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GUIDED DROGUE FLIGHT TEST REPORT

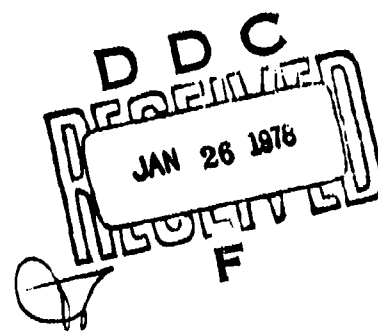
Beech Aircraft Corporation
Wichita, Kansas 67201
U. S. A.

SEPTEMBER 6, 1977

FINAL REPORT

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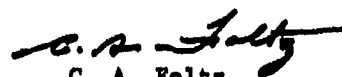
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PREFACE

This report documents the flight test program of a guided aerial refueling drogue conducted during the period from November 1976 through November 1977 at Beech Aircraft Corporation (~~Missile Systems Division~~) for the Department of the Navy under the Naval Air Systems Command.

Messrs. R. A. Hodges and C. V. Lassmann managed the program for Beech Aircraft Corporation.

This final report has been reviewed and is approved for publication.



C. A. Foltz
Director-Missile Systems Division
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SYMBOLS

C_A	Axial Force Coefficient
C_D	Drag Coefficient
C_L	Lift Coefficient
C_C	Chord Force Coefficient
ARM	Rolling Moment Arm (18.5 in)
S	Reference Area (1.0 sq ft.)
q	Dynamic Pressure (PSF)
V_o	Free Stream Velocity (KEAS)
l	Rolling Moment (In-Lb)
I_x	Roll Inertia (Slug-Ft ²)
I_y	Pitch Inertia (Slug-Ft ²)
I_z	Yaw Inertia (Slug-Ft ²)
α	Angle of Attack (DEG)
β	Angle of Sideslip (DEG)
θ	Hose Trail Angle (DEG)
ϵ	Drogue Tilt Angle (DEG)
ϕ	Drogue Roll Angle (RAD)
$\dot{\phi}$	Roll Rate (RAD/SEC)
$\ddot{\phi}$	Roll Acceleration (RAD/SEC/SEC)
δ	Fin Deflection (DEG)

INTRODUCTION

This flight test program is an intermediate step in the development of a guided aerial refueling drogue, capable of aligning with the probe of the receiver aircraft during approach for engagement. The end objective is to alleviate engagement difficulties, including conditions of drogue instability.

In the initial phase, aerodynamic force generators were developed for the Beech 1080 drogue. The general feasibility of the concept was demonstrated by wind tunnel testing and analysis. In this current program, the concept has been developed into a maneuverable drogue system suitable for flight and adapted for radio control.

SUMMARY

The objectives of this program were to design, fabricate and flight test an experimental model maneuverable aerial refueling drogue. The drogue configuration was developed based on modifications to the Beech Model 1080 refueling system. The modified drogue assembly included aerodynamic force generators which were developed from previous wind tunnel investigations. The drogue system included actuating mechanisms, a radio control receiver and a self-contained power source. The drogue configuration was compatible with the Model 1080 refueling store, although no provisions were made for fuel transfer.

The experimental drogue was trailed from the Model 1080 refueling store which was installed on the wing tip of CC-137 tanker. Tests were conducted at 200, 250 and 300 KEAS. Drogue maneuvers were commanded by a radio transmitter from a EA-6B chase airplane. The resulting movements of the drogue were recorded by movie cameras from the tanker and the chase aircraft.

The drogue exhibited stable trail at all steady state conditions. The maneuvering commands resulted in drogue displacements similar to predicted data. However, an unexpected roll characteristic was encountered which made displacements characteristics difficult to evaluate. This rolling motion was believed due to the wing vortex and induced rolling moment due to control fin deflection.

The fins failed to respond to maneuver attempts at 200 KEAS. It was found that a component malfunction in the voltage regulator prevented the voltage from being supplied to the radio control receiver.

DISCUSSION

DESIGN

The test article was an experimental maneuverable aerial refueling drogue with adapter coupling and regulator (Figure 1). The drogue assembly is a modified version of the Beech variable diameter constant drag drogue. The physical arrangement consists of 32 leaves of which alternate leaves are aluminum alloy bar and corrosion resistant steel tubing. The bar and tube leaves are pivoted directly to a drogue mounting ring. The bar leaves are provided with a sheet metal deflector at the tip which is the principal element in controlling the drag level of the drogue. The leaves are fixed in a 25 degree leaf position by means of a machined ring.

Four of the deflector bar leaves are adapted with aluminum control surfaces (6.0 x 12.0) and spaced at 90 degree intervals in order to provide a method of aerodynamic control. The control surfaces are actuated by electrically driven linear actuators. The control surfaces are parallel to the airstream in the neutral or unactuated position and have a maximum of 60 degrees travel in the actuated position.

The adapter coupling is made of aluminum sheet and bar and is the same basic overall dimensions as a standard MA-2 coupling. It incorporates a gimbal which simulates the coupling ball joint and a swivel with a spring loaded indexing ball detent to orient the drogue control surfaces at the full trail position. The adapter coupling also provides a housing for the remote control receiver, power package and associated electrical hardware necessary for control surface operation.

The adapter regulator is a machined aluminum hogout that replaces the fuel regulator and plugs the end of the hose. The coupling/regulator assembly mates with the normal 40 pound ballast weight, and associated hardware for attachment to the hose.

Mass properties for the gimbale portion of the drogue assembly are shown below. The data is summarized as follows:

Weight - 64.75 Pounds

Center of Gravity - 16.49 inches aft of gimbal socket

Pitch or Yaw Inertia about gimbal - 5.287 Slug ft²

Roll Inertia about Centerline - 1.0 Slug ft²

These data were obtained from actual measurements except for the roll inertia. The roll inertia was estimated from calculations made on a comparable design assuming symmetry about the drogue axis.

Certified scales were used for all weighing operations. The center of gravity was obtained by suspending the drogue from single point and ballasting to level position. The yaw inertia was measured using a bi-filar torsional pendulum arrangement as shown in Figure 2. Procedure is to start the drogue oscillating about its centroidal axis and measuring the period of oscillation, "T", to provide input for the equation:

$$I = (R^2 T^2 W) / 4 \pi^2 L \text{ where:}$$

I = Test article mass moment of inertia about oscillation axis - (slug-ft²)

R = Distance from filars to oscillation axis - (ft)

L = Length of filars - (ft)

The drogue was reinforced with a beam and strap assembly as shown to make compatible with the required geometry. The yaw inertia about the c.g. of the suspended configuration was calculated using inputs as follows:

W = 78.25 Pounds

R = 12.00 Inches

L = 153.83 Inches

T = 4.576 Seconds per oscillation. Measured over 52 cycles.

$$I = \frac{(1)^2 (78.25) (4.576)^2}{4 \pi^2 (153.83/12)} = 3.238 \text{ slug ft}^2 = 15000 \text{ lb-in}^2$$

CG and Inertia (about socket) of the basic drogue are calculated in the table below.

	<u>W</u> <u>Pounds</u>	<u>X</u> <u>In. aft of socket</u>	<u>WX²</u>	<u>I_o</u> <u>Lb in²</u>
Suspended Config.	78.25	16.862	22249	15000
Beam	-12.4	20.30	-5110	-7633
Straps	<u>-1.1</u>	<u>0</u>	<u>0</u>	<u>-11</u>
	64.75	16.49	17139	7356

$$I_y \text{ or } I_z \text{ about socket} = EWx^2 + EI_o = 24495 \text{ lb-in}^2 = 5.287 \text{ Slug ft}^2$$

ELECTRICAL

The four drogue fins were controlled with linear actuators with limit switches at half travel and full travel position for the option of 30° or 60° of fin deflection. The actuators were in turn driven by relays in the output circuit of a 72.4 MHz radio link. Actuators and radio receiver were both battery powered by a 16V, 5.0 ampere hour sealed lead acid battery. The transmitter was hand held and powered by ni-cad cells.

A common r.f. carrier was amplitude modulated with five control channels on a time sharing basis where each of the five channels are sampled sequentially for on/off information. (Figures 3 and 4).

Each channel at the transmitter generates a pulse each time it is sampled and pulse width determines the on/off logic level of the fin driver at the receiver end of the link. A synchronous channel scanning technique is used at the receiver. Synchronization with the channel scanner at the transmitter is accomplished with a comparatively long time duration pulse transmitted at the end of each scan sequence.

Eight momentary DPDT push button switches on the transmitter case (Figure 5a) are arranged in a quadrature pattern of four pairs with one button for half deflection and one button for full deflection for each of the four

control fins. Since there are eight buttons on the transmitter and only five available channels to carry information, the modulation has been arranged such that four of the channels provide on/off data for the half deflection condition for each of the four fins and the fifth channel provides a single data link where the same on/off data for the full deflection condition is common to all four fins.

At the receiver end of the radio link, the half deflection driver relays and full deflection driver relays for any given fin are wired such that it requires both half and full drivers for that fin to be turned on for full deflection, but only the half deflection driver to be turned on for half deflection. Thus, although the fifth channel is common to all four fins for full deflection, the four half deflection channels differentiate which fin is driven to full deflection. This wiring set-up causes full deflection of a fin when a half deflection button for that channel is pushed, if simultaneously any one of the four full deflection buttons are pushed. However, half deflection of a given fin with simultaneous full deflection of any other fin was not a necessary requirement for the test.

Fin deflection options were:

- (a) Half or full deflection of any one fin.
- (b) Half deflection of any simultaneous combination of fins.
- (c) Full deflection of any simultaneous combination of fins.

The actuator current and stroke time was determined by installing an oscillograph pickup in the electrical circuitry. Bracket devices were installed at the control surface pivot and to the adapter coupling. A shockcord was installed between the brackets to simulate the air loads at predetermined air speeds (Figure 5b). The following results were obtained:

	Extend		Retract	
	Amps	Time (Sec)	Amps	Time (Sec)
No Load	1.66	1.99	1.72	1.85
250 Knot Load	2.20	2.41	1.82	1.86
300 Knot Load	2.80	2.97	1.95	1.99

FLIGHT TEST

A flight test of the experimental maneuverable drogue system was conducted at Trenton, Ontario. The drogue was installed on the Model 1080 refueling store (Figure 6a), which was attached to the left hand wing tip of a Canadian Forces CC-137 tanker (Figure 6b). A similar model 1080 refueling store and an unguided drogue were installed on the right hand wing tip.

