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Nonlinear Dynamic Simulation of a Tethered Aerostat: A Fidelity Study

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Full-scale flight tests of an instrumented TCOM 71M™ tethered aerostat conducted by the U.S. Army provide a database for determining the fidelity of the TCOM nonlinear dynamic simulation. Six global position system sensors, accurate to ± 5 cm, determined the position and attitude of the aerostat, and winds were measured using a three-axis anemometer mounted on the aerostat's fin near the tip. A 32-min window of data was selected for comparison with the simulation, using the recorded winds to derive a turbulence table. This required correcting the winds for aerostat velocity and transforming to an Earth-fixed coordinate system aligned with the mean aerostat heading. Best results were obtained when the turbulence was propagated through the reference point with uniform flow over the aerostat, rather than the segmented hull with nonuniform flow. This is shown clearly by comparing standard deviations of the flight parameters. This unexpected result is attributed to the strong influence of aerostat velocity in reconstructing the true wind. Graphical comparisons are made in the time domain of the aerostat's position and orientation as well as tether tension. Qualitatively, the comparisons are very good, generally showing the same patterns of motion and order of magnitude as the standard deviations. Tether tension in particular showed a remarkable duplication by the simulation. Frequency spectra based on fast Fourier transformation of the time histories are also compared.

Introduction

IN March of 1997, the U.S. Army conducted flight tests of a highly instrumented TCOM 71M™ tethered aerostat at the McGregor Range of the White Sands Missile Range. These tests provided data on the motions of the aerostat in various levels of turbulence for payload design and to assess the fidelity of flight-simulation computer programs. This paper deals with a comparison of selected flight data with the motions and tether tensions predicted by the TCOM nonlinear dynamic simulation (NLDS) using the measured, time-dependent wind vector as an input. The comparison is made in the time domain, comparing the position, orientation, and tether tension as a function of time. This is a much more stringent test of fidelity than comparisons made on a statistical basis or those relying solely on the frequency spectrum of the motions. It is a test not only of the flight dynamic model, but also of the frozen-field wind model that is assumed by the simulation.

The TCOM NLDS has been in development for well over 20 years. The first version was published in 1982,[1] and it has been refined and recoded in modern computer language with many options and improvements added in the intervening years, including the full implementation of the aerodynamic model of Jones and DeLaurier.[2] It has been the tool used in a number of studies, including the dynamics of the small tethered aerostat radar system (STARS)[3] and the simulation of a moored aerostat.[4] The NLDS was used in the design and development of the 71M aerostat, which was flown with the simulation to determine its stability and response to turbulence before the first gore was cut. Studies with the NLDS have been used to determine the optimum free lift for safe aerostat operation and to provide guidance for the design strength of tethers. It has been an important tool in accident investigation by simulating the flight involving an incident. Thus, verification of its veracity is of utmost importance.

The NLDS is a six-degrees-of-freedom dynamic model with a finite element tether. In the aerodynamic model the hull is divided into a number of panels or longitudinal segments, which permit a nonuniform flow as turbulent gusts are propagated from nose to tail. This variation in local angle of incidence produces moments due both to turbulence and rotation. A similar model has been developed by Evans and DeLaurier for powered airships.[5] The force on aerostat hulls resulting from turbulence has been controversial. Based on research by Calligeros and McDavitt,[6] the present model does not include forces due to fluid acceleration because the turbulence is represented as a frozen field or traveling wave translated at the mean wind speed. Tischler and Jex[7] not only include these forces, but assert the existence of an additional force due to a presumed pressure gradient associated with the fluid acceleration. Etkin has taken issue, particularly with the latter point[8] (see also Ref. 9). Etkin and D'Eleuterio[10] have objected to the inclusion of convective acceleration terms in the present model as derived by Jones and DeLaurier.[2] In response, Jones and DeLaurier have shown that these terms are required by classical theory.[11] Of equal importance is the wind input model. Unlike airplanes and airships, which create their own relative wind, usually large compared with the ambient wind, the tethered aerostat is anchored in one location, subjected to the ambient mean wind and turbulence, with its motions constrained by the tether. Thus the frozen-field model is not the same. In the former, the turbulence is assumed to be frozen in space and the vehicle is translated through it,[12] whereas for the tethered aerostat, the turbulence is modeled as a frozen volume translated through the vehicle at the mean wind speed. Verification of this model is an important aspect of these studies.

