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A Computer-Controlled Video Instrument for Wind-Tunnel Testing of Lifting Parachutes

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Wind-tunnel tests of parachutes require that aerodynamic data be obtained simultaneously on both the forebody and the parachute. In particular, it is necessary to correlate the relative motion between the parachute and forebody to the loads exerted by the parachute on the forebody as a function of time during dynamic tests, disreefing, and for the full-open canopy. A computerized video instrumentation technique was developed to provide this correlation during a full-scale wind-tunnel test of a unique lifting parachute configuraton. The instrumentation consisted of a small, rugged TV camera, mounted on the forebody base, which tracked the positions of two lights attached to the inside of the parachute canopy. The positions of the lights were digitized by an on-line minicomputer and converted to yaw, pitch, and roll angles relative to the forebody. These data were obtained 30 times per second and stored on disk memory along with instantaneous values of the axial force and rolling moment exerted by the parachute on the forebody. The motion-force correlations made it possible to determine the yaw damping of the lifting parachute and provided information on the specific sources of rolling moments generated by the parachute. Test results indicate that this computer-controlled video instrumentation can be applied to free-flight tests, dynamic tests, and measurements of relative motion among multiple bodies.

Nomenclature

C_A	= axial force coefficient
C_l	= rolling moment coefficient
F_A	= parachute axial force
FL	= lens focal length
K_α	= camera calibration constant in pitch direction
K_β	= camera calibration constant in yaw direction
l	= parachute reference length
M_R	= parachute rolling moment
q	= dynamic pressure
S	= parachute reference area
X_0, Y_0	= coordinates of camera centerline
X_1, Y_1	= coordinates of left light
X_2, Y_2	= coordinates of right light
α_F, β_F	= forebody angle of attack and sideslip
α_P, β_P	= parachute angle of attack and sideslip relative to the wind
$\Delta\alpha, \Delta\beta$	= parachute angle of attack and sideslip relative to forebody
$\Delta\phi$	= parachute roll angle relative to the forebody
$\Delta\phi_0$	= initial roll angle offset of lights with parachute at zero roll

Introduction

A LIFTING parachute[1] is being developed for low-altitude aircraft deliveries of a payload. At transonic speeds, this parachute is designed to decelerate the payload and simultaneously lift it above the aircraft release altitude. The additional altitude is needed to insure that the payload impacts the ground at sufficiently low velocity and high trajectory angle so that the structure of the payload is not compromised. Lift is created by varying the porosity asymmetrically throughout the canopy: a nonporous liner is located at the top of the circular canopy and high-porosity ribbons are positioned at the bottom. Additional porosity can be added at the sides of the canopy to change the stability, drag, yaw damping, and yaw stiffness of the chute. In order to optimize the altitude and deceleration of the lifting parachute while retaining adequate stability and yaw characteristics, it was necessary to conduct a wind-tunnel test of full-scale lifting parachutes with different porosity distributions. The test program required that the motion of the parachute relative to the payload (forebody) be measured and correlated to the forces and moments exerted by the parachute on the forebody. Parachute motion was measured in earlier quarter-scale wind tunnel tests using a slender, instrumented rod which connected the parachute to the forebody. While this approach was acceptable for small-scale testing, it could not be used in full-scale tests because the rod would have to be too heavy in order to prevent errors due to its curvature under aerodynamic loading. The subject of this paper is the computer-controlled video technique which was developed to measure parachute motion relative to the forebody while avoiding all of the potential measurement errors associated with previous intrusive techniques.

The test program called for several different experimental phases, each of which placed special requirements on the video system. The principal objective was to measure the motion of fully-inflated parachutes relative to the forebody and correlate that motion with instantaneous values of parachute axial force and rolling moment. For these tests, the parachutes were in a steady-state configuration, but some dynamic motion existed due to the instabilities of the low-overall-porosity canopy configurations under investigation. The sources of canopy rolling moments were of particular interest during this experimental phase, since excessive roll causes increases in lateral dispersion and reductions in staging altitude. Measurements were required for flight-tested parachutes, new parachutes, and experimental canopy configurations. In the second phase of the test program, each parachute was pulled away from its trim position and released in order to obtain dynamic stability data. The video system was required to track the parachute motion during the high lateral accelerations occurring immediately at release. The final test phase required measurements of parachute motion during the inflation of the canopy. High accelerations in both pitch and yaw were anticipated in these experiments. For all phases of the test, motion data were required immediately after each run so that the limited amount of wind-tunnel test time could be used to study only those phenomena which were

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most important in optimizing the performance of the lifting parachute.