Tests were conducted at 200, 250 and 300 KEAS. The drogue control surface deflections were radio controlled by a transmitter in the EA-6B chase aircraft (Figure 7). The resulting movements of the drogue were recorded by movie cameras from both the tanker and the chase aircraft.

Figures 8 thru 11 show photographs which were made from the movies taken during the test. Figure 8 shows the drogue in its normal trail position at 200, 250 and 300 KEAS. Figure 9 shows a view of the drogue at 250 KEAS with the bottom fin deflected zero and 60 degrees, and another view with the bottom fin deflected zero, 30 and 60 degrees. Photographs of the drogue at 250 KEAS with two adjacent fins deflected 60 degree each are shown in Figure 10. A photograph taken from the chase aircraft at 300 KEAS is shown in Figure 11.

Maneuvering characteristics of the drogue are shown in Figures 12 thru 15. These data show comparisons between theoretical predictions and data actually measured from the flight test movies.

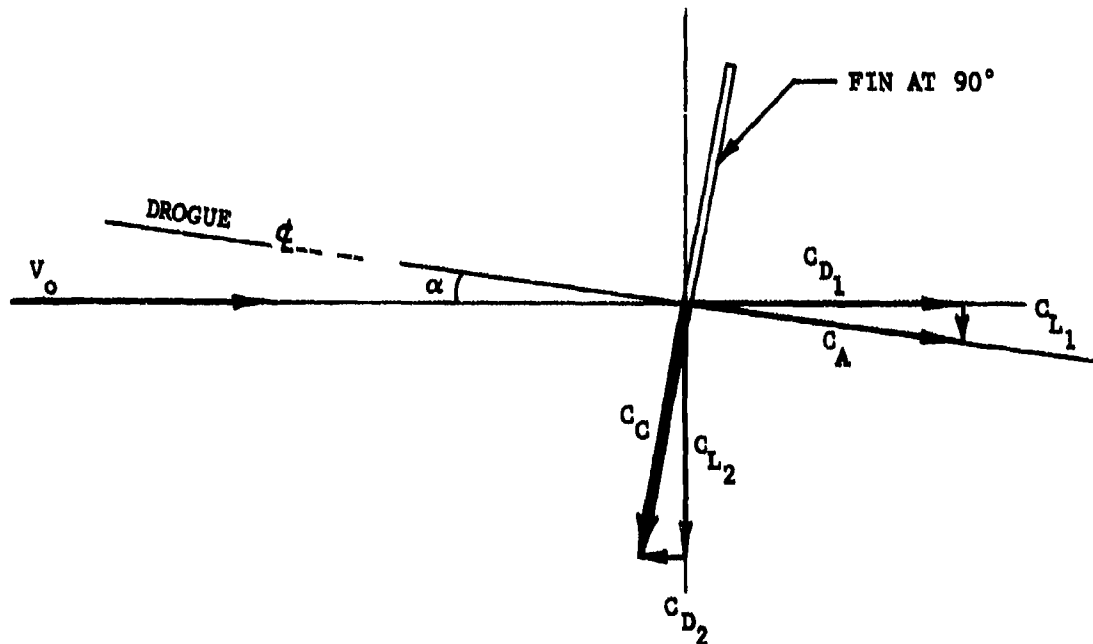
The hose trail angle is shown in Figure 12. It is noted that the trail angle decreases with increasing speed, as would be expected. The flight test data tend to agree within one or two degrees of the theoretical data.

Figure 13 shows the drogue displacement at 250 KEAS. The flight test data indicate that when the bottom fin is deflected 60 degrees, the drogue displaces about 2.4 feet downward. This is slightly greater than the predicted value of 2.2 feet.

The drogue tilt angle at 250 KEAS due to one fin and due to two adjacent fins deflected is shown in Figures 14 and 15, respectively. Both sets of data indicate that the actual tilt angle is about one or two degrees greater than predicted.

Preflight test planning provided for more data to be taken. However, an unexpected roll characteristic encountered during the test made it difficult to evaluate the drogue's maneuvering characteristic. Also, the loss of the drogue receiver part way through the test, prevented any control commands from being executed at 200 KEAS.

It was observed from the movie film, that whenever one control surface was deflected, the drogue would rotate until the surface reached the bottom (6 o'clock) position. It was also noted that when two adjacent surfaces were deflected, the drogue would rotate until the surfaces reached the 4:30 and 7:30 positions. The following theory is proposed as an explanation of these characteristics.



The above sketch represents a view looking at the left hand side of the drogue. The drogue is at an angle of attack α to the freestream V_o , and the left hand fin is deflected 90 degrees.

The total forces acting on the fin are the axial force (C_A) and the chord force (C_c). Then by resolution of the forces, it is seen that:

$$C_{L1} = C_A \sin \alpha$$

$$C_{L2} = C_c \cos \alpha$$

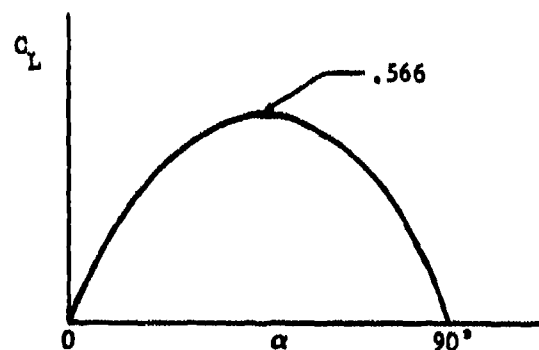
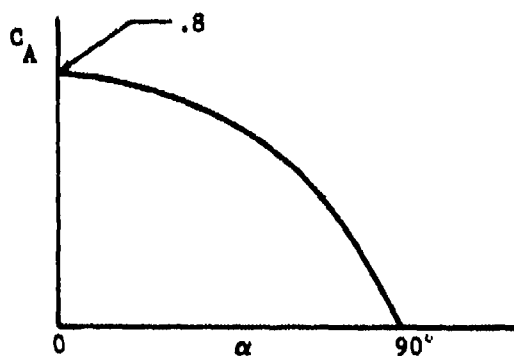
The total lift force coefficient is the sum of the components.

$$C_L = C_{L1} + C_{L2} = C_A \sin \alpha + C_c \cos \alpha$$

Therefore, the chord force can be expressed

$$C_c = \frac{C_L - C_A \sin \alpha}{\cos \alpha}$$

Then it is assumed that the axial force (C_A) and the lift force (C_L) are sinusoidal functions of the angle of attack (α), when the fin is deflected 90 degrees.



The expressions for the axial and lift forces and then expressed

$$C_A = .8 \cos \alpha$$

$$C_L = .566 \sin 2\alpha$$

The magnitude of these curves was estimated from fin force data obtained from previous wind tunnel testing. If it is further assumed that the chord force is a sinusoidal function of the fin deflection, then the chord force equation can be expressed:

$$C_c(\alpha) = \left[\frac{0.566 \sin 2\alpha - 0.8 \cos \alpha \sin \alpha}{\cos \alpha} \right] \sin \delta F$$

(Positive C_c is Down)

Finally, the induced rolling moment of either left or right fin due to α can be expressed

$$l_{L,R} = C_c(\alpha) q S \cdot \text{ARM}$$

(Positive l is clockwise)

Similarly, the chord force due to sideslip (β) can be expressed

$$C_c(\beta) = \left[\frac{0.566 \sin 2\beta - 0.8 \cos \beta \sin \beta}{\cos \beta} \right] \sin \delta F$$

(Positive C_c is to the right)

and the rolling moment of either the top or bottom fin due to β can be expressed

$$l_{T,B} = C_c(\beta) q S \cdot \text{ARM}$$

(Positive l is clockwise)

Now, consider a typical flight condition

300 KEAS, 305 PSF, R.H. Fin at 60 Deg.

$$\alpha = 1.1^\circ \text{ \& \; } \beta = -6.7^\circ$$

$$C_{c(\alpha)} = \left[\frac{.566 \sin(2) (1.1) - 0.8 \cos (1.1) \sin (1.1)}{\cos (1.1)} \right] \sin (60)$$

$$= .0055$$

$$C_{c(\beta)} = 0 \text{ Since top \& bottom fins are at zero degrees deflection}$$

$$l_R = (.0055) (305) (1) (18.5) = 31 \text{ IN-LB (C.W.)}$$

This moment would tend to rotate the drogue clockwise until the right hand fin reached the bottom (6 o'clock) position. In this position, $\alpha = -5.5^\circ$ & $\beta = 0$. Therefore, both $C_{c(\alpha)}$ & $C_{c(\beta)}$ go to zero. So it is seen, that when a deflected fin reaches the bottom position, the induced rolling moment disappears. It can also be shown analytically, that this induced roll due to two adjacent fins would be equal and opposite, and therefore balance when the fins reached the 7:30 and 4:30 o'clock positions.

Data was read from the movie film for a 250 KEAS condition with two fins deflected. Figure 16 shows the roll angle (ϕ) time history when fins 2 and 3 are deflected 60 degrees. Initially, fins 2 and 3 are in the 3 o'clock and 6 o'clock positions, respectively. The drogue rolls clockwise thru 90 degrees in about 1.9 seconds. Then it rolls counter-clockwise until the fins 2 and 3 remain at the 4:30 and 7:30 o'clock positions, respectively.

The first and second derivatives of the roll time history can be taken to give the roll rate ($\dot{\phi}$) and the roll acceleration ($\ddot{\phi}$). Assuming the friction of the system to be small, the rolling moment is found to be

$$l = 12 I_x \ddot{\phi}$$

This rolling moment is plotted in Figure 17. The peak values of moment are seen to be about 40 to 50 in-lb.