The opportunity to verify a simulation with real flight data is rare, primarily because of the expense involved and the need for restricted air space. During the late 1970s, TCOM instituted a program of instrumented flight of a 365 aerostat on Grand Bahamas Island, with the objective of obtaining data to verify the NLDS. Those results, published in Ref. 1, were thought to duplicate the recorded flight data fairly well; however, some of the parameters, particularly the tether tension, were greater than actual. Since then the code has been improved in many ways. The present studies are, therefore, important in reexamining the fidelity of the simulation with improved technology for measuring and recording data. They have already lead, in the course of this study, to an improvement in the code with respect to the wind model and its interface with the aerodynamic model. These flight data will continue to provide a base for testing new developments and modifications of NLDS codes.

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Sources of error in these studies include reconstruction of the true ambient wind from the relative wind obtained from the anemometer and the aerostat's velocity from integration of the position and orientation as a function of time. In addition, the idealized turbulence model requires an assumption of a constant mean wind over the sampling period. The wind measurements are subject to question due to the proximity of the three-axis anemometer to the aerostat. In addition, the boundary conditions differ for the flight data and the simulation. For the latter, the aerostat was initially in static equilibrium, whereas the real aerostat was in dynamic motion. For integration, as in the simulation, errors may accumulate. Thus, an exact duplication by the NLDS should not be expected.

Coordinate Systems and Nomenclature

In both the NLDS and the full-scale flight data, the aerostat's position and orientation are described relative to an Earth-fixed coordinate system (EFS), shown in Fig. 1. The winds, which were measured with a three-axis anemometer mounted on the port fin, were recorded relative to a body-fixed system (BFS). The two systems are related by a transformation matrix, which rotates the latter through roll, pitch, and heading angles, and by the vector location of the BFS relative to the EFS as shown in Fig. 1. Forces and moments are computed in the former and integrated in the latter. In the simulation, the EFS is fixed by the initial position of the aerostat in static equilibrium, with x parallel to the mean wind direction. Likewise, in the BFS, x' is parallel to the aerostat's longitudinal axis. The coordinate systems are conventional with x, y, and z being forward, to starboard, and down, respectively. The rotations, roll, pitch, and heading, are clockwise about the x, y, and z axes, respectively. The components of the wind vector parallel to x, y, and z are u, v, and w, respectively, with the subscript g indicating the turbulence component, which is the standard deviation σ of the fluctuations in velocity.

Aerostat and Instrumentation

The geometric and other parameters of the TCOM 71M aerostat are given in Table 1. It has an inverted Y empennage and can carry a 1800-kg payload to 4500 m and, due to a power tether, stay at that altitude for a number of days. A Kevlar® reinforced tether provides power to the system and communications through a fiber optic link.

The instrumentation for determining aerostat position and orientation consisted of six global position system (GPS) sensors capable of measuring position in Earth-fixed coordinates with an accuracy of ±5 cm. They were located at the nose, near the tail, forward port and starboard, and aft port and starboard. The data from these sensors were used to compute, in 1-s intervals, the x, y, and z location of the aerostat in EFS coordinates and its pitch, roll, and heading. Velocities were computed by integrating the position and orientation and used to correct the anemometer data for aerostat motion. The tether tension was sensed at the confluence point and at the winch on the ground.

