JOURNAL OF GUIDANCE, CONTROL, AND DYNAMICS
Vol. 32, No. 2, March–April 2009

Engineering Notes

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Flying: With Strings Attached

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DOI: 10.2514/1.41347

Introduction

THERE has been a large body of published literature over the years discussing the behavior of tethers towed behind a moving vehicle traveling along a circular path [1–3]. The interest is due to both the practical implications and the mathematical disciplines involved in the analysis and modeling. Multiple studies by many published authors, including the current authors [4], as far back as the Swiss mathematician Euler, have analyzed the motion and stability of both the tether and the end mass attached to the free end of the tether [5–7].

The ability to position the free end of the tether is important in underwater applications such as towed sonar arrays or towed geologic survey instruments. It has also long held the promise of practical application to aerial towed tethers. In the airborne case, the interest arises from the tendency of the free end of the circularly towed tether to move toward the center of a circle well below the towing aircraft and to become, if not stationary, at least very close to that state. This suggests the possibility of using circular towing as a means of delivering and retrieving payloads attached to the free end of the tether. This was achieved for small payloads by a missionary pilot in the jungles of Ecuador in the 1950s [8]. The recent development of the mathematical tools and computational ability to accurately model the towed-tether behavior is leading to increased confidence that the technique can be applied to automatic guidance of the towing aircraft. This potentially opens the way for delivery and retrieval of payloads of greater mass and over longer distances than can currently be achieved with helicopters [9]. The predicted shape of the towed-tether/payload system is well known and is illustrated in Fig. 1.

RMIT University in Melbourne, Australia, has a research team working on the development of this capability. Work is directed toward the control techniques necessary to bring the free end of the tether to a stationary state for short periods of time. This would allow ground crews to remove or attach payloads to the free end of a tether towed behind a circling aircraft. The authors believe that this technique, when fully developed, will enable a number of unique applications. These could include, but are by no means limited to, pinpoint delivery of large volumes of water for forest fire suppression, delivery of aid packages to isolated victims of natural disasters in remote regions beyond the range of helicopters, and delivery and retrieval of personnel in a manner less risky than the now-unused Fulton Skyhook. The technology is also transferable to ships, submarines, and spacecraft applications.

The inability of the pilot to accurately determine the position and motion of the tether free end, and the complexities of the tether motion, drives researchers to find an automated process. The RMIT team is working to develop an intelligent system to maneuver the towed tether, towed from an aircraft, to pick up or set down a payload with zero surface velocity. Because of the complex nonlinear dynamics of a cable-body system, advanced modeling and nonlinear optimal control are applied to this task. The team has extensive experience and worldwide recognition for the expertise in complex modeling of dynamic systems.

Methods

As part of the research work, a small-scale experiment was designed by the principal author to enable rapid observation of the changes in tether behavior as variations were made in the configuration. Initially, this experiment served to confirm the tether behavior predicted and analyzed in published literature.

The experimental setup consisted of a 1-m-diam ($d1$ in Fig. 1) ceiling fan at a height of 3 m from the floor (H in Fig. 1). A 3-m-long tether was attached to the tip of one blade of the fan. Initially, a small range of masses were attached to the free end of the tether and the behavior of the masses was studied. The masses were small pieces of modeling clay (plasticine). This study was conducted over a range of fan speeds and masses. Under these conditions, and assuming International Standard Atmosphere, the Reynolds number for the tether was in the range of 130 to 460. The behavior of the tether under these conditions closely matched the analytical models in published literature. The tether took up a helical shape, with the free end following a horizontal circular path. It was found that the diameter of the circular path followed by the mass on the free end of the tether was approximately 10% of the towing-end circle diameter ($d2$ in Fig. 1). This was consistent over a range of fan speeds (ω in Fig. 1) from 250 to 880 rad/s and end-body mass from 1 to 12 g. It was also consistent for shorter tether lengths. Of interest was the observation that the end-mass behavior followed predictions found in the referenced literature for much-larger-scale studies in which masses and tether lengths that were orders of magnitude greater were involved and in which rotational speeds that were orders of magnitude less were involved. (In Fig. 1, X, Y, and Z are the fixed coordinate system and i, j, and k are the rotating coordinate system.)

Skop and Choo [10], in their paper on circularly towed cables, predict the existence of single-value and multivalue regions of cable motion. The current authors found that the analytically predicted single-value (stable) and multivalue (unstable) regions also existed for various combinations of length, mass, and velocity at the smaller scale of these experiments. In the stable regions, disturbances in the circular path of the end mass were quickly damped, with the mass returning to the original path. In the unstable regions, small disturbances in the motion of the mass quickly diverged to large-magnitude, undamped, aperiodic motion, both vertically and laterally.

It was during this experimental activity that the new modes of tether behavior, which are the focus of this Note, were first observed.

Received 1 October 2008; revision received 15 December 2008; accepted for publication 23 December 2008.