Consequently, both methods indicate an induced rolling moment due to fin deflection to be about 30 to 50 in-lb. This moment is approximately the magnitude required to overcome the 50 in-lb detent on the drogue. If the drogue was not in the detent at the time the moment was applied, then a moment less than 50 in-lb would cause the drogue to rotate thru the detent.

Drogue rotation was also noted as the speed increased to about 270 KEAS and again when the drogue was initially deployed at 200 KEAS. The fins were not deflected.

Figure 18 shows a time history of the roll angle, read from movie films, as a speed of 270 to 300 KEAS was reached. These data indicate a rolling velocity of 13.4 RPM (CCW). Also, the calculated rolling moment is about 16 in-lbs.

During drogue deployment at 200 KEAS, the drogue rotated clockwise as the boom started to lower. Then the rotation stopped and began in the opposite (CCW) direction before the boom reached the full down position. The rotation stopped when the drogue reached full trail.

The counter-clockwise time history is shown in Figure 19. These data indicate a maximum roll rate of 95.5 RPM (CCW). The calculated rolling moment is about 60 in-lb. It was also noted from the film that the initial roll velocity was also about 95 RPM (CW).

It is believed that the wing vortex caused the roll during deployment and again as the speed approaches 270 to 300 KEAS. When the drogue is near its normal stowed position (see position 1, Figure 20), the clockwise wing vortex causes the drogue to rotate clockwise. As the boom approached its full down position (position 2), the outward vortex flow on the top of the drogue caused a counter clockwise rotation. Then, as the drogue reached its full trail position at 200 KEAS (position 3), the influence of the vortex was no longer felt and the rotation stopped. However, as the speed was increased and the drogue was pulled up in the vortex field (position 4) again, the counter-clockwise rotation began.

CONCLUSIONS

The following conclusions were reached as a result of this program.

The flight test data indicated that the drogue displacement was about the same, or slightly greater, than predicted.

Both the hose trail angle and the drogue tilt angle agreed with predicted data.

Unexpected rolling motion was encountered which was believed to be due to the wing vortex and an induced rolling moment due to control fin deflection.

RECOMMENDATIONS

This flight test program has demonstrated capability to maneuver an aerial refueling drogue in a stable manner and has verified prior wind tunnel results. The following items are recommended for consideration in a further program to develop an operational guided drogue system:

1. Eliminate the swivel and spring loaded indexing ball detent in order to prevent the drogue from rotating due to induced rolling moments.
2. Revise control system to minimize drag change during the maneuver, which modifies the direction and magnitude of displacement. The control surfaces can be rigged at a partially deflected initial position, with the maneuver achieved by increasing deflection of one surface while reducing deflection of the opposite surface.
3. Further flight test on the Model 1080 refueler should include a movie camera mounted on the lower end of the refueler boom.
4. Reconfigure the drogue as a fixed geometry target with optimized features, including increased displacement capability, reduced physical envelope and improved engagement compatibility.
5. Incorporate constant drag by variation of control surface initial position as a function of air speed. Also investigate the capability for free trail stabilization by autopilot control.
6. Develop a wind driven alternator as power supply for the operational system. Alternator frequency/air speed relationship can provide control input for constant drag (item 5 above).
7. Incorporate a low friction gimbal into the reception coupling, replacing the ball joint. It appears that high and variable friction of this joint will seriously compromise the maneuver capability of the drogue.
8. Integrate the probe alignment (homing guidance) electronics into the drogue/coupling system.

All the above items can be incorporated into a single follow-on program, which will consist of design studies, laboratory tests, wind tunnel test and flight test. A second alternate is recommended, wherein an immediate follow-on phase will include items 1 thru 6 with a final phase to develop items 7 and 8. A three-phase program is also feasible; the first phase will incorporate items 1 thru 3 and will use the existing hardware. The second phase will consist of items 4 thru 6, with a third phase completing the program.

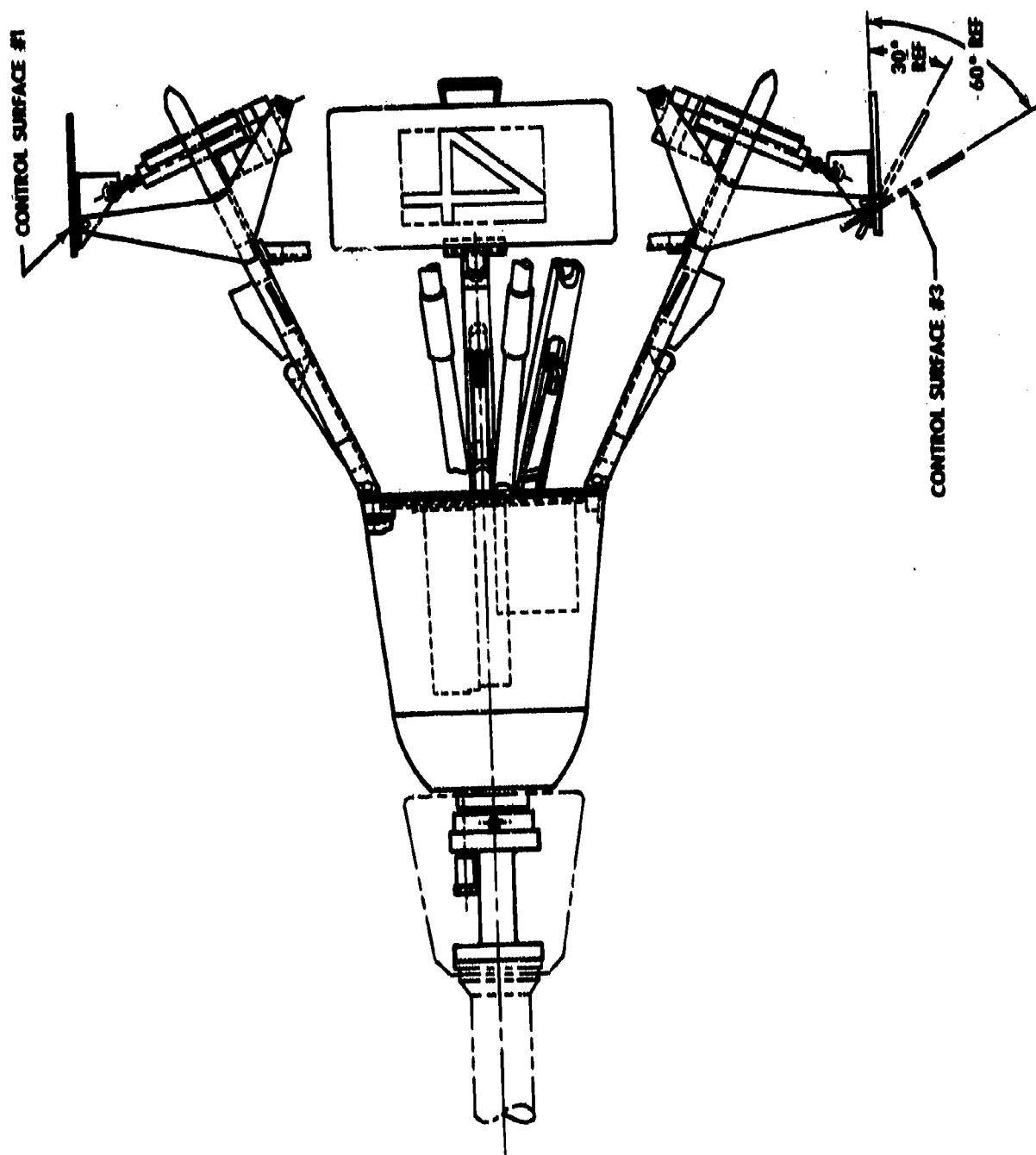
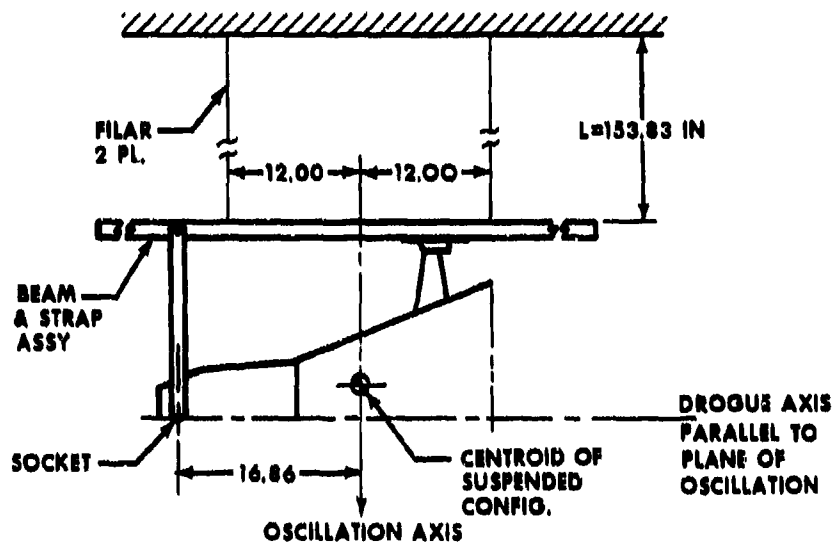
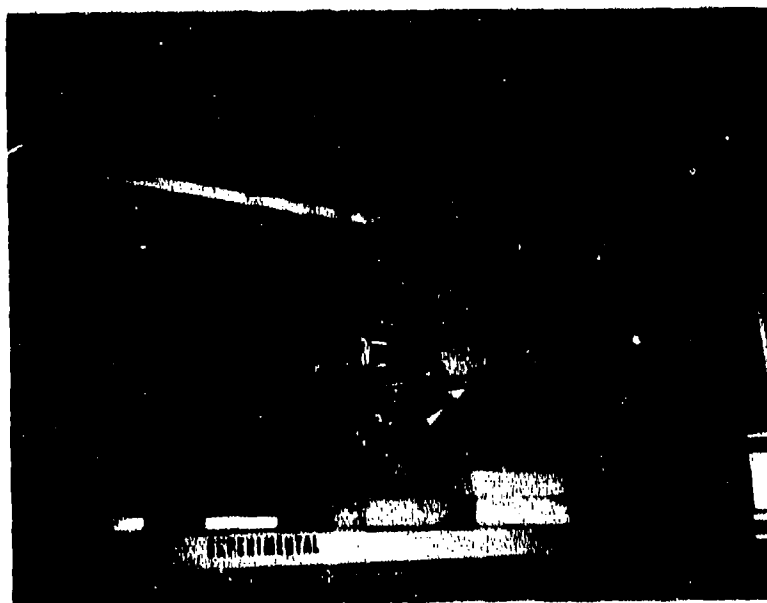


