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Measurement of the Yawing Moment of Inertia of an Aircraft (HP 115) in Flight

By R. L. POULTER
Aero/Flight Dept., RAE. Bedford

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Aero/Flight Dept., RAE, Bedford

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Summary.

The yawing moment of inertia has been obtained by measuring the acceleration in yaw resulting from the release of a wing-tip parachute. Lateral accelerometers mounted near the fore and aft extremities of the aircraft on a line parallel to the principal axis of inertia were used to measure the yawing acceleration. The principal axis is known in this case from previous ground measurements, but it is shown that 1 degree error in axis inclination would only produce an error of about 3 per cent in the measured inertia.

The results obtained from the flight tests are encouraging and are about $3\frac{1}{2}$ per cent lower than earlier measurements on a ground rig and about $2\frac{1}{2}$ per cent greater than the manufacturer's original estimate.

Operational problems are discussed and some improvements to the parachute equipment are also suggested.

*Replaces RAE Technical Report 70223—A.R.C. 32 787.

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1. Introduction.

Accurate determination of the moments of inertia is essential for the measurement of stability and control derivatives of an aircraft by dynamic test techniques. Aircraft manufacturers estimate the moment of inertia but these figures may not be sufficiently accurate. For example, the estimates for the Fairey Delta 2, Handley Page HP 115 and Avro 707B differ markedly from results obtained on ground rigs^{1,2,3,4}.

Measurements of moments of inertia are usually made on specially-constructed ground rigs. These rigs are large and expensive, which makes this method impractical for aircraft over about 50000 lb (25000 kg), and the tests are time consuming. Consequently alternative methods of measuring moments of inertia are constantly being sought.

One possible method for measuring the yawing moment of inertia of an aircraft in flight is based on the yawing acceleration generated by jettisoning a small parachute streaming from a wing tip. The yaw inertia can then be determined from the comparison of the yawing moment applied by the parachute with the angular acceleration in yaw when the parachute is jettisoned.

A suitable opportunity for assessing this method arose on the Handley Page HP 115 research aircraft during some lateral stability tests, which involved the use of wing-tip parachutes. As a suitable angular accelerometer was not available, the yaw acceleration achieved was measured by sensitive lateral accelerometers mounted near the extremities of the longitudinal axis of the aircraft.

The results obtained by this method are compared with data obtained from earlier tests¹ on a ground rig. The comparison is encouraging and it is considered that the method of in-flight measurement warrants further development.

In principle this method could also be adapted to measure pitch inertia. This would involve jettisoning a parachute from the fin tip. Roll and pitch inertia in flight could also be determined by measuring the accelerations produced by jettisoning ballast from the wing tip or nose of the aircraft.

2. Description of Aircraft, Installation and Parachute.

2.1. The Aircraft and Installation.

The Handley Page HP 115, Fig. 1, is a low-speed slender-wing research aircraft with a leading-edge sweep of 75 degrees. It is powered by a single Bristol Siddeley Viper 9 engine mounted above the rear upper surface of the wing. All controls are manually operated.

The installation, Fig. 2, consisted of a strain gauged post, perpendicular to the plane of symmetry, attached at one end to the aircraft structure in the region of the port wing tip and carrying the parachute strop at its outer end. A shroud enclosed the post over most of its length to reduce airloads to a minimum. The release mechanism for the parachute was mounted on the shroud.

The parachute pack was positioned on the release unit under the shroud and held by means of bungee cords, the free ends of which were held in the jaws of the release mechanism. The parachute strop was attached via an explosive bolt and a swivel link assembly to a yoke on the parachute post.

The bungee cords were freed when the release unit was operated, allowing the parachute pack to drop from its stowed position and aerodynamic loads to deploy the parachute. Jettisoning the parachute was achieved by blowing the explosive bolt. A safety device was incorporated in the release unit so that if the parachute pack became detached, without the release unit being operated, the explosive bolt would automatically blow, jettisoning the parachute before it deployed. This was to avoid embarrassing the pilot with an unexpected yawing moment at any critical period of flight.

The streaming and manual jettison of the parachute were controlled by the pilot from switches in the cockpit. A rearview mirror was also fitted in the cockpit to enable the pilot to monitor the parachute behaviour.

To ensure a clean break, and minimise damage to surrounding parts on detonation, the shank of the explosive bolt was encased in a tight-fitting steel tube which terminated at the weak point of the bolt.