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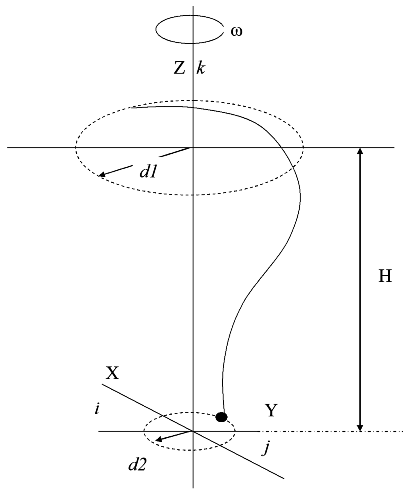

Fig. 1 Towed-tether system.

New Tether Modes

A fortuitous accident occurred when the tether tangled, creating a loop at a point about 30% of the total length above the end body. When this occurred, the diameter of the circular path of the free end mass was observed to decrease. This suggested that there could be a benefit in deliberately introducing a mass partway along the tether or, perhaps, a point drag partway along.

A new set of experimental studies was made with a range of masses attached at a range of positions along the tether at a range of fan speeds. The masses were used in place of the string loop. The masses were of the same order of magnitude as the free end mass. Additionally, tests were conducted using blocks of foam to create low-mass/high-drag points. It was observed that results were similar for mass or drag being added to the tether. Fan speeds and tether length were as previously tested.

The simple nature of the experiment prevented the use of instrumentation on the tether and masses. Instead, measurements were made from a video record of the events. This results in a lack of precision, which leads to the use of terms such as *approximate* and *around* in the following description.

Two useful results emerged, with both midtether mass and midtether drag.

1) The multiple unstable states observed with the simple system initially studied were no longer present. The free end mass was now stable over the range of fan speeds at which it had previously been unstable. It was also found to be stable with the range of end-body masses that had previously resulted in unstable behavior.

2) The diameter of the end-body circle was reduced by half, to around 5% of the diameter of the towing circle.

The second of these, the reduction of end-body circle diameter is particularly significant in the attempts to induce a stationary state in the tether free end.

In addition to these two behaviors at fixed fans speeds, a new phenomenon was also observed as the fan accelerated from stationary. Three distinct states of motion of the tether-mass system occurred at different speeds.

As the fan first started to turn, the entire tether/mass system swung outside the diameter of the fan blade tip. The tether was in roughly a straight line from the fan blade tip through the point of the midtether mass to the end-body mass. As the fan speed increased, the circle diameter, followed by the end-body mass, also increased to approximately twice the fan diameter. The tether/mass system motion was steady, with no significant motion outside of the horizontal circular path being observed for either the end body or the midtether mass.

With further fan speed increase, the system moved to a second state, with the midtether mass following a circle with a diameter about 40% of that of the fan blade tip. The tether shape became that of the expected helix from the fan blade to the midtether mass. At the midtether mass, the tether turned sharply outward to the end body, which was following a circle approximately 75% the diameter of the fan blade tip. The transition to this second state occurred at a fan speed of approximately 25% of the highest fan speed. This state remained stable, with little change in the diameters of the end-body and midtether-mass circles until the fan speed reached about 60% of the ultimate speed, when a second state transition occurred.

At speeds greater than 60%, up to the maximum fan speed, the midtether-mass circle diameter decreased again, to a diameter of around 25% that of the fan blade. The end body swung inside the circle of the midtether mass to follow a circle around 5% the diameter of the fan-blade-tip circle. This is the state that was observed initially and that led to this series of experiments. The three states observed during acceleration are shown in Fig. 2. The same motion was observed as the fan speed was decreased to stationary.

Figure 3 is a plot of the end mass and midtether-mass circle diameters. This shows the circle diameters for the three states of motion sketched in Fig. 2.

The preceding experiment was further extended by adding a second midtether mass: in this case, supplied by way of two loops of string. These duplicated the single string loop that was initially observed and that led to the experiments described previously. The addition of the second loop further reduced the end-body circle diameter, resulting in the final segment of the tether being almost vertical and close to the axis of the rotating tether/mass system. The end-mass circle diameter was about 2% of the fan diameter. This was a single-point test, in that no attempt was made to investigate altered loop positions or sizes.

Finally, the effect of using dual tethers was examined. Two tethers were attached to opposite fan blades and to a single end mass. This also resulted in a reduction in the diameter of the end-body circle, from 10% for the single tether to 5% for the dual tether. It also prevented any swing of the end body outside the fan diameter during fan startup. The dual-tether arrangement holds promise for minimizing the towed-body circle diameter, at the expense of the complexity of coordinating the flight paths of two aircraft, each towing a tether. It makes for a very interesting analytical study.

In addition to the outcomes already discussed, some interesting observations were made when correlating the results with later analytic work carried out by others in the RMIT team and when comparing with published literature describing analysis of large-scale airborne systems.