Figure 1. Guided Drogue Platform View



(a) Geometry



(b) Test Set Up

Figure 2. Geometry and Test Set Up For Inertia Test

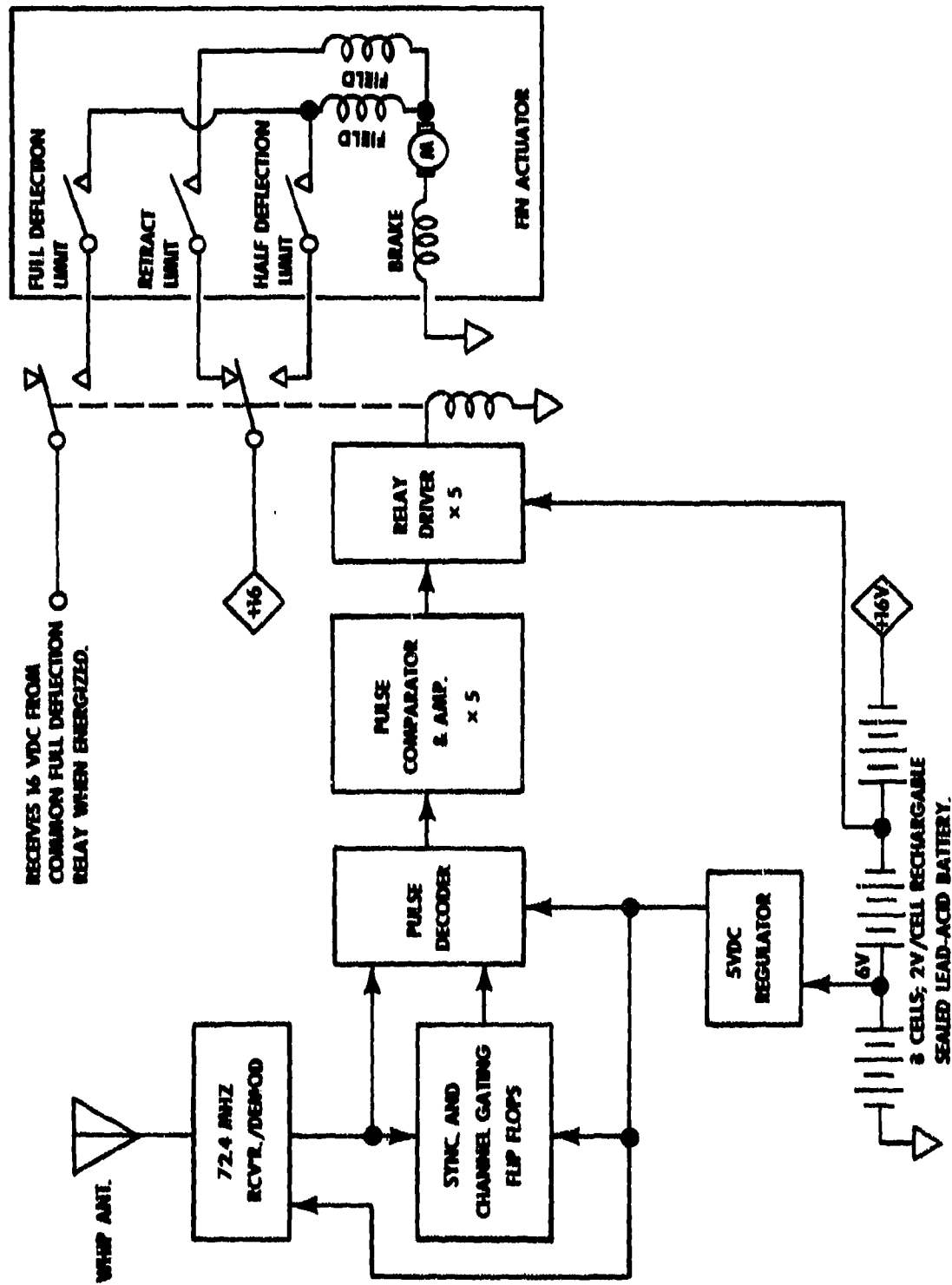


Figure 3. Receiver For Drogue Control Radio Link

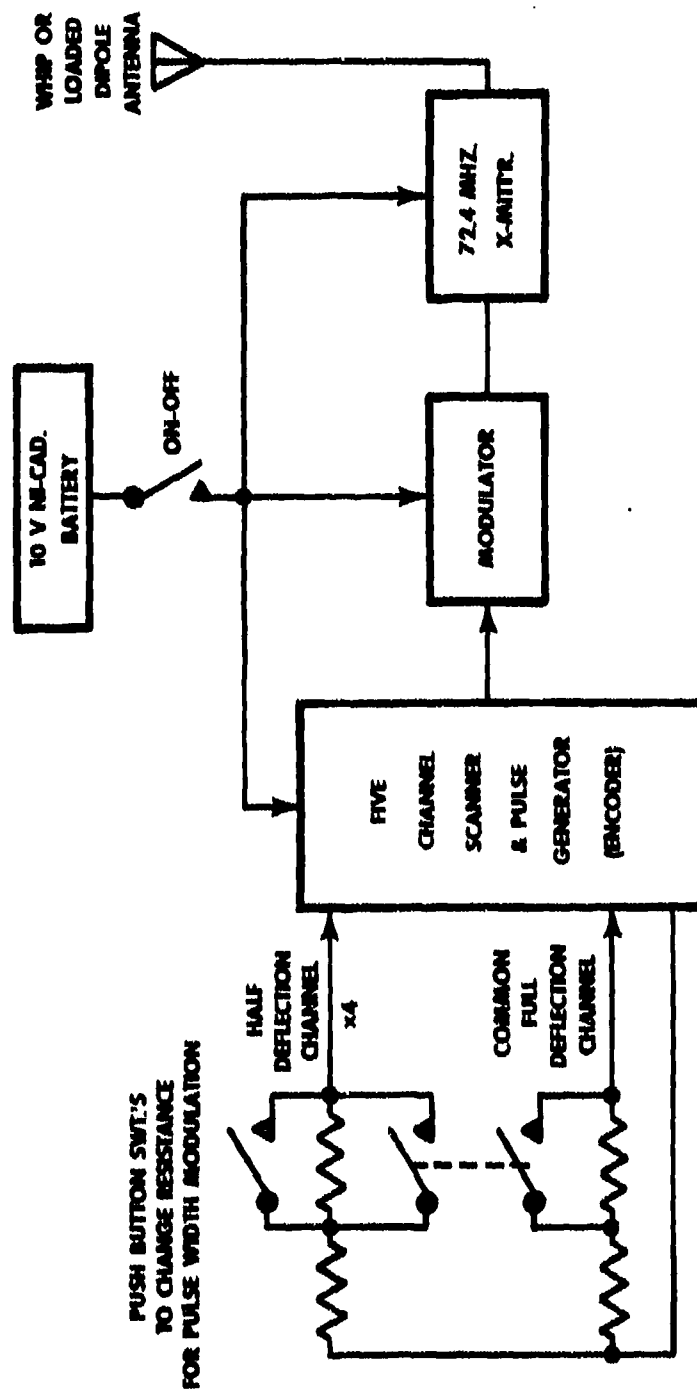
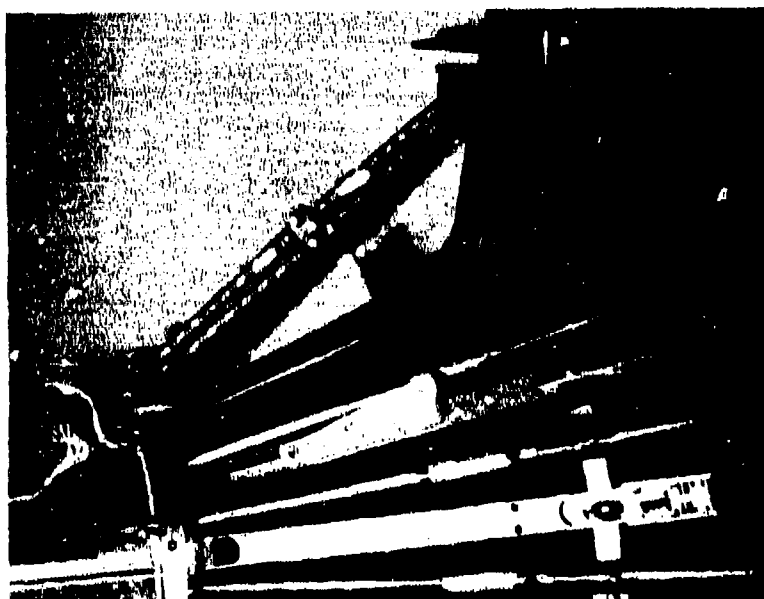
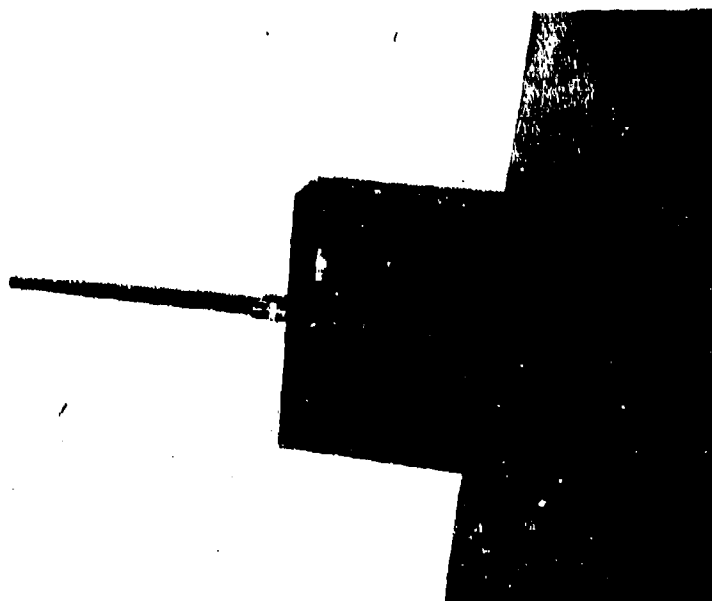