The symmetry of the aircraft was maintained by fitting a dummy installation on the opposite wing tip. This dummy installation was not strain gauged nor did it carry a parachute.

2.2. The Parachute.

The parachute used was a 24 in (0.61 m) guide-surface parachute with twelve gores, having a nominal

drag coefficient of 0.75 and a calculated drag of 215 lb (960 N) at 170 kt. The parachute was designed and manufactured by Irvin Airchute GB Ltd.

The towing strop was made of two thicknesses of 700 lb (3 kN) Celanese 'Fortisan', a form of artificial silk tape claimed to reduce strop oscillations to a minimum. Strop lengths of 10 ft were standard but it was found necessary to alter this length for some flights, to reduce parachute oscillations.

The packing of the parachute was such that it allowed the strop and rigging lines to pull out of the bag before the parachute, so reducing the chance of hang ups on streaming. It had the additional advantage of slightly increasing the time of parachute deployment. This gave the safety system more time to operate in the case of an unexpected deployment.

3. Instrumentation.

The following quantities were measured :—

Lateral acceleration at *CG*

Lateral acceleration at forward position

Lateral acceleration at aft position

Rudder angle

Elevon angles

Incidence

Airspeed

Altitude

Parachute cable angle

Parachute normal (*Z*) load

Parachute longitudinal (*X*) load.

In the absence of a satisfactory angular accelerometer, two sensitive ($\pm 0.25 g$) lateral accelerometers were fitted to the aircraft. These accelerometers were mounted in the plane of symmetry on a line parallel to the principal axis, which in this case was known from previous tests, and were positioned as far apart as was convenient, Fig. 1. The forward accelerometer was located on the bulkhead behind the pilot's seat 16.6 ft (5.06 m) forward of the centre of gravity. The rear accelerometer was positioned on the rear ballast mounting plate 16.7 ft (5.09 m) aft of the *CG*. The signals from these accelerometers were recorded by a photographic trace recorder.

The parachute post was rectangular in section and two Teddington Control Type SE/A/2 strain gauges were attached symmetrically about the neutral axis of each of the four faces. The gauges on opposite faces were in a bridge arrangement (Fig. 3). The post was mounted horizontally on the wing tip of the aircraft in such a manner that the normal (*Z*) and longitudinal (*X*) forces on the post due to the parachute were measured. The end loads (*Y*) on the post were calculated knowing the *Z* and *X* forces and the cable angle.

The parachute cable angle relative to the parachute post, in the yaw sense, was measured by a potentiometer which was operated by a cam attached to the yoke. Signals from both strain gauge circuits and the cable angle potentiometer were recorded by another photographic trace recorder and the two recorders were synchronised by an event marker operated when the explosive bolt circuit was energised.

4. Calibrations.

4.1. Parachute Post Calibrations.

Preliminary calibrations of the parachute post were carried out in the laboratory for three main reasons ;

- (1) to set the sensitivity of the bridge/galvanometer system,
- (2) to ensure the strain gauges functioned without hysteresis or slipping of the gauges,
- (3) to determine whether there was any cross-coupling between axes due to small errors in alignment of the gauges.

Final calibrations on the aircraft were necessary to obtain a final check on the sensitivity and to ensure that the strain gauges still functioned correctly after the lengthy, and potentially damaging, process of fitting and assembling the post shroud equipment.

4.1.1. *Laboratory calibrations of parachute post.* The fixed end of the parachute post was clamped to a stationary platform with the post horizontal (Fig. 4). The post was calibrated with the X axis at angles of inclination to the vertical $\theta = 0, 5, 10, 15, 20$ and 90 degrees by hanging weights, which were compatible with the angles, on the parachute strop. The components in the Z and X directions were then calculated.

The strain gauges functioned with no hysteresis but the outputs of the two channels, when resolved, were found to vary very slightly with the inclination, θ . This was due mainly to slight misalignment of the gauges which caused a pure X load to be registered on the Z gauges and *vice versa*. Another small contributory factor was the weight component of the post on each axis which varied with the inclination.

4.1.2. *Aircraft calibrations of parachute post.* For the aircraft calibrations the HP 115 was held stationary by means of chocks and ties. The parachute strop, which was parallel to the plane of symmetry of the aircraft, was passed over a pulley wheel the height of which could be varied, so altering the inclination θ . Weights were then applied in a similar fashion to the laboratory calibrations.

The aircraft calibration had the advantage that the weight component of the post did not vary, consequently the differences between results at various inclinations, Figs. 5 and 6, were due only to gauge misalignment.