There was only one sensor for measuring the instantaneous wind vector, a Gill-type three-axis anemometer located on the port fin near the tip. Unfortunately, it was located very close to the fin, the lower vane being only 60 cm from the surface. Thus, the flow was undoubtedly accelerated and the wind measurements probably higher than in the freestream, although this effect is impossible to quantify. The wind measurements were corrected for position and transformed to true relative wind components in the BFS. To be meaningful, these winds were corrected for the aerostat's translation velocity obtained by integration of the position. Finally, to be useful in this analysis, the winds were transformed to true winds in the EFS of the measurements.

Table 1 Nominal parameters of the 71M aerostat

Property	Value
Aerostat length	71 m
Aerostat volume	16,700 m^3
Fineness ratio	3.2
Gross weight	4,400 kg
Helium lift	10,300 kg
Tether unit weight	0.65 kg/m
Tether diameter	2.40 cm

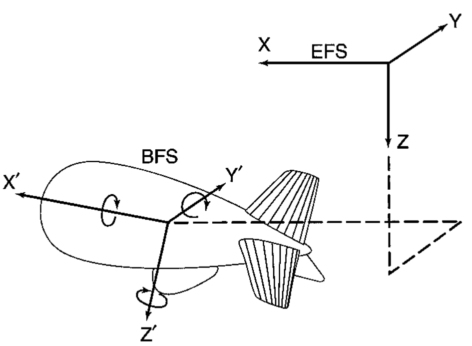

Fig. 1 EFS and BFS of the NLDS.

NLDS Wind Model

The method of applying winds to the NLDS is patterned after that described in MIL-F-8785B[12] with modifications for a tethered aerostat. The mean wind is assumed to be constant, parallel to the x axis of the EFS, which is fixed by the initial position of the aerostat in static equilibrium. The turbulence is the variation in velocity in each of the coordinate axes and in the standard model is isotropic above 533 m (Ref. 12). Of course, in the real world, this may not be the case. In normal use of the NLDS, the turbulence is synthesized using a Dryden power spectrum as described in Refs. 1 and 4. The turbulence, or fluctuations in velocity, is translated through the theoretical model at the mean wind speed. For powered vehicles such as airplanes and airships, this mean translation velocity is the vehicle's speed, but for a tethered aerostat it is the ambient wind velocity. This is an adaptation of the frozen-field model in which the turbulence in each coordinate axis appears to be frozen in space and translated at the mean wind speed.

For comparing the NLDS with real flight, a window of data should be selected that is at a constant altitude and has a reasonably constant wind direction, which can be judged by the wind vector or the aerostat's heading angle. To conform to the model and make comparisons possible, the EFS in which the measurements were made must be rotated about the z axis so that the x axis is parallel with the mean wind direction.

To apply the real winds to the NLDS model, a wind table is made containing the real wind fluctuations about the mean in each of the orthogonal directions in the rotated EFS. Ideally, the mean wind parallel to the y and z axes should be zero and that in the x direction should be the velocity of the frozen field or the propagating velocity. Because the wind table represents turbulence or fluctuations in velocity, the mean must be subtracted from each component of velocity in the wind table. In summary, the following steps are taken in preparing a wind table from the flight data:

1) Select from the data a window of significant time interval, in which the wind direction is relatively constant as judged by the aerostat's heading.

2) Transform all of the data to an EFS with the x axis parallel to the mean heading angle.

3) Make a wind table by subtracting the mean value from the u, v, and w components of the wind. The mean value of the u wind is the wind speed, which is assumed to be the propagation velocity.

Flight Data Selected for Simulation

A window of data was selected from flight 48 with wind components shown in Fig. 2. The 1900 s (32 min) of real wind data have been transformed to an EFS rotated 264.34 deg from that in which the data were recorded in order that the u component is parallel to the mean aerostat heading. The mean values and standard deviations are given in Table 2. Note that the u wind has a steady component of 10.3 m/s, which represents a mean wind speed of 20 kn.