Figure 4. Transmitter For Drogue Control Radio Link



(b) Fin Actuator



(a) Transmitter

Figure 5. View of Transmitter and Control Fin Actuator

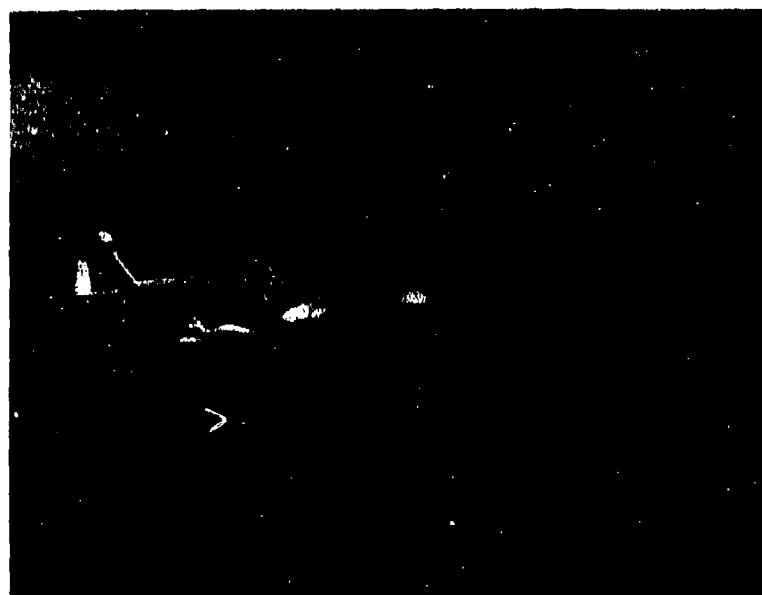


(a) Drogue and Refueling Store



(b) CC-137 Tanker

Figure 6. CC-137 Tanker and Store Wing Tip Mount

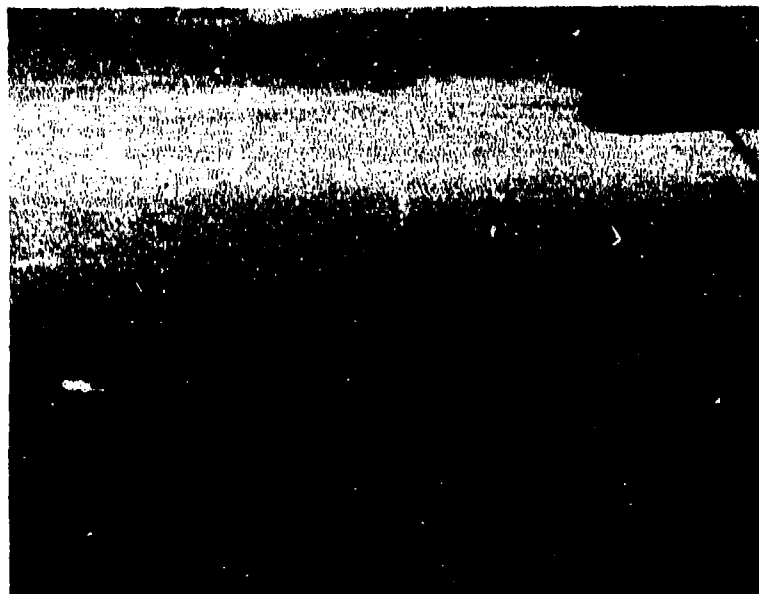


(a) EA-6B Chase Aircraft

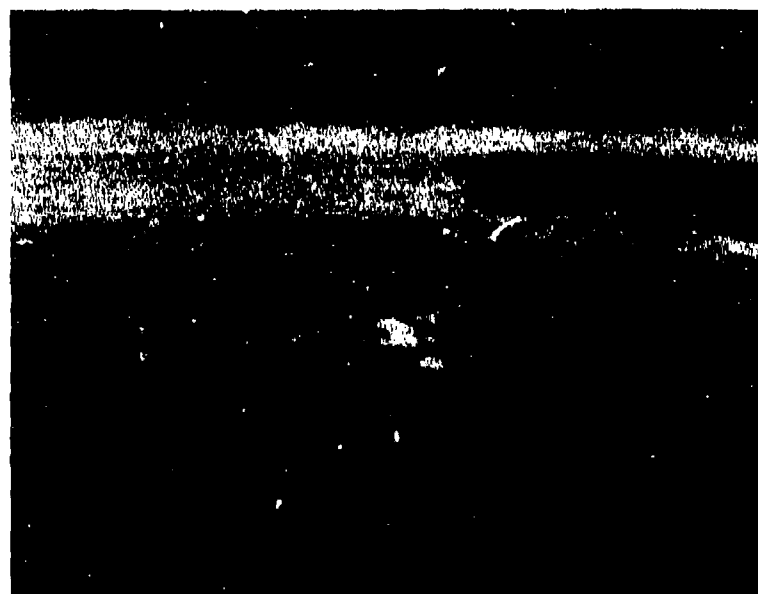


(b) Drogue At Trail

Figure 7. EA-6B Chase Aircraft and Drogue



(a) 200 KEAS



(b) 250 KEAS

Figure 8. Drogue At Normal Trail



(c) 300 KEAS



(a) $\delta = 0$



(b) $\delta = 60^\circ$

Figure 9. Drogue with Bottom Surface Deflected, 250 KEAS

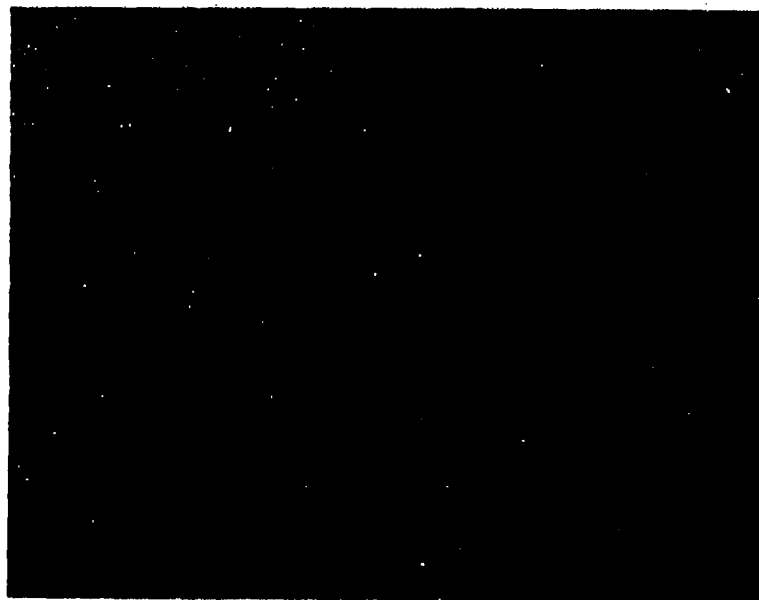


(c) $\delta = 0^\circ$



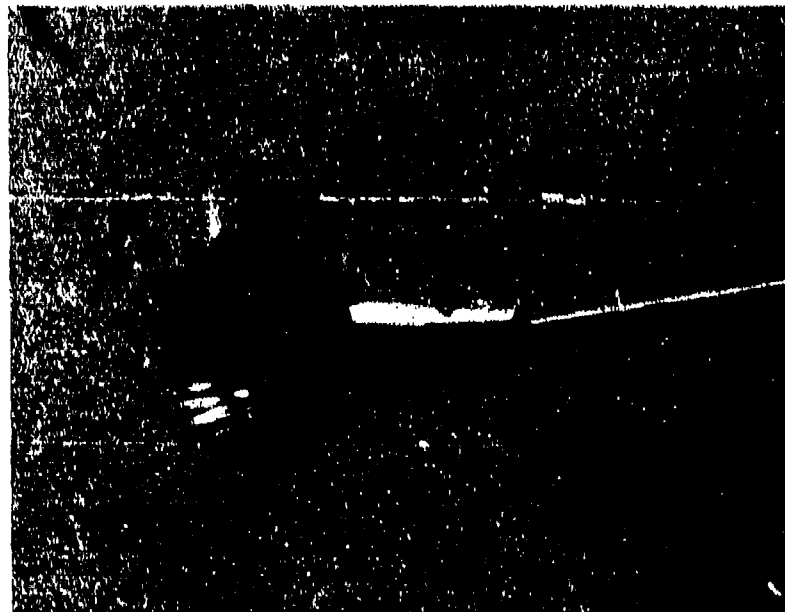
(d) $\delta = 30^\circ$

Figure 9. (Cont'd)



(a) $\delta = 60^\circ$

Figure 9. (Cont'd)

