Tetroon Drag Coefficients from Experimental Free-Flight Data

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ABSTRACT

Drag coefficients were determined for a 152-cm (60-inch) tetrahedral Mylar plastic balloon in free flight as functions of Reynolds numbers ranging from 10^4 to 3.3×10^6 . Vertical relative air speeds ranged from 9 to 270 cm sec⁻¹. Most drag coefficients derived from the 186 tests lay between 0.7 and 0.8. The average drag coefficient was 0.73 for point-first motion and 0.72 for broadside-first motion. For relative speeds ≤ 100 cm sec⁻¹, the range of interest of the Air Resources Laboratories, the average drag coefficient was 0.74 for both point- and broadside-first motions. Five force (free lift) category observations were duplicated on different days giving generally good repeatability of drag coefficients.

1. Introduction

Since about 1960, tetrahedral-shaped constant-density balloons (hereafter called tetroons) of Mylar plastic have been used for tracing horizontal, and in some cases, vertical air movements (e.g., Angell *et al.*, 1972). Little criticism has been expressed on the tetroon's horizontal air-parcel tracking accuracy. However, questions have been raised about the ability of the tetroon to depict vertical air speeds since its vertical speed is the sum of air vertical speed and tetroon relative vertical air speed, the latter due to the tetroon's displacement from its equilibrium float surface.

The tetroon drag coefficient has been assumed to be 0.8 for both point- and broadside-first relative motions and only Whannel (1965) attempted to confirm this value, deriving an average drag coefficient of 0.75 for the 152-cm (60-inch) tetroon at a relative speed of 150 cm sec⁻¹. Apparently, no wind tunnel drag data are available for geometric tetrahedrons (Hoerner, 1958). However, such drag data would have been of doubtful value since the inflated tetroon is quite rounded and, unlike the geometrical tetrahedron, has no fixed boundary-layer-separation edges.

Reliable tetroon drag coefficients have been needed to provide more accurate estimates of vertical air speed. To this end, 186 drag measurements were made in 1971 with the full-scale tetroon in free flight to approximate field-experiment conditions. Relative air speeds ranged from 9 to 270 cm sec⁻¹, which included not only the low speeds most frequently encountered by the tetroon but also speeds high enough to partially overlap Whannel's tests. Both point- and broadside-first motions were tested.

2. The test environment

The drag tests were made in the center of the enclosed sports arena of the University of Idaho at Pocatello. The floor-to-ceiling distance was about 34 m and the floor dimensions were 128 m $\times$ 122 m. An Arriflex 16-mm movie camera, having governor-controlled framing rates and positioned near mid-height of the test track, photographed the tetroon ascents (broadside-first motion) and descents (point-first motion) alongside a measuring strip, marked at every foot of elevation, that extended from floor to ceiling. Also in the camera view was a large-faced clock and a date/run-number card. Air temperature, for density estimates, was measured and recorded each minute by thermocouples suspended along the measuring strip at 1.5, 7.6, 15.2, 22.7 and 30.5 m above the floor. Heated air was blown horizontally into the arena from ports arranged along the two end walls near the arched ceiling. For some low-speed tests, the heaters and blowers were turned off to minimize air movements. Fig. 1 shows the test arrangement and a portion of the closed arena.

3. Test procedure

The drag tests were made by trimming the tetroon to static balance at the floor then removing or adding a specified weight for ascents or descents respectively. For descents the tetroon was pulled to an appropriate height then released. For each free-lift or weight category used, 4 to 9 runs were made. Ascent and descent speeds were averaged both over the run individually and among the several runs of a lift category to cancel the effect of any ambient vertical-component gusts introduced by the heater fans. Chemical smoke, released at several levels

up to about 9 m from the floor, did not show any organized vertical drafts but did indicate slight lateral air motions. Except for the 250 cm sec⁻¹ ascents, the usual radar transponder was suspended below the tetron to simulate actual field experiment conditions. The clock photographed during each run was used in determining tetron speed. The tetron was tethered for ascents with No. 12 nylon thread (2.2 gm per 30 m) in order to recover it at the top of the run. During ascent allowance was made for the resultant decreasing tetron buoyancy due to the thread, but acceleration of the thread was estimated to have a negligible retarding effect. For descents the tether was not used.

The buoyancy force acting on the tetron was measured near the floor before each ascent and descent and was measured at the top of the run for every second ascent, and at the start and finish of each set of descents. The integrated buoyancy force for the category was then found from these measurements plus an adjustment for any non-linearity of the ambient air-density lapse measured by the five thermocouples arranged along the measuring strip. Ambient air-density differences between stadium floor and the top of the run were remarkably stable during the tests.

The 186 ascent and descent tests were grouped for analysis into 31 specific free lift or weight categories (30 gm, 50 gm, etc.) as measured at the floor. Five force category tests were duplicated on different days to test the repeatability of the experiments.

4. Data analysis

The 31 grouped data sets (speed vs force) were applied to Eq. (1),

$$C_d = 2F/(\rho_a A V^2), \quad (1)$$

the standard drag formula for bodies whose speed and size provide a Reynolds number ($Re = LV/\nu$) $\gtrsim 10^5$ (see Table 1 for list of symbols). Since the strong starting acceleration was eliminated from the tetron's average speed, and the remaining minor accelerations, due to density variation with height, were averaged out, the drag force (D) was equated to the free lift or weight force (F) in (1). The resulting drag coefficients were

TABLE 1. List of symbols.