Table 2 Mean and standard deviation of winds in selected window of data

Vector component	Mean, m/s	σ, m/s
u (longitudinal)	10.30	1.898
v (lateral)	0.39	1.606
w (vertical)	1.46	1.908

Table 3 Flight data and static inputs for the simulation

Parameter	Value
Flight altitude	2587 m
Pad altitude	1354 m
Pad temperature	22°C
Pad pressure	862 mbar
Mean wind speed	20 kn
Static pitch angle	7.2 deg

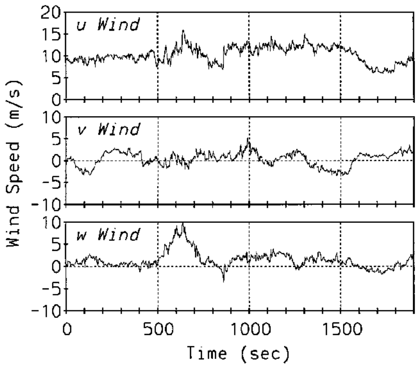

Fig. 2 Wind data from flight 48 from 20:58:13 to 21:29:53 (Greenwich mean time); EFS has been rotated 264.34 deg for application to the NLDS.

A significant feature of the winds, shown in Fig. 2, is a large updraft beginning at about 500 s, in which the upward velocity reaches 10 m/s or 19 kn.

There is a substantial mean value to the vertical component of wind due to the large updraft and possibly the accelerated and diverted flow on the anemometer due to the proximity of the fin. To make a table of turbulence applicable to the NLDS, the mean values of the winds must be subtracted as stated earlier. This obviously introduces some error in representation of the winds. Another source of error is the assumption that the mean wind is constant and in the same direction. This introduces a certain ambiguity between the u and v components of the turbulence. If the real mean wind varies in speed or direction it will be interpreted by this model as turbulence and may exaggerate the lateral turbulence, which will contain a component of the mean, propagating wind. Such an ambiguity will not exist for the vertical component of turbulence.

NLDS Inputs and Outputs

The NLDS is one of a family of supporting programs. The input data file is generated by a static analysis program, which contains the weight and balance and other data on the aerostat as well as environmental parameters. Some of the input data for this simulation are given in Table 3.

Another program reads the NLDS output and presents it in statistical or graphical form. This output usually consists of 34 parameters dumped to the hard drive at 1-s intervals throughout the run. The data dump time can be varied down to the time interval of the integration, which, in the present case, was 0.05 s. The number and type of parameters computed and the output can also be varied. Normally included are the aerostat's location in EFS coordinates, angular attitude in pitch, roll, and heading, vector components of the translation and rotational velocities, and tether tensions at the aerostat and at the winch, as well as accelerations at the payload or any other location on the aerostat.

Reconstruction of the True Wind

The experimental data consist of the aerostat's position and orientation as a function of time and the vector components of the relative wind as measured with the three-axis anemometer. From these data, the actual or true wind must be reconstructed. The relative wind as seen by the anemometer consists of the true or ambient wind in the freestream and an induced wind equal in magnitude to the aerostat's velocity, which is obtained by integration of its position and orientation. The difference between these two components is the relative wind seen by the anemometer. If the transfer function is large and the aerostat moves freely with the wind, then the induced wind is close to the same magnitude as the true wind and the relative wind is the small difference between these two larger numbers. This is shown in Fig. 3 for the lateral component of wind, where the effect is most pronounced.

In the frozen-field model, the turbulent fluctuations are assumed to propagate at the mean wind speed; however, that is not the case for the induced wind. It is a reflection of the aerostat's velocity where, except for rotation effects, every part of the body moves at the same speed at the same instant. Because the induced wind is the major part of the reconstructed true wind, it may very well have an averaging effect on the latter.

Although the aerodynamic model of the NLDS is designed to take into account the nonuniform flow from nose to tail (mode 1), it is possible to run the simulation in a mode such that the turbulence is propagated through the reference point only (mode 2). In this mode, except for rotational effects, all parts of the aerostat see the same wind at the same instant.