The video system which was developed in response to these test requirements is described in detail in this paper. The use of an on-line minicomputer as an integral component of this technique is also explained. Typical results from the test are presented and further applications of this type of video instrumentation in aerospace test facilities are suggested.

Experimental Setup

Figure 1 provides a side view of the full-scale model installed in the NASA Ames 40×80-ft wind tunnel. The model is shown at typical trim conditions, which were $\alpha_F \approx -30$ deg and $\Delta\alpha \approx -5$ deg. The full-scale model had a forebody diameter of 18 in. and a length of 12 ft. The constructed diameter of the parachute was 13 ft. Some of the parachutes tested had been recovered from previous flight tests. Several had been wind-tunnel tested, flight tested, and were being wind-tunnel tested again to measure flight changes.

The model was supported in the wind tunnel from a horizontal beam which was attached at its ends to the two vertical tunnel support struts. The forebody was free to move in pitch and yaw. Forebody motions (α_F, β_F) were measured with geared potentiometers located inside the forebody. It was also possible to lock out forebody yaw motion with mechanical stops as was required for a portion of the test program. Parachute axial force, F_A, and rolling moment, M_R, were measured by strain gage load cells also located within the forebody. The parachute suspension lines were attached to a mechanism within the rear of the forebody which transmitted the parachute loads to the F_A and M_R transducers. This attachment allowed the same lifting parachute freedom of motion in pitch, yaw, and roll as in conventional flight.

Two battery-powered light packs were attached to radial ribbons inside the parachute canopy. The lights were diametrically separated across the parachute vent, with the parachute centerline passing midway between them. Separation distance between the lights was varied from 3 ft to 5.33 ft depending upon the parachute configuration and the anticipated parachute motion. For clarity, Fig. 1 has been drawn to indicate a nonzero parachute roll angle, $\Delta\phi$.

The TV camera was rigidly attached to the base of the forebody and its centerline was coincident with the forebody centerline. The focal length (FL) of the camera lens was selected to be short enough to contain the two lights within the camera field of view for the maximum excursions of the anticipated parachute motion. An excessively large field of view results in the loss of resolution for the optical measurements.

Electrical instrumentation lines for the camera, transducers, and firing signals for explosive cable cutters all passed through the model forebody, down the vertical support struts and on to the control room for processing. Computer processing of the camera data provided the pitch, yaw, and roll of the parachute relative to the forebody, as will be presented later.

TV Camera/Image Digitizer

Characteristics of the TV cameras, lenses, and image digitizer used during the two tunnel entries are described in Table 1. Both cameras used silicon diode vidicon tubes which are very sensitive to infrared radiation. Incandescent lamps as used in the battery-powered light packs produce considerable amounts of infrared radiation. Thus, by using an infrared selective filter and adjusting the lens aperture on the camera, it was possible to suppress sufficiently the background radiation so that the camera only "sees" the two lights which appear with good contrast as two white spots on a black background. The X and Y coordinates of each of these spots are then used to calculate the parachute angular position relative to the camera lens. A transformation of axes then references the parachute motion to the base of the forebody.

The TV camera used on the first tunnel entry (April 1977) was a laboratory environment camera with extremely good optical characteristics but with a susceptibility to vibration. Because there is considerable high-frequency vibration transmitted from the parachute to the base of the forebody and the camera in this type of testing, this camera became quite noisy and unreliable as the test program progressed. In addition, this camera, lens and mounting support were quite large (18-in. length, 3.5-in. diam), which resulted in more interference and potentially could have become entangled in the parachute suspension lines during the more dynamic disreefing phases of the second test program. Therefore, during the second tunnel entry (Nov. 1977), a more rugged, miniature camera (4-in. length, 1.6-in. diam) was acquired and used with excellent results.

