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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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