Statistical Comparisons of the Simulation with Flight Data

The fidelity of the NLDS on a statistical basis was determined by comparing simulations with flight data. The standard deviations of fluctuations in location and attitude as well as tether tension are compared in Table 4. In these simulation runs, the wind input from

Table 4 Standard deviations of parameters from simulations compared with flight data

Parameter	Flight data	NLDS (mode 2)	NLDS (mode 1)
x Location, m	31.6	30.7	54.8
y Location, m	55.4	63.1	99.3
z Location, m	3.1	2.6	3.9
Pitch, deg	1.2	1.9	4.4
Roll, deg	1.2	2.1	3.5
Heading, deg	12.8	11.1	15.7
Tether tension, kg	353	497	665
u_g, m/s	2.2	2.2	2.2
v_g, m/s	1.7	1.7	1.7
w_g, m/s	1.3	1.3	1.3

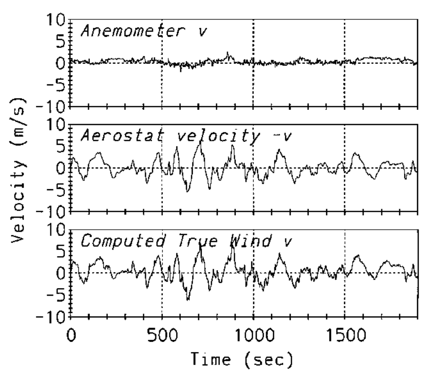

Fig. 3 Lateral components of relative wind as measured by the anemometer, aerostat velocity (induced wind), and computed true wind; negative aerostat velocity is plotted for better comparison with the true wind.

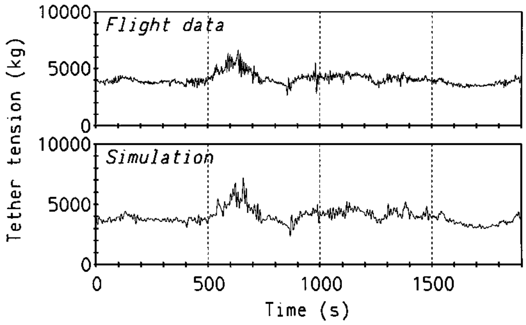

Fig. 4 Tether tension from flight data and NLDS.

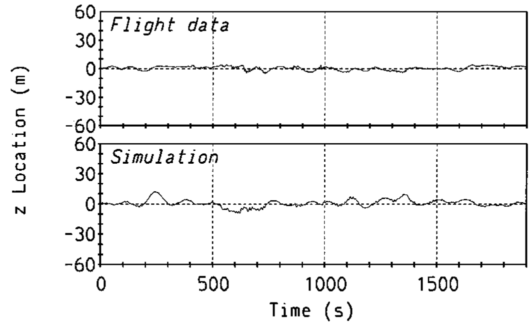

Fig. 7 Aerostat location in the z (downward) direction.

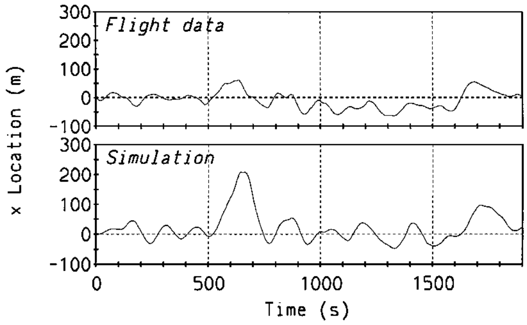

Fig. 5 Aerostat location on the x axis of the EFS.

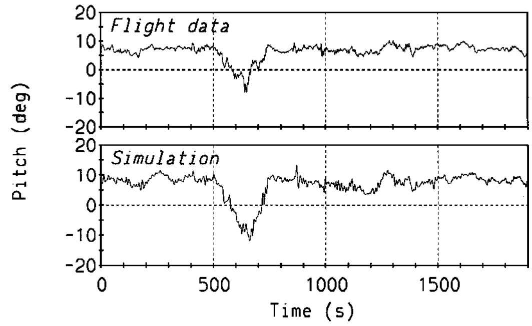

Fig. 8 Aerostat pitch angle from flight data and NLDS.

