concept of effective tension as first explained by Goodman and Breslin [23]. Erroneous results may be obtained by ignoring the hydrostatic force.

Delmer, Stephens, and Tremills [24] studied the three-dimensional dynamics of cable-towed acoustic arrays using the lumped element method and a stiff integration technique. They applied their methodology to several examples and compared their results with experiments, including those reported by Meggit, et al. [19] and Meggit and Dillon [25]. They also compared their results to a simulation of a 180 degree turn maneuver of a towed system. Their applications met with varying degrees of success. A reason for some discrepancies observed may lie in the rather primitive modeling of drag adopted by the authors.

Chapman [26] studied the effects of ship motion on a neutrally buoyant fish. He modeled the cable as consisting of straight inextensible rods, freely interconnected at the ends. He discovered the "sheath" action of drag, i.e. the reduction of lateral motion at the expense of considerable stretching and the considerable effect of cable length on the pendulum motion of a suspended fish. For short cable lengths, the response is that of a damped pendulum, while for long lengths, the action of drag practically decouples bottom and top transverse motions, hence causing a length-independent pendulum motion of the cable.

Chapman [27] also studied the response of a cable to towing ship maneuvers. He omitted cable stretching and inertia forces on the cable, while he considered drag forces only on the cable and not on the towed fish. He distinguished between sharp and gradual maneuvers in terms of the ratio of the radius of ship turn and the scope of the cable. A distinctly different cable response was obtained for sharp maneuvers, which caused a rapid descent of the cable lower end.

Further, Chapman [28] studied the attenuation of ship-induced lateral motions along a towed cable, supporting a heavy fish. He employed the Bath Mk-3 Sonar Fish to establish the validity of his results. In an experimental study, Bettles and Chapman [29] considered the response of a towed fish to dynamic excitation. Delmer and Stephens [30] considered the dynamics of a weight towed through a long cable; they addressed in particular the response of the weight to the cross-tack oscillation of the upper end of the cable.

Schram and Reyle [31] considered the three-dimensional analysis of an inextensible cable and towed system, using the method of characteristics, which is discussed extensively in the context of the application studied. De Laurier [32] studied the stability of towed and tethered bodies when the cable has general curvature and tension variation. Paul and Soler [16], referenced above, considered the dynamics of towed cables by ignoring inertia forces on the cable and modeling the cable through finite interconnected links. They considered also optimal strategies for positioning submersibles, and they showed moderate advantages in using overshooting in the position of the surface vessel to overcome the time lag in the response of the submersible. Ivers and Mudie [33] considered the three-dimensional, slow (i.e., well below the wave frequency range) dynamics of towing a very long cable (up to 4 km) at low speeds (up to 3 knots), ignoring inertia and tangential drag. The drag coefficient was found by minimizing the error of the model predictions with respect to full scale data; its value was estimated to be $c_D = 2.7$. The authors note the long delays in achieving changes in the position of an unpowered towed vehicle, which reach, in their estimation, values of 30 min for a 4 km long cable.

Le Guerch [34] studied the deep towing of fish using long cables, 2 to 6 kilometers in length, and at low speeds up to 2 knots, using a model based on Ivers and Mudie's study. His primary objective was to study the 180 degree turning maneuver with a radius of turning of the order of 500 meters. He compared his results with full-scale data, with particular attention to the value of the drag coefficient, which he reports to be $c_D = 1.5$.

Triantafyllou and Hover [35] and Hover, et al. [36] used a simplified version of the governing equations for a cable to study the slow and fast dynamics of a cable used in towing remotely operated vehicles. The simplification consists in assuming moderately large deviations from an average configuration and quasi-static tangential cable motion. The simulations were compared with full-scale data, reported by Yoerger, et al. [37], Triantafyllou, et al. [38], Grosenbaugh, et al. [39] and Grosenbaugh [40].

Drag Forces on Mooring and Towing Cables. Vessels moored through several mooring lines possess a natural frequency of oscillation, due to the low damping available in the system. The mass, plus added mass, of the vessel and the overall stiffness of the mooring system are the equivalent mass and spring stiffness, respectively. A variety of low-frequency forces, particularly due to the non-linear wave forces, cause such vessels to oscillate with relatively large amplitudes. The mooring lines are subjected to large drag forces as they are forced in these large amplitude oscillations, hence providing a substantial damping mechanism. In the case of towed cables, the drag coefficient is a principal parameter affecting the accuracy of prediction for the position of the towed body and the shape of the cable.

Despite considerable effort, the value of the drag coefficient in a flexible cable still cannot be predicted with the required accuracy. There are two basic causes for this: first, the well known Karman street causes out-of-plane motions, which may cause substantial drag increases (up to a factor of 3 or more); second, the superposition of wave-induced motions and slowly varying motions results in an apparent increase of the damping of the slowly varying motions. The two phenomena together can cause an unexpectedly large increase in the apparent drag coefficient.

In the case of short cables, low-frequency motions are practically absent, hence the principal unknown physical mechanism is the appearance of lock-in; i.e., vibrations synchronized with the formation of vortices. This is a subject of considerable interest, but will not be reviewed here since the mechanics of the cable itself are of secondary importance.

For long cables, however, both mechanisms mentioned above are present, while the mechanics of the cable are of primary importance even for the vortex formation problem, since the system is practically of infinite extent, and lock-in is continuous. The significant variation of drag coefficient reported in towed cables was noted above (Ivers and Mudie [33] report 2.7, while Le Guerch [34] reports 1.5). An apparent explanation is offered by the recent work of Yoerger, et al. [37] Triantafyllou, et al. [38], Howell [41], Grosenbaugh, et al. [39] and Grosenbaugh [40]. In these papers it is noted that the shear in the flow causes amplitude modulated response, which, in turn, lowers the value of the drag coefficient (which also becomes dependent on the modulation amplitudes traveling along the cable length). Hence, sharp transient maneuvers will result in lower values of drag coefficient, while steady towing results in higher values.

In the case of mooring lines, Huse [42] and Huse and Matsumoto [43,44], Wichers [45], Wichers and Huisjsmans [46], Koterayama, et al. [47], and Koterayama, et al. [48] studied the increase of drag coefficient due to the superposition of low- and high-frequency motions. Although an exact calculation is still lacking, the apparent increase in drag coefficient of the low-frequency motions is well documented. An outline of the basic mechanism can be found, among others, in the paper by Demirbilek, et al [49].

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