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Dynamics of Towed Payload System Using Multiple Fixed-Wing Aircraft

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The payload capability of many aircraft is typically limited by the maximum takeoff weight. However, when in flight, many aircraft can handle larger loads, but this capability is rarely exploited. The possibility of using an aircraft cable system to lift large payloads is studied in this paper. This concept has been studied previously for single-aircraft, single-cable systems in some detail. The major limitation of such systems is the need to fly very tight circles at high-lift coefficients. This limits the size of the payload that can be retrieved with such a system. To overcome this, it is possible to employ a multiple-aircraft, multiple-cable system to allow greater control of the payload position as well as allowing a much wider choice of aircraft speed and lift coefficient. In this paper, an object-oriented cable modeling approach is used to study the relative equilibria of such a system. Parametric studies of different payload masses and aircraft orbit parameters are presented, and the dynamic stability is analyzed. Collision-free transition trajectories that take the multiple-aircraft system from circular flight into straight and level flight are derived.

I. Introduction

THE possibility of performing remote payload pickup and delivery using long cables towed by fixed-wing aircraft has received attention in the technical literature for several decades. In fact, the possibilities were developed conceptually as early as the 1930s [1,2] and were rediscovered in the 1940s [3] by the missionary pilot, Nate Saint, who used the technique to deliver small items to remote regions in Ecuador [4] (see [5] for a photograph of the technique). These and other documented concepts and applications [6,7] are concerned with using a single aircraft flying constant radius circles with a tether deployed to the ground. For certain combinations of aircraft orbital parameters and cable parameters, the cable takes on a stable relative equilibrium configuration (relative to a rotating frame) with the orbit radius of the cable tip very small compared to the aircraft orbit radius. This translates to nearly stationary motion in the inertial frame, depending on the aircraft angular velocity.

The stability of so-called circularly towed-cable systems has received considerable focus [8–16]. Much of the earlier work on such systems has focused on multivalued solutions at high angular velocities. However, many of these high-angular-velocity solutions are not relevant to aircraft-towed systems due to the relatively low angular velocities and longer cables involved. Therefore, more recent effort has studied optimal configurations and ways of enhancing the near-stationary motion of the cable tip [17]. Williams and Trivailo [18] also studied the dynamics of the cable during aircraft transition maneuvers and showed that the aircraft transition from straight flight to circular flight can have a significant influence on the cable dynamics. Periodic solutions of a single-cable towed system for vertical aircraft oscillations, elliptic orbits, and crosswinds were presented in [19]. Periodic optimal solutions including cable winch control in the presence of crosswinds were determined in [20] using direct transcription methods. A method for delivering payloads to the ground or ocean was studied in [21] by anchoring the cable tip and sliding the payloads on the cable. Control of the aircraft motion for stabilizing wind-induced oscillations of a circularly towed-cable system (for the E-6A TACAMO) using fuzzy logic was presented by Borst et al. [22] and Brushwood et al. [23].

The conventional circularly towed-cable system is based on the idea of using a single aircraft with a single towed cable. The major problem with such a system is that, when the mass at the cable tip increases, there is a significant change in the equilibrium condition, which causes the orbit radius of the cable tip to increase. Hence, the desired near-stationary motion is lost. The most important consequence of this is when it is desired to deliver the payload to an alternative location using the same physical principles. It would not be possible to initiate the near-stationary motion with such a large mass. Another significant drawback is that the required aircraft orbit parameters to maintain the desired cable tip motion are at the extremes of the aircraft operational envelope, that is, maximum lift coefficient and bank angle. The increase in cable tension due to the increased load could then stall the aircraft, thereby severely restricting the range of operation of the system. It must be noted that the original system used by Nate Saint involved only lightweight payloads.

An alternative technique that was originally suggested by Alabrune [24,25] is to use two or more aircraft to retrieve a payload by using a similar technique as just described, but connecting the same payload to more than one tow cable, as shown in Fig. 1. In the case of a two-aircraft system, the aircraft would fly at diametrically opposite sides of the circle (spaced 180 deg apart) so that the cable tips approach the center of the circle. At this point, the cables can be connected to the payload. The advantage of this technique over the single-line method is that the components of cable tension acting to pull the payload away from the center of the circle is ideally balanced by the second cable. Hence, the new equilibrium position is with the payload at the exact center of the circle, with zero inertial velocity. Naturally, this technique extends to multiple-aircraft and multiple cables. Alabrune [24,25] discussed techniques for maneuvering the aircraft to raise the payload from the ground. Essentially, he suggested accelerating one of the aircraft relative to the other. Wilson [26] proposed different procedures for the "tow-in" and "tow-out" maneuvers using the two-aircraft configuration.

Despite the considerable apparent value in developing a multi-aircraft cable pickup system, there is no publicly available technical literature that studies the dynamics of multicable systems for vertical pickup and delivery of payloads. This paper seeks to fill this void by developing an object-oriented mathematical model for dealing with the multicable dynamics and using the model to assess the stability of the system under a variety of operating conditions. The model is used

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