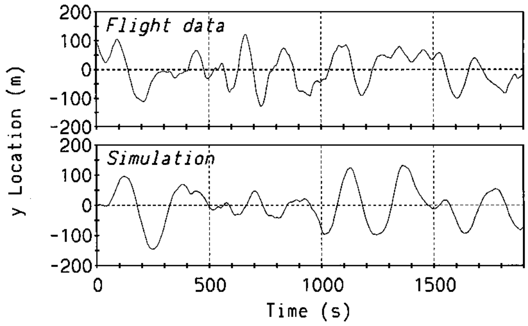

Fig. 6 Aerostat location on the y axis of the EFS.

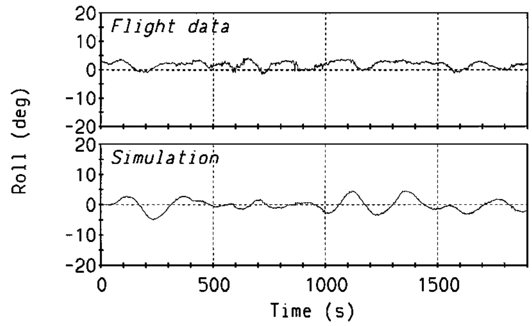

Fig. 9 Aerostat roll angle from flight data and NLDS.

900 to 1900 s in Fig. 2 was taken. This avoids the large updraft at about 600 s, which is regarded as a discrete event and not random turbulence on this scale.

To explore the effects earlier discussed, the simulation was run in the two modes described. Clearly, mode 2 gave better results than the standard mode. It is also evident that for this mode the agreement in x, y, and z location and heading are good, all being within 20% of the standard deviations for the flight data. Tether tension and pitch are significantly higher in the simulations. Roll is very small in all cases, but is nearly double the flight data for mode 2 and a factor of 3 higher for mode 1.

Plots of the data in the time domain confirmed the much better results on a qualitative basis with mode 2. All of the data presented here for the time domain were run in mode 2.

Results of the Simulation in the Time Domain

A simulation run was made with a wind table derived from the data in Fig. 2. The results are shown in Figs. 4–10, in which the NLDS output is compared with the actual flight data. Figure 4 shows that the NLDS reproduces the tether tension of the aerostat over the 32-min period with remarkable fidelity, although the standard deviation is slightly larger. This may be attributed to the accelerated flow over the anemometer giving an apparent wind velocity greater than that in the freestream. This may also account for the exaggerated downward pitch in response to the updraft at about 650 s (Fig. 8). This greater downward pitch is responsible for the charge forward at the same

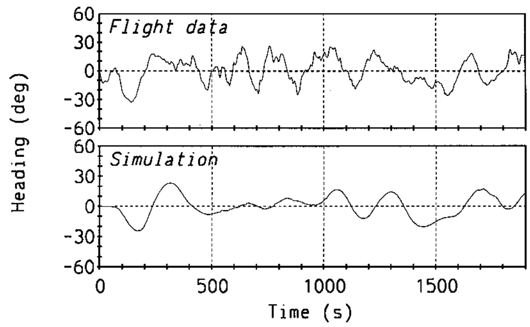

Fig. 10 Aerostat heading, comparing simulation with flight data.

time (Fig. 5). The downward pitch and charge forward in response to updrafts are common phenomena in desert regions such as White Sands. For other parameters, the simulation appears to follow the flight data to a reasonable degree, considering the potential sources of error.

Frequency Spectra

Another important aspect of the simulation's fidelity is in the frequency spectra of the various parameters. This was determined by fast Fourier transformation (FFT) of the time-history data, which gives a frequency distribution dependent on the number of data

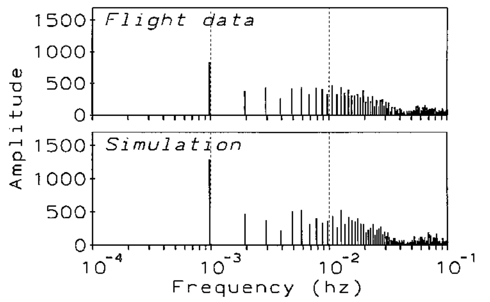

Fig. 11 Frequency spectra of tether tension from flight data and NLDS.