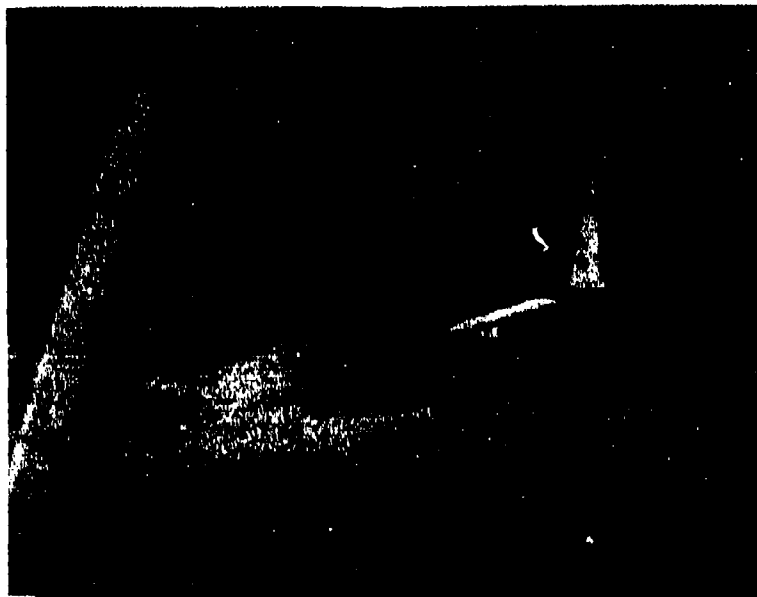


(a) $\delta = 0$



(b) $\delta = 60^\circ, 60^\circ$

Figure 10. Drogue With Two Adjacent Surfaces Deflected, 250 KEAS



300 KEAS

Figure 11. View from Chase Aircraft, 300 KEAS

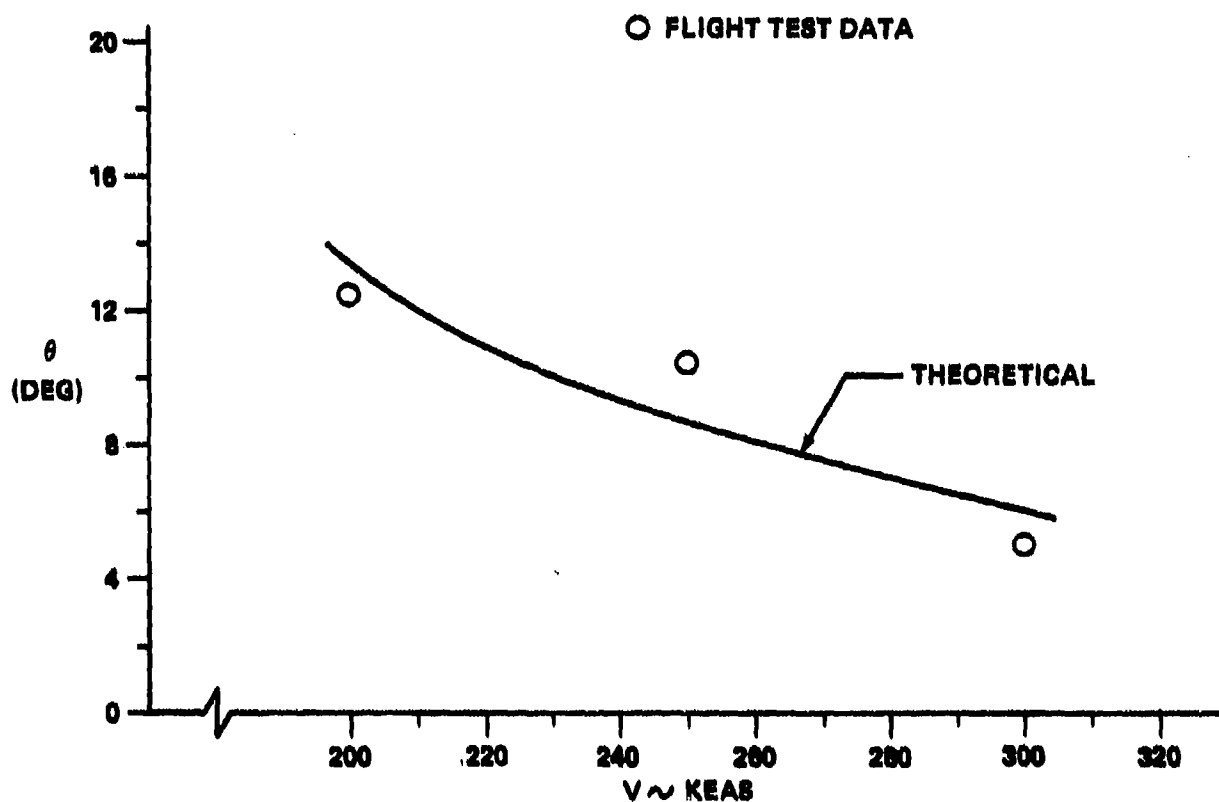


Figure 12. TRAIL ANGLE

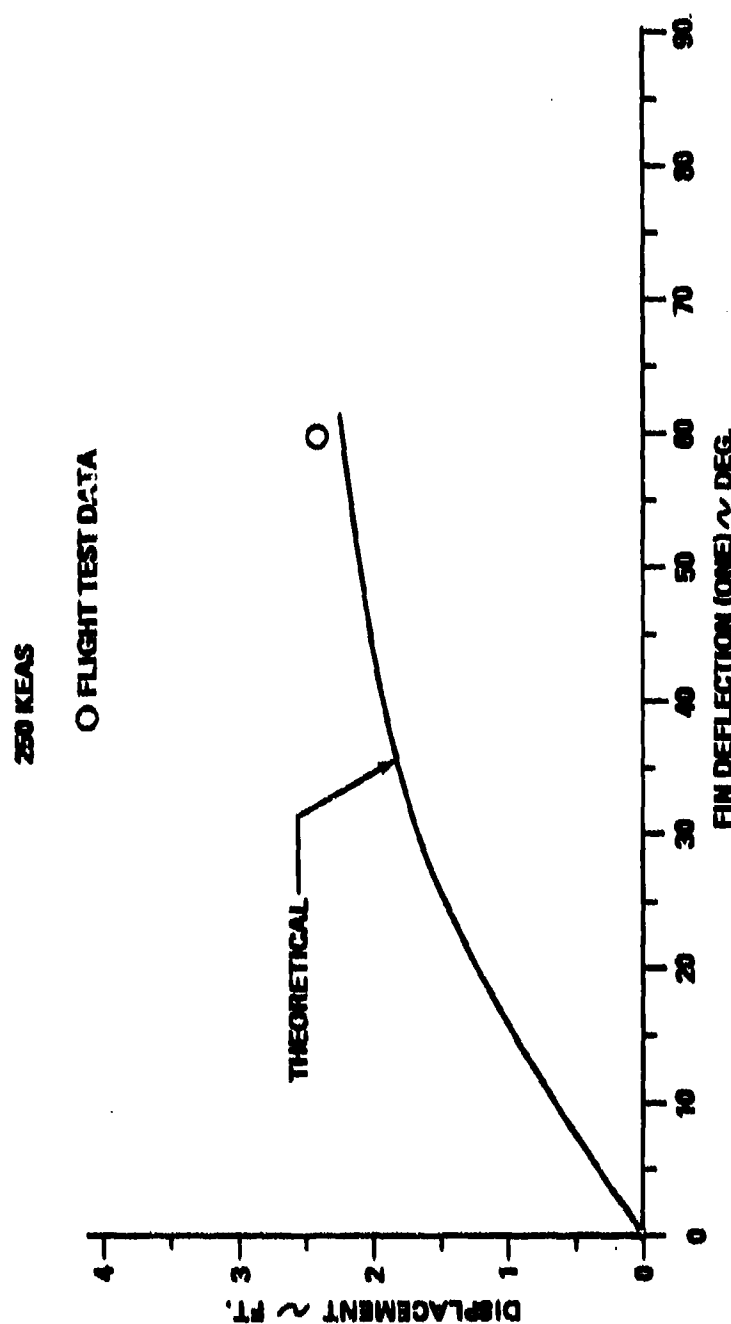