The real-time image digitizer scanned the TV image every 1/30 of a second and recorded the intensity value of each

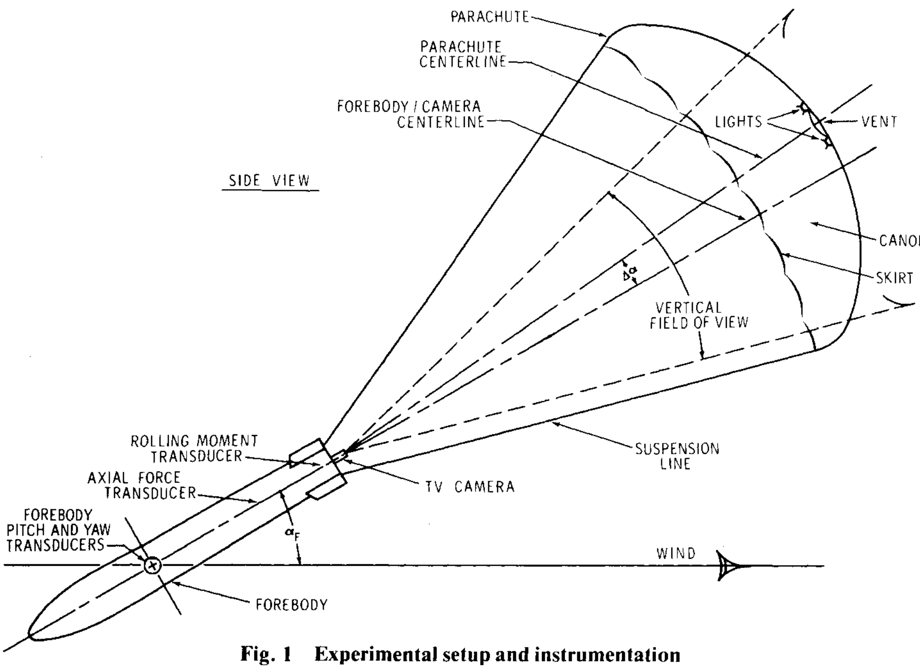

Fig. 1 Experimental setup and instrumentation

Table 1 Camera/digitizer charactertistics

Camera	Lens, *FL*, mm	Field of view, deg vertical	Field of view, deg horizontal	Scanning box size, deg	Resolution, deg $\Delta\alpha,\Delta\beta$	Resolution, deg $\Delta\phi$ [a]	Max. tracking velocity, deg/s
Standard 18-in. length 3.5-in. diam	25	21	28	1.75×1.75	0.09	0.35	26
Miniature	25	13.5	18	1.13×1.13	0.06	0.31	16
4-in. length	12.5	27	36	2.25×2.25	0.11	0.62	33
1.6-in. diam	10	34	45	2.83×2.83	0.14	0.64-0.78	42

[a] Function of distance between lights (3 ft to 5.33 ft) and distance from lights to camera (16.5 ft to 24 ft).

picture element (pixel) in its 76,800 word memory. These pixels were uniformly distributed over the TV image in a matrix composed of 240 rows and 320 columns. The pixels corresponding to the two parachute lights had a value 1 stored in the digitizer memory; the pixels corresponding to the black background had a value of 0 stored in the digitizer memory. To determine the location of each light, it was necessary to interrogate the digitizer's memory and locate the matrix coordinates (pixels) which contained the value 1. Unfortunately the computer which searched the digitizer's memory was not sufficiently fast to interrogate the entire 76,800 words and perform its other functions before the next image frame was available from the TV camera/digitizer. (This task is not possible for any known general purpose minicomputer.) The compromise solution required that the computer be constrained to perform only a limited memory search based upon the position of the lights as determined from the previous search and to update this value for the next scan. Based upon the time available after completing the image digitization and before the next camera image refresh, it was found possible to search two boxes, 20 pixels square, centered about each of the previously acquired light positions. The corrersponding scanning box size (in degrees), as presented in Table 1, was a function of the camera lens focal length and vidicon target size. The optical system resolution (in degrees) for the angular measurement of $\Delta\alpha$ and $\Delta\beta$ was only a function of the camera field of view (lens *FL*) and the number of horizontal (320) and vertical (240) pixels resolved by the image digitizer.

The resolution for $\Delta\phi$ depended upon the resolution for $\Delta\alpha$ and $\Delta\beta$ and also upon the actual measured distance between the lights on the parachute and the distance from the lights to the camera. A wider separation of the lights provides improved roll resolution, but increases the probability of one light exiting the field of view during large yaw oscillations.