A	frontal area of tetron*
C_d	drag coefficient
D	drag force acting on tetron
F	measured free lift or weight acting on tetron
H	vertical distance over which drag was measured
L	length of tetron along its vertical axis
Re	Reynolds number
ρ_a	ambient air density
T	time interval over which drag was measured
U	relative vertical air speed of tetron
ν	kinematic viscosity of air

* The triangularly-shaped area projected from the tetron along its vertical-motion axis onto a plane perpendicular to that axis.

FIG. 1. Photograph of test arrangement and a portion of the closed sports arena where tetron drag tests were conducted.

plotted on a logarithmic scale as functions of Reynolds number and are displayed in Fig. 2, where dot and cross symbols represent, respectively, broadside- and point-first motion. Most of the drag coefficient values lie between 0.7 and 0.8 and no systematic difference between the two modes of motion is apparent. A slight trend for

TABLE 2. Comparison of drag coefficient measurements duplicated on different days (broadside-first movement only).

Date	Force category	Drag coefficient	Percent differences
3-23	150 gm	0.72	4
3-24	150 gm	0.75	
3-23	100 gm	0.70	0
3-24	100 gm	0.70	
3-23	50 gm	0.70	7
3-25	50 gm	0.75	
3-25	20 gm	0.72	1
3-26	20 gm	0.73	
3-26	10 gm	0.68	14
3-29	10 gm	0.79

FIG. 2. Derived tetron drag coefficients as a function of Reynolds number (and relative velocity) for broadside-first measurements (dots) and point-first measurements (crosses). The heavy dashed line is the resultant regression line while the solid line connects Whannel's drag coefficients.

increasing drag coefficient with decreasing Re is shown by the linear regression (dashed) line in Fig. 2. The one standard deviation range is also shown in the figure. The relatively high drag coefficient at $Re = 3.1 \times 10^5$ was caused by the tetron's tilting in high-speed ascent without a transponder.

Weighted overall average drag coefficients were 0.73 for point-first motion and 0.72 for broadside-first motion. For vertical relative speeds ≤ 100 cm sec $^{-1}$, the range of interest of the Air Resources Laboratories, the weighted average drag coefficient was 0.74 for both point- and broadside-first motion.

Fig. 2 also shows the results of the high-speed tetron drag tests for broadside-first motion made by Whannel (1965) in the Re range of 1.5×10^5 to 6.1×10^5 . His data (solid line) merge well with the experimental data reported here. Whannel's three higher speeds are apparently entering the critical Re region, but in a much smoother manner than do spheres (Rouse, 1938).

The results of the drag measurements duplicated on different days are shown in Table 2 for broadside-first motion only. The repeatability of these experiments was generally good but there was a large discrepancy for the 10-gm category.

5. Error analysis

Errors in deriving drag-coefficient values for the different force-speed categories arise from measurement errors in buoyancy force acting on the tetron, tetron speed, and ambient air density. Experimentally, it was

found that the buoyancy error was not more than ± 0.5 gm and tetron position error no greater than ± 3 cm. Timing error, for a force category, was taken as the magnitude of the average deviation from the mean ascent or descent time as measured (three times for each run) from the clock second-hand image in the movie film. The percentage variation of ambient average air density ($\bar{\rho}_a$) in (1) was small so it was not used as an error argument. Error estimates were made by logarithmic differentiation of (1) and $V = H/T$, and by use of the time error defined above. Several force categories from 5 to 370 gm were selected for probable error computation and the results are shown in Table 3. Probable drag coefficient errors are within 5–10% for force categories down to 10 gm but are fairly high for the 5-gm category.

6. Discussion

Drag tests were made with full-scale tetroons under free-flight conditions at relative air speeds actually encountered in field experiments. The assumption was that the drag coefficients so derived would be more accurate than those obtained from wind-tunnel tests with their complex scaling problems (Bacon and Reid, 1924). By way of comparison, Cherry (1971) tested the drag characteristics of a 31-cm scale model tetron in a wind tunnel for both point- and broadside-first motions. His drag coefficients average 11% greater than those found in this experiment (Fig. 3) for the overlapping Re range. This is unexpected since wind-tunnel-derived

TABLE 3. Probable percentage errors in drag coefficient for a selection of force categories.

Force category [gm]	Broadside-first movement							Point-first movement	
	370	255	200	50	20	10	5	—100	—30
Average speed [cm sec $^{-1}$]	255	223	159	88	52	40	25	—138	—78
$d(C_d)/C_d$ [%]	± 5.7	± 8.4	± 6.0	± 4.9	± 4.4	± 9.5	± 19.0	± 5.2	± 5.9

FIG. 3. Comparison of drag coefficients found by Whannel (by pulling tetrons through the air on an instrumented cart), by Cherry (on a scale model in a wind tunnel), and by this study (ARL). "BS-F" and "P-F" indicate broadside- and point-first motion respectively.

drag coefficients should be smaller for given Reynolds numbers (MacCready and Jex, 1964).

The drag coefficients derived by Cherry, Whannel, and this study are compared in Fig. 3. The variations in results that can arise from making drag tests with different methods are well illustrated in the somewhat divergent C_d values found by Whannel and Cherry at the higher Re values. Whannel's broadside-first drag coefficients are quite compatible with those of this study (ARL, Fig. 3) for overlapping Re values, but his point-first coefficients are somewhat higher. Although he tested full-scale tetrons, he pulled them through the air on an instrumented cart the proximity of which may have adversely affected the flow of air around the tetron at the lowest point-first air speed.

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