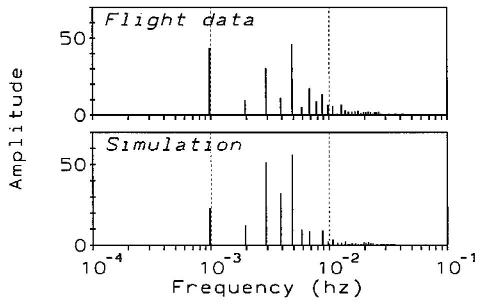

Fig. 12 Frequency spectra of lateral displacement comparing flight data and NLDS.

points used in the analysis. The spectra of two important parameters, tether tension and lateral displacement, are presented in Figs. 11 and 12, respectively, where frequency distributions derived from the simulation and the flight data are compared. The comparisons, which are necessarily qualitative, show a correspondence in the dominant frequencies. Figures 11 and 12 also show that the energy is concentrated at very low frequencies, with very little above 0.1 Hz.

Conclusions

This study demonstrates that real flight data of a tethered aerostat, including recorded relative winds, can be used to assess the fidelity of a dynamic simulation computer program. This requires recording the data in an EFS, which can be transformed to coincide with the mean wind axis as required by the simulation. The wind model, in which the mean wind is assumed to be of constant speed and direction with the perturbations superimposed in each of the coordinate axes, is a satisfactory representation with a properly selected window of data. In this model, the frozen-field concept is applied to an ambient wind, which propagates the turbulence.

A surprising finding, presented in Table 4, was that the simulation run in mode 2, where the turbulence is propagated through a reference point only, with every segment seeing the same wind at the same instant, gave superior results to mode 1, for which the aerodynamic model was designed. This is attributed to the nature of the data, which require correcting a small relative wind with a large induced wind due to aerostat velocity. Because the latter is non-propagating, it may tend to average the turbulence over the whole body.

Much of the evaluation of fidelity by comparing the simulation output to the flight data is qualitative. In that respect, the response of the simulation to the vertical component of the real wind is excellent in reproducing the tether tension and pitch angle of the flight data in detail, including the response to a strong updraft. That the magnitude of the simulated tension and pitch is somewhat exaggerated can probably be accounted for by the accelerated flow on the anemometer, indicating a higher velocity than actually existed. Accelerated flow near the fin would also be enhanced by an increased angle of attack due to the updraft. The vertical motion in the simulation is greater than recorded by the aerostat (Fig. 7) but both are less than 12-m displacement from the initial position. The longitudinal location (Fig. 5) is reproduced very well, except for response to the updraft, which is also exaggerated. As noted, the pitch down and charge forward are typical behaviors of tethered aerostats responding to updrafts commonly seen in desert regions. The lateral motions, y location, heading, and roll, generally follow the flight data but in less detail than in the vertical and longitudinal motions. These are likely more sensitive to deviations of the real winds from the idealized frozen-field wind model. The aerostat heading (Fig. 10) shows a relatively high-frequency component not found in the simulation, the origin of which is unknown at this time.

The simulation is sufficiently close to the real flight data to validate the aerodynamic model, which excludes the effects of fluid acceleration as proposed in Ref. 7 and includes forces due to convective accelerations as discussed in Refs. 10 and 11.

The weakness of these flight tests is in the quality of the wind data, which suffers from the unfortunate placement of the three-axis anemometer in the boundary layer of the fin. This should be corrected in future experiments, possibly by placing the anemometer at the aerostat's confluence point. Even with this deficiency, however, the wind data are remarkably useful and illustrate the importance of onboard wind measurements from which detailed time-history comparisons can be made.

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