The maximum angular tracking velocity presented in Table 1 was derived from the scanning box size and the camera refresh rate of 30 times per second. This was the angular rate to move one-half the box width or height in 1/30 s. If the parachute moved at a faster rate, the computer search algorithm would not find the light on the subsequent search and position data would be lost. Thus, for dynamics testing, a larger field of view was required with corresponding higher tracking velocity but lower measurement resolution for the same image digitizer characteristics.

The TV camera and image digitizer were calibrated before the tunnel entry for each of the fixed focal length lenses required for the various anticipated test conditions. The calibration procedure consisted of placing a test fixture, composed of uniformly spaced pinholes forming a grid pattern, a measured distance in front of the camera lens. The test fixture was adjusted such that a central pinhole was coincident with the camera longitudinal axis and so that the test pattern filled the entire camera field of view. The fixture was then backlighted, which provided a calibration pattern of small bright spots. The angular displacement from the centerline to any hole was then easily computed. The entire hole pattern image was then digitized and served as the calibration for that camera/lens/digitizer combination. This procedure was repeated for each of the lenses to be used. This extensive calibration could be used to provide local corrections to any region of a nonlinear vidicon tube. In practice, both camera tubes were very linear, which resulted in only requiring four calibration constants (K_α, K_β, X_0, Y_0) to characterize each of the lens/camera combinations.

Data Reduction

Using the coordinates of each light (X_1, Y_1); (X_2, Y_2) as obtained by the minicomputer search of the digitized camera image, it was then possible to calculate the pitch, yaw, and roll of the parachute centerline relative to the forebody. These angular displacements are given by

$$\Delta\alpha = \tan^{-1}\left(K_\alpha\left[\left(\frac{Y_1+Y_2}{2}\right)-Y_0\right]\right) \tag{1}$$

$$\Delta\beta = \tan^{-1}\left(K_\beta\left[\left(\frac{X_1+X_2}{2}\right)-X_0\right]\right) \tag{2}$$

$$\Delta\phi = \Delta\phi_0 + \tan^{-1}\left(-\frac{K_\alpha}{K_\beta}\left[\frac{Y_2-Y_1}{X_2-X_1}\right]\right) \tag{3}$$

where $\Delta\phi_0$ was the initial roll offset of the lights when the parachute was at zero roll orientation.

The parachute angles of attack and sideslip relative to the wind axis were obtained by algebraically combining the forebody deflections and the parachute deflections relative to the forebody to give

$$\alpha_P = \alpha_F + \Delta\alpha \tag{4}$$

$$\beta_P = \beta_F + \Delta\beta \tag{5}$$

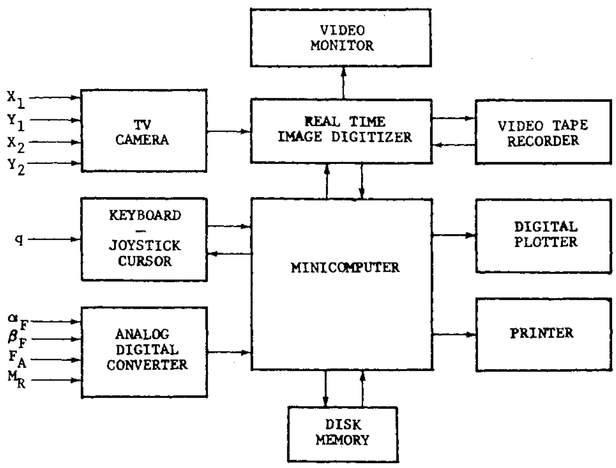

Fig. 2 Data acquisition and processing system.

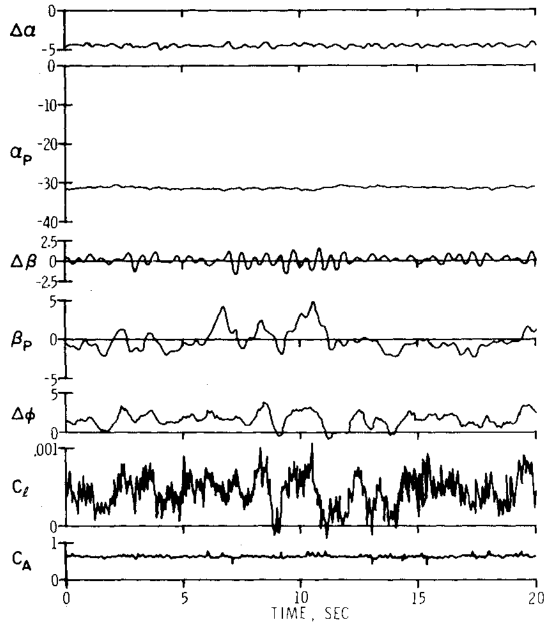

Fig. 3 Parachute motion and forces near trim conditions.