Figure 13. DROGUE DISPLACEMENT

250 KEAS

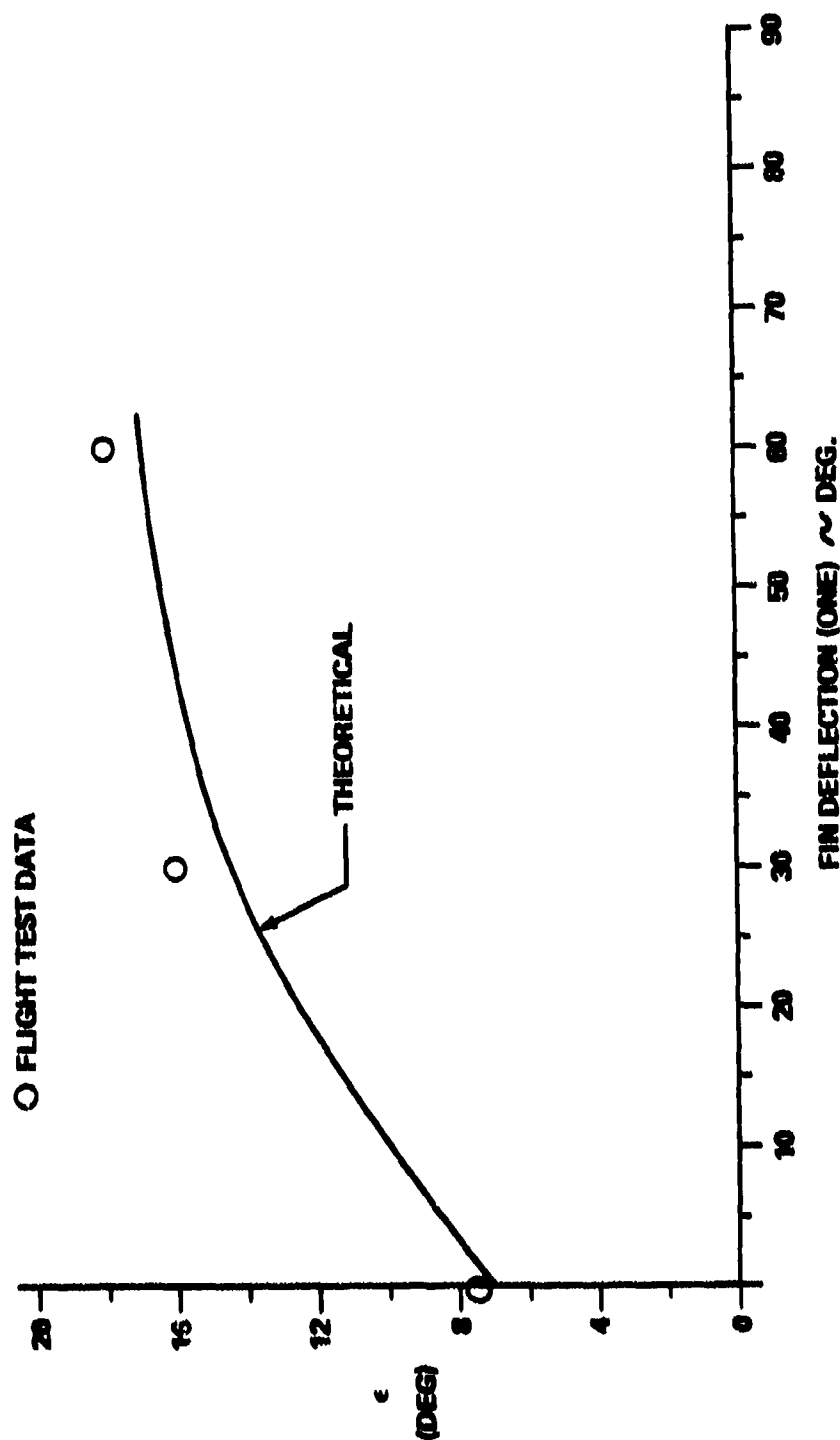


Figure 14. DROGUE TILT ANGLE, ONE FIN

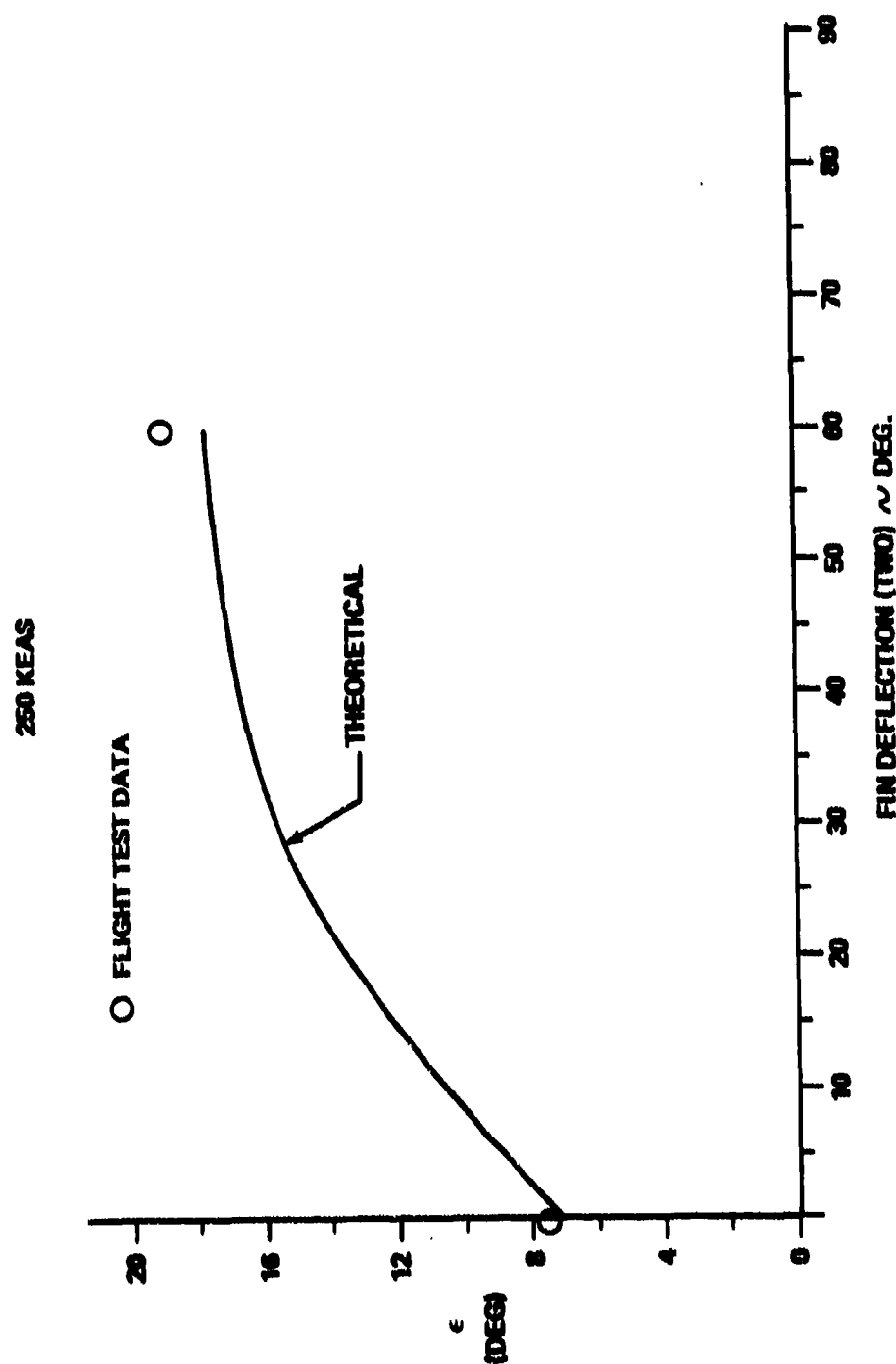


Figure 15. DRAGUE TILT ANGLE, TWO FINS

○ FLIGHT TEST DATA

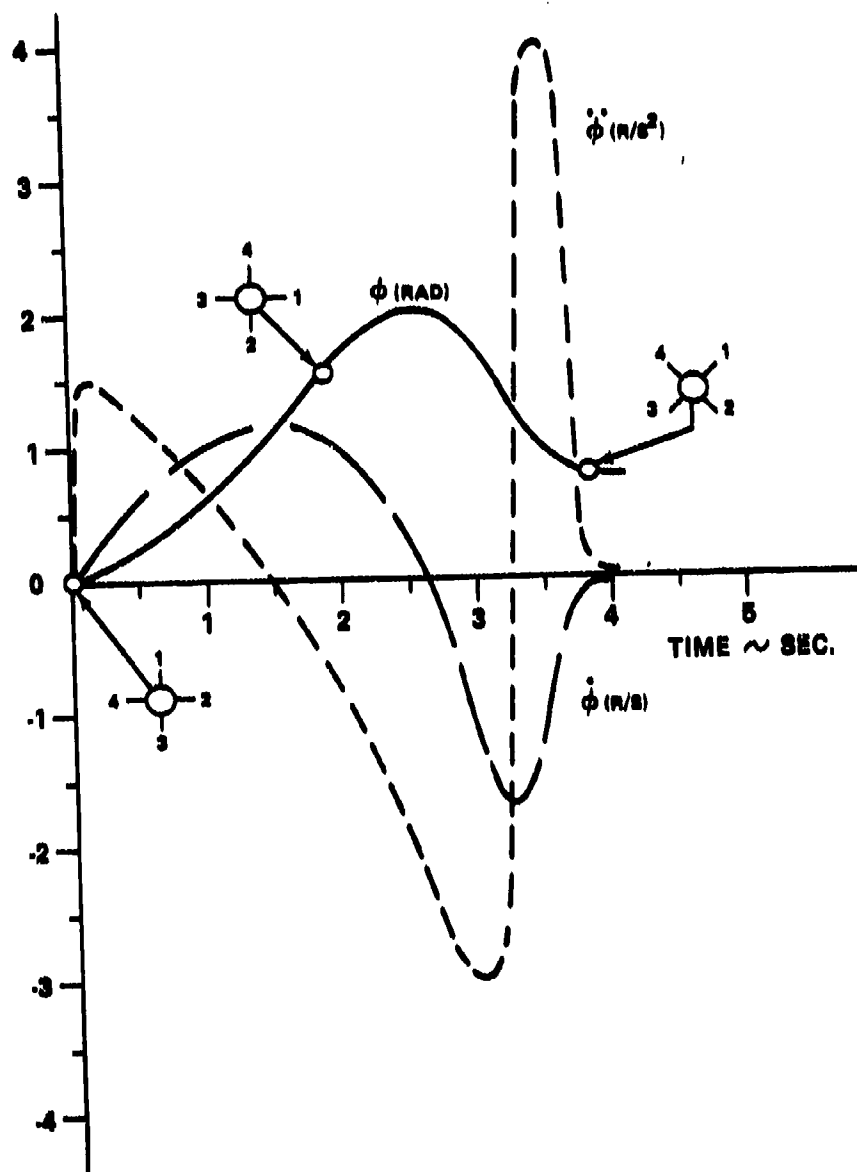


Figure 16. DROGUE ROTATION AT 250 KEAS $\delta_2 = 60^\circ$, $\delta_3 = 60^\circ$