1) The experiments conducted here were under conditions of high rotational speeds on the order of 250 to 880 rad/s. Published literature for the airborne case has considered full-scale systems rotating at around 2 rad/s. Later experiments were conducted by the author

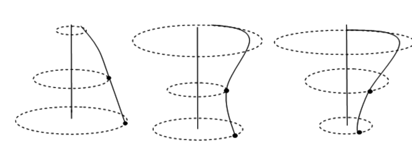

Fig. 2 Low-speed, mid-speed, and high-speed tether shapes.

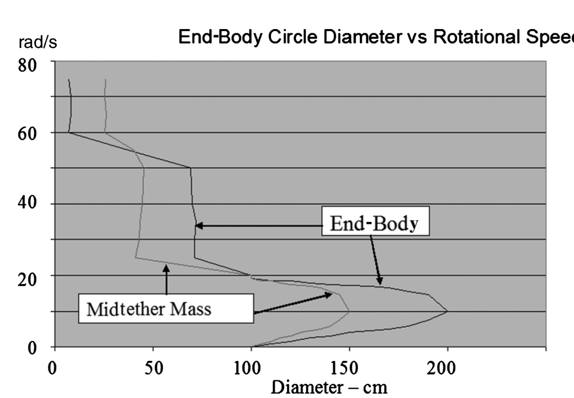

Fig. 3 Fan startup with double-weighted string.

using radio-controlled aircraft circling at 40 rad/s. Results are comparable in all three cases.

2) Related to point 1, the small-scale system operates under conditions in which centripetal acceleration is significant due to the high rotational speed. By comparison, the low rotational speeds of the large-scale case make mass and aerodynamic drag dominant.

3) Midtether drag and mass provide similar outcomes in terms of tether shape and end-body circle diameters. This effect was tested in a further experiment, described subsequently, in which midtether drag was used instead of mass.

Larger-Scale Experiments and Further New Findings

Subsequent to these experiments, a further experimental validation was carried out using a 200 m tether towed behind a radio-controlled model aircraft. This towing was carried out both with and without a midtether drogue attached. The drogue was found to stabilize the entire system, with the end body achieving a near-stationary state behind/under the towing aircraft. This allowed the end body (a 2-m-long, 150-mm-wide fabric banner chosen for visibility) to be easily placed gently on the ground and picked up just as gently.

The noninstrumented experiments described previously were a precursor to testing at a larger scale using radio-controlled model aircraft. A 1.7-m-span-high-wing aircraft was instrumented along with a towed payload pod. The two instrument packages were MP-2028 unmanned aerial vehicle autopilots from MicroPilot of Canada. This combination was used to gather real-time data during experiments. Altitude, speed, Global Positioning System position, accelerations, attitude, and control positions were captured.

The testing carried out yielded consistent results with published work. There were two unexpected results that are the subject of further work. First, a test was flown to observe the result of the aircraft rolling out of the circle and flying away from the grounded payload in a straight line. With the payload stationary on the ground, the tether formed a complete circle and a half from the aircraft to the payload. Tension came onto the tether as the aircraft began its straight-and-level flight. At this point, the tether at the stationary payload was pointing away from the aircraft. The increase in tension resulted in the payload being picked up. The initial motion of the payload was in the direction of the tether, opposite to the direction of the towing aircraft.

A further interesting result, again previously undocumented, emerged during this phase of testing. In all of the published analytical papers found by the authors, an assumption was made that there is no ambient wind impacting the system. The majority of the authors' test flying was carried out under zero-wind, or very light-wind, conditions (less than 2.5 m/s). However, several flights were deliberately carried out in higher-wind conditions (greater than 15 m/s). This crosswind was sufficient to carry the towed instrument payload outside the 100-m-diam circle of the towing aircraft. The payload continued to exhibit the expected circular motion. However, an interesting new phenomenon was observed. The payload was seen, confirmed by subsequent data analysis, to descend when the circling aircraft was flying toward the payload. When the towing aircraft turned away from the payload, the payload was seen to rise. This behavior is attributed to the change in tension on the tether.

Conclusions

The discovery of the stabilizing effect of a midtether mass or drag has been a significant step forward in the search for practical realization of the promise of a useful towed-tether payload-delivery system. The discovery of the multiple stable states during fan acceleration adds greatly to understanding the behavior during transition from straight tow to circular tow. The unexpected payload motion observed during the high-wind test suggests practical limits on the wind conditions under which a circular-tow payload-delivery technique will be viable.

Taken together, these new results indicate that there is still much to be learned in making a transition from analytical predictive work to actual deployment. This is, perhaps, further illustrated by the description of a flying technique[‡] provided by a New Zealand pilot who had flown the pickup maneuver in air shows using a stuffed pair of overalls to simulate a human payload. It was his practice to decrease the towing circle diameter and dive the aircraft to pick up speed when picking up the payload. Both of these maneuvers are counterintuitive and are not predicted in any analytic work to date.

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