The parachute axial force and rolling moment coefficients were computed in the usual manner as

$$C_A = F_A/qS \tag{6}$$

$$C_l = M_R/qSl \tag{7}$$

The preceding equations were used to provide reduced data plots immediately after each wind-tunnel run. Computed mean values and standard deviations of selected data were also obtained for the model at the trim condition. All of the raw digital test data were permanently retained for subsequent detailed analysis and modeling at Sandia Laboratories.

Data Acquisition and Processing System

Figure 2 is a block diagram of the data acquistion and processing system used for the two full-scale lifting parachute tests. The data acquistion devices are located on the left of the figure and consisted of the TV camera, the computer console keyboard/joystick cursor, and the analog-to-digital converter (ADC). The operation and characteristics of the TV camera and the real-time image digitizer were presented previously. The camera output was displayed on a video monitor during the test and recorded on video tape for more detailed viewing after the test. It was also possible to play the video tape into the digitizer in order to evaluate the effect of programming changes and for system hardware checkout. The keyboard was used for system control and for entering test parameters. The joystick cursor provided a means to acquire initially the position of each parachute light prior to starting the data run. The ADC digitized the data from the load cells and the forebody angular position transducers as discussed previously.

The heart of this instrumentation system was the minicomputer. Because of the large quantity of data acquired per run (~8200 points) and the constraints of real-time image processing, the computer was the critical element in this measurement technique. With a computer in the system, it was then possible to reduce the data on site and make it available to the test engineers. This resulted in timely informed decisions regarding test direction, data reduction changes, and parachute modifications with a better utilization of the available testing time.

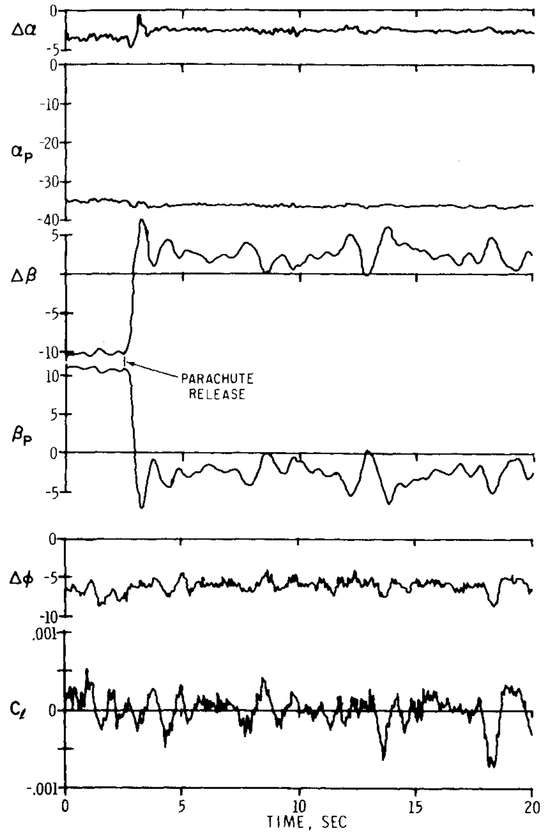

Fig. 4 Yaw dynamic motion and forces with forebody restricted in yaw.

Under direction of the computer, the light coordinate data ($\Delta\alpha, \Delta\beta, \Delta\phi$) along with the model forebody position data (α_F, β_F) and the parachute load data (F_A, M_R), obtained from the ADC, were recorded at a rate of 30 times per second for the duration of the wind-tunnel run and then stored on the disk memory. After the run these data were retrieved, reduced, and presented in the form of digital plots and summary listings using the plotter and printer shown on the right side of the figure.