260 KEAS $\delta_2 = 60^\circ$, $\delta_3 = 60^\circ$

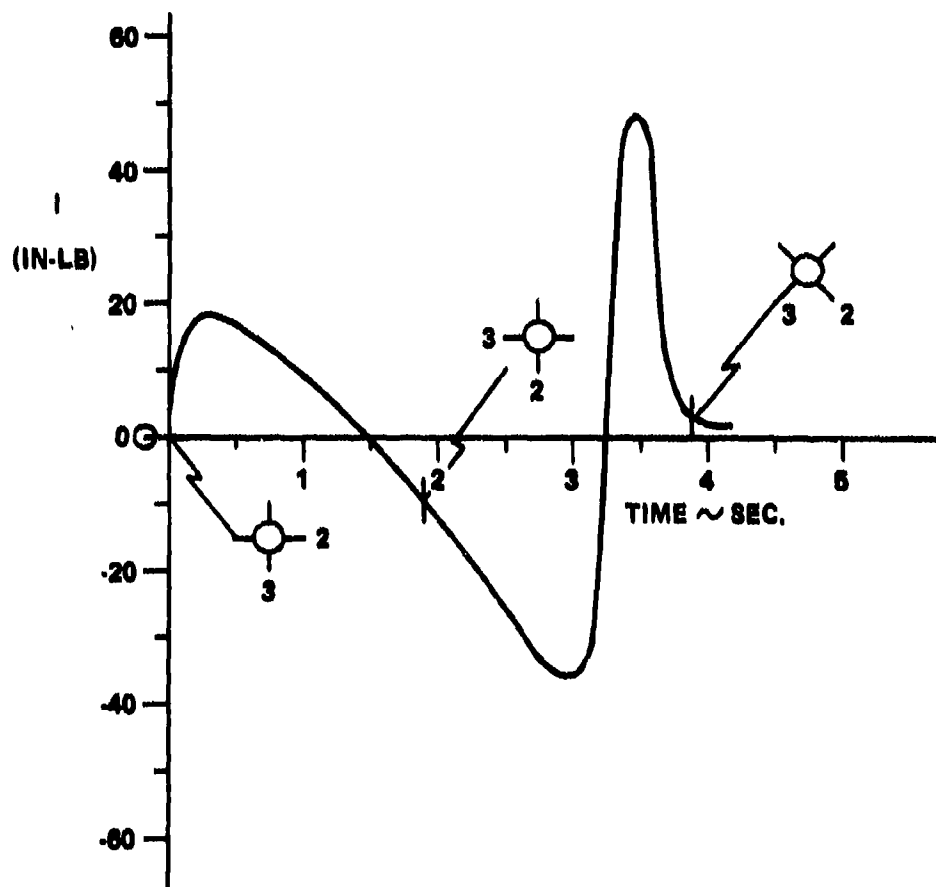


Figure 17. INDUCED ROLLING MOMENT ON DROGUE

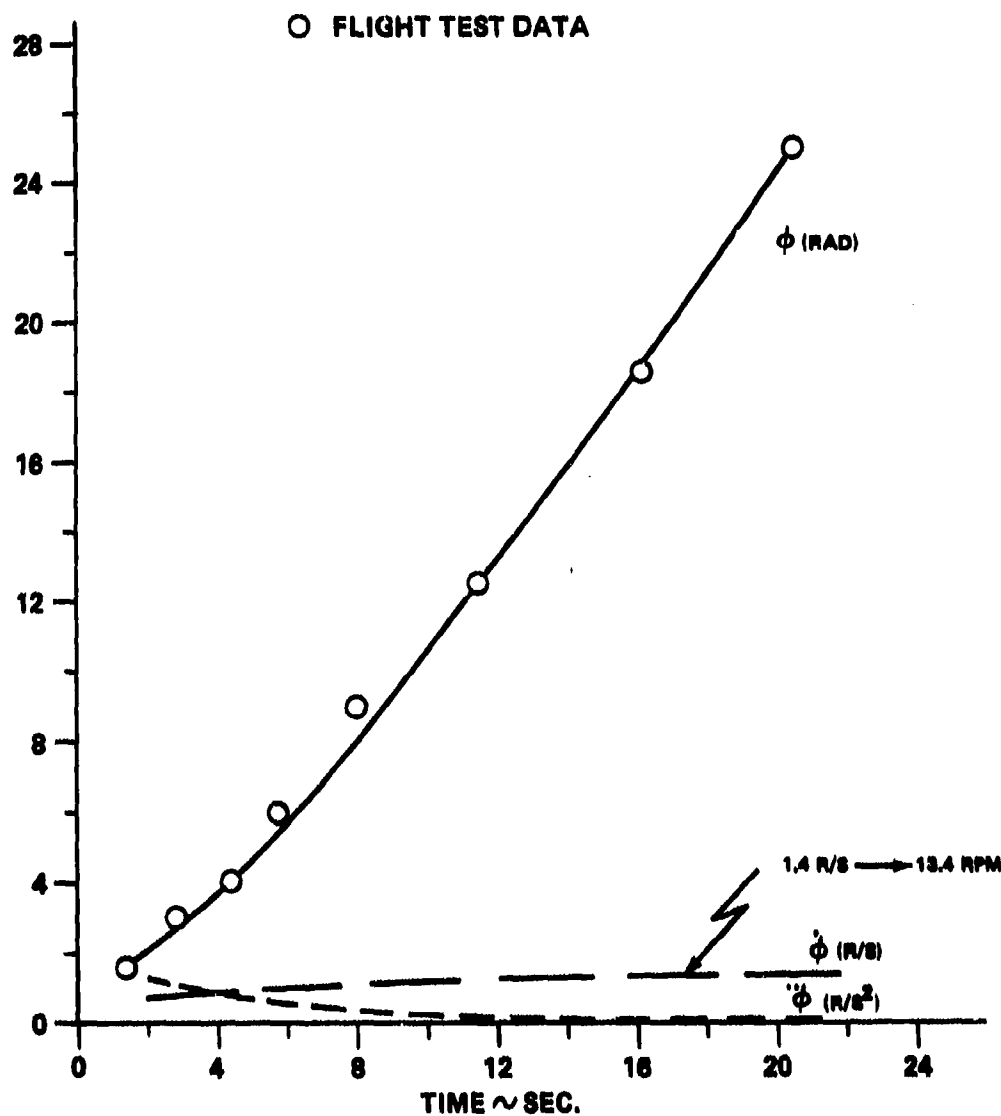


Figure 18. DROGUE ROTATION (c.c.w) AT 270-300 KEAS

○ FLIGHT TEST DATA

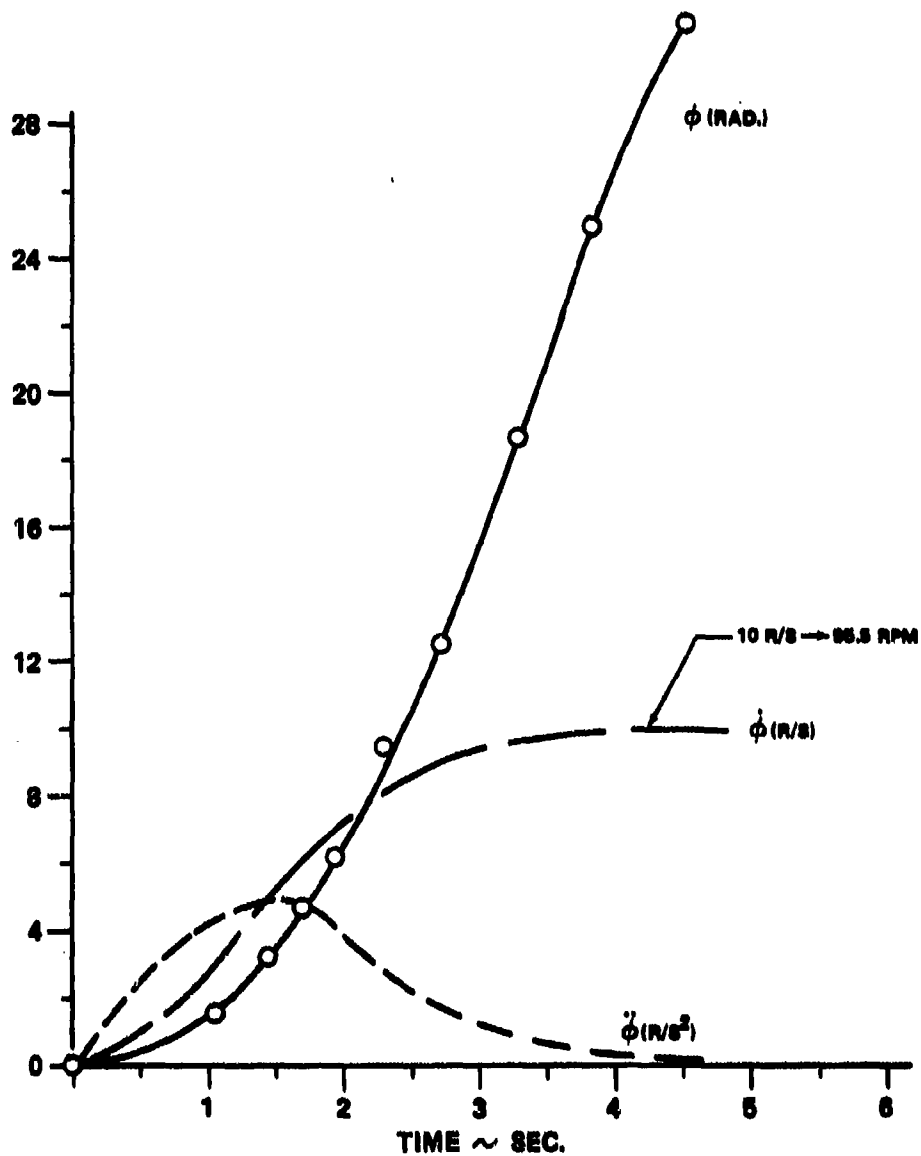


Figure 19. DROGUE ROTATION (c.c.w.) DURING DEPLOYMENT 200 KEAS

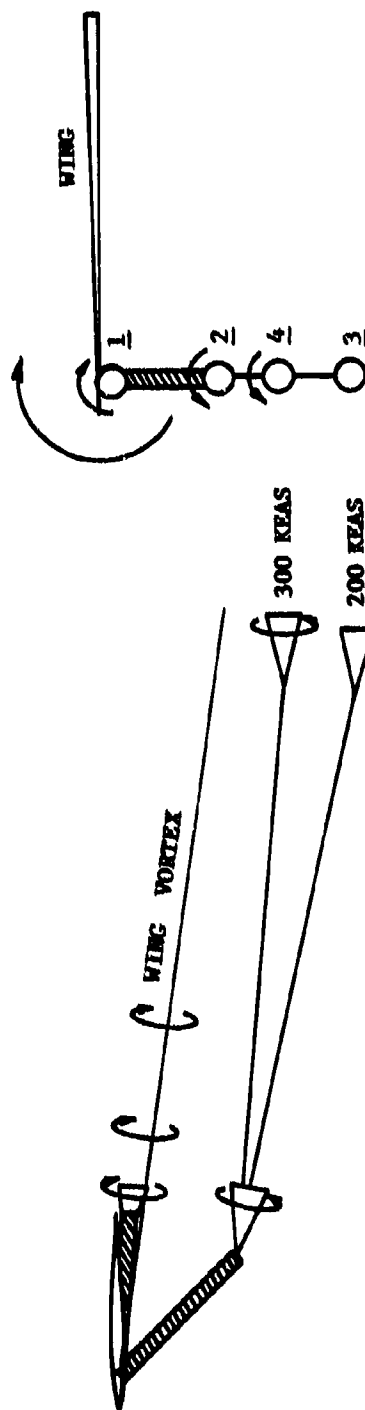


Figure 20. DROGUE ROTATION AT DEPLOYMENT AND TRAIL