Discussion of Results

Parachute motion data and rolling moment coefficient results are shown in Fig. 3 over a 20-s test segment for the case where the lifting parachute is nearly at trim conditions. The time-dependent variation of the rolling moment coefficient does not seem to correlate with the relative pitch or yaw angles between the forebody and the parachute. However, a time correlation does exist between C_l and the relative roll angle $\Delta\phi$. Values of C_l were plotted vs $\Delta\phi$ as a function of time for several of the lifting parachutes tested. Each correlation had the same slope, and the slope was consistent with the incremental increase in C_l which would be caused by twisting the suspension lines by an incremental amount in $\Delta\phi$ at the parachute.

The rolling moment coefficient is not solely dependent upon $\Delta\phi$, however. To prove this from the data, the computer calculated mean values of C_l and $\Delta\phi$ from the 1024 digitized data points over a 34-s run. A correlation exists between these mean values for all of the parachutes tested, but the slope of this correlation is different from the slope of the time-dependent $C_l - \Delta\phi$ correlation. This result indicated that rolling moment coefficients may be affected by parameters whose source is not in the canopy, such as variations in suspension line lengths.

Typical results from parachute yaw dynamic tests are shown in Figs. 4 and 5 for the cases where the forebody was first constrained in yaw (using mechanical stops) and then

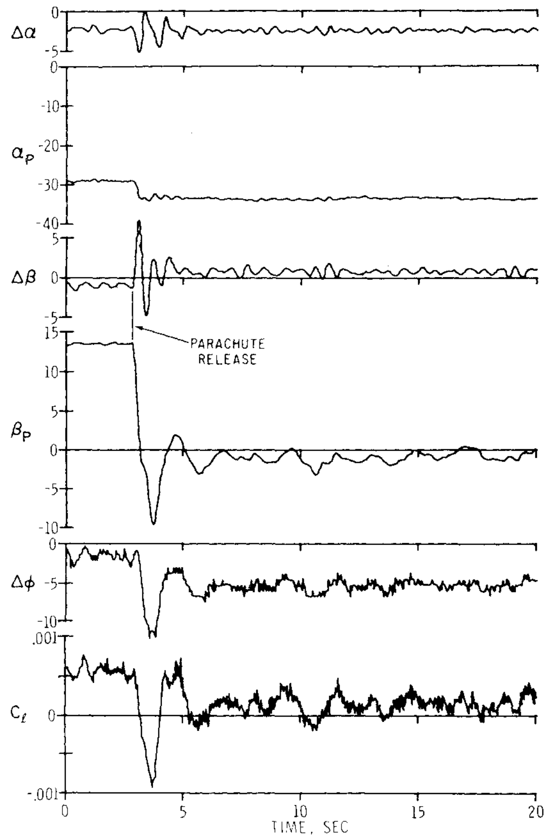

Fig. 5 Yaw dynamic motion and forces with forebody free in yaw.

allowed freedom in yaw. The yaw dynamic tests were performed by mechanically deflecting the parachute with cable winches located on the tunnel side walls and floor. These cables were attached to the parachute in the vicinity of the vent so as to provide uncoupled displacements in parachute pitch, yaw, or roll from the trim conditions. The testing sequence consisted of establishing tunnel flow and displacing the parachute to the desired initial offset conditions. Next, the data-taking sequence was initialized and the explosive cable cutters, located near the vent, were fired, which released the parachute. The motion and load data were then recorded as the model returned to its initial trim conditions.

Parachutes with low porosity at the sides of the canopy were not stiff in yaw, and the resulting accelerations were easy to track using this video system. Some of the new canopy configurations with high-porosity sides were much stiffer in yaw, however, and the computer search algorithm had to be biased in the direction of the initial parachute motion in order to provide tracking after release. In each of these tests, care was taken to perturb the parachute only in yaw (not in roll) so that coupling among other degrees of freedom could be minimized. The initial yaw motion (roughly 3 s after releasing the parachute) showed one or two cycles of oscillation before the parachute motion is dictated by canopy instabilities. The peaks of the oscillations and the period of oscillation were taken from the video motion data and used in a linear aerodynamic model of the canopy motion to calculate yaw damping coefficients for each parachute. Although this model assumes linear aerodynamic restoring forces (which is not true for large displacements), the estimates of yaw damping from this model were adequate for comparing the performance of the different canopy configurations. The yaw damping data provided by the video system showed that increases in porosity at the sides of the canopy caused increases in yaw damping. Future canopies for lifting parachutes are being designed with high porosity at the sides as a result of these measurements.

Several exploratory disreefing runs were made to evaluate the video technique and identify problem areas which must be resolved before the next tunnel entry. Two major problems were identified. The first problem concerns the visibility of the lights when the parachute is fully reefed. The second problem results from the very large and unpredictable angular accelerations which occur during asymmetric inflations of the parachute canopy from the reefed condition.

With the lights located inside the canopy near the vent, they cannot be "seen" by the camera when the parachute is too closed, as in the fully reefed condition where the opening was about 1 ft in diameter. For an intermediate condition of a 6-ft reefing diameter, the lights remained visible and were tracked for some runs. By installing the lights on the parachute skirt, they would be visible continuously even when fully reefed, but this would require a lens with a very large field of view and a subsequent loss in measurement resolution. On two disreefing runs, lights were fractured either by impacting an adjacent radial line or by the acceleration loads imposed during the inflaton process. This problem was corrected and new light packs will be made more rugged.

The large angular acceleration of the lifting parachute which occurs at disreefing requires that the computer algorithms which searched for the lights be modified. If the direction of the initial motion can be predicted, then the scanning box shape can be elongated in that direction while maintaining the same search area. Alternately, it is possible to program an adaptive algorithm which initially searches a box of twice the area, but half the resolution, by only interrogating every other pixel. After the acceleration has decreased, the algorithm returns to the smaller, but higher resolution, scanning box. These techniques and others may improve the frequency response of this video technique for special cases, but the actual TV camera refresh rate of 30 scans/s will ultimately limit this hardware for measurements of high-frequency phenomena. The development of addressable, large array diode matrix and charge-coupled device (CCD) cameras will significantly alleviate sampling rate limitations for this type of application.

Summary and Conclusions

A computer-controlled video instrumentation technique was developed to provide time-resolved data on the relative motion between a lifting parachute and a model forebody during tests in the NASA Ames 40×80-ft wind tunnel. A small TV camera, mounted on the base of the forebody, tracked the position of battery-powered lights on the canopy. An on-line minicomputer digitized the positions of the lights, converted the positions to relative angles between the parachute and forebody, and provided correlations between the relative motion and measured parachute axial force and rolling moment. The inclusion of a minicomputer in the system resulted in an instrument which was very adaptive to evolving test requirements and responsive to the engineering need for timely and informative feedback of testing direction and progress. This instrumentation made it possible to identify some of the mechanisms which cause roll of the lifting parachute. Additionally, video measurements of canopy yaw motion provided comparative values of yaw damping among candidate lifting parachute canopy configurations. Future canopy designs will have higher porosity at the sides of the canopy to obtain higher yaw damping and yaw stiffness. Limited success was obtained in the final test phase, which investigated the applicability of this instrumentation technique for obtaining data during the very dynamic motions associated with disreefing of either the fully or partially reefed lifting parachute.

This type of computer-controlled video instrument could be applicable to a number of aerospace measurement requirements, in addition to the measurement of relative two-body motion for which it was designed. For wind-tunnel free-flight testing of symmetric models such as bomb and rocket shapes, the darkened model could be provided with two small reflective dots, separated along the model axis, which are repeated at 120-deg intervals around the model body. Utilizing a single camera, viewing from the side, it would be possible to obtain the model pitch, roll, and axial displacement. By using two cameras, viewing from the top and side, the computer could be programmed to provide model pitch, yaw, roll, and trajectory information. Alternately, high-speed movies of this same model could be taken from orthogonal views, using two cameras, with suitable time base correlation or using a single camera with a split frame of the two orthogonal views. Each frame of this film could then be scanned and the model motion could be computed. Dynamic stability testing of models supported on air-bearing rigs represents a simplified application of the free-flight technique.

Unusual testing situations might require measurement of sting deflection, model bending or torsional deflection. By accurately placing a suitable dot pattern on the object to be measured and then digitizing the pattern image, it would be possible to measure the changes and compute the loads. The accuracy of these measurements will depend on the camera field of view and the system calibration procedure. Model leveling could be accomplished using the same procedure.

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Reference

[1] Rychnovsky, R. E., "A Lifting Parachute for Very-Low-Altitude, Very-High-Speed Deliveries," *Journal of Aircraft*, Vol. 14, Feb. 1977, pp. 184–187.