The cable angle potentiometer was calibrated by means of an angular scale fitted onto the post.

4.2. Accelerometer Calibrations.

The sensitive ($\pm 0.25 g$) lateral accelerometers were statically calibrated in the usual manner on a tilting table.

These lateral accelerometers were subjected to significant 'noise' inputs by the structure, so to render the traces more legible the outputs were filtered. It was therefore necessary to measure the dynamic response of the filtered instrument. Since the dominant response following the step input of yawing moment, N , (at parachute release) is in the dutch roll mode, it was necessary for the dynamic response to be known at the dutch roll frequency.

In order to find the dynamic response the accelerometer was mounted at one end of a long horizontal arm pivoted near the other end. The arm was restrained by springs 'tailored' to give the required frequency when the system was set oscillating. The arm was displaced by an amount such that on release the first peak was of a similar amplitude to those achieved in the flight tests. Since the damping of the aircraft dutch roll response and the calibrating system were small and of the same order, the response achieved on the ground could be directly applied to the results of the flight tests.

As the geometry and frequency of the system were known and the first peak after release could be measured, the response to a step input at the natural frequency of the aircraft was known.

5. Tests.

5.1. Taxy Tests.

In order to ensure that the parachute equipment functioned correctly a series of taxy runs was performed. During these tests, parachutes were streamed and jettisoned several times, at increasing speeds up to 80 kt using the conventional stream/jettison arrangement. The auto-jettison safety circuit was also tested and found to function correctly.

These taxi runs indicated to the pilot that the aircraft could be landed with the parachute streamed should this become necessary.

5.2. Flight Tests.

The pilot was briefed to fly straight and level, to keep the controls fixed from about two seconds before to three seconds after jettison and to note fuel state at the time. Airspeeds at jettison were to be within the range 110 kt to 140 kt.

Records of the zeros of the strain gauges were taken prior to the streaming of the parachute so that allowance could be made for any temperature effects at the test altitude.

For these tests it was necessary to fly in calm air, so that the sensitive lateral accelerometers registered only the accelerations due to the parachute jettison. It was therefore necessary to jettison the parachute above the turbulent layer near to the ground. The optimum height for the jettisons was, in general, between 2000 and 3000 ft, but this meant that it was often impossible to reclaim the parachutes as they drifted out of sight downwind. These high jettisons could not therefore be employed until the lateral stability work was nearly over, when the parachutes became expendable.

A total of thirty-six flights with parachutes was performed but of these only the last ten were intended to be high jettisons. Only four of these last ten flights proved to be suitable for yaw inertia measurement. Significant turbulence was present on four of the remaining six flights and made the records unsuitable for analysis; one auto-jettison and one inadvertent jettison made up the total.

It had been feared that the parachute might get entrained in the wing-tip vortices and oscillate as had happened in previous wing-tip parachute tests on another aircraft⁵. This fear proved groundless for the conditions of flight that were required at jettison. A typical set of records for the jettison of the parachute is shown in Fig. 7.

6. Analysis.

The change of the loads on the post when the parachute was jettisoned was measured from the trace records. The parachute strop angle and aircraft incidence immediately prior to jettison and the lateral accelerations at the first acceleration peak were also measured. In addition the aircraft control positions were monitored to confirm they did not move in the period from two seconds before to three seconds after jettison. Knowing the loads from the parachute and their moment arms the yawing moment applied to the aircraft was calculated.

P_y , the load along the post, was found by combining the X and Z loads and the strop angle

$$P_y = \sqrt{P_x^2 + P_z^2} \tan \psi$$

where ψ is the strop angle

$$P_y \quad +ve \text{ inboard}$$

$$P_x \quad +ve \text{ rearwards}$$

and $P_z \quad +ve \text{ upwards.}$

The total yawing moment referred to the aircraft principal axis is thus:—

$$N_B = P_z y \sin \varepsilon + P_x y \cos \varepsilon + P_y x \cos \varepsilon$$

where ε is the inclination of the principal axis to the body axis, +ve nose up.

In general

$$N_B = C\dot{r} - E\dot{p}$$

and

$$L_B = A\dot{p} - E\dot{r} .$$

This becomes (see Appendix I)

$$C_o = \frac{N_B \left[1 + \frac{L_B}{N_B} \left(\frac{C_o}{A_o} - 1 \right) \sigma \right]}{\dot{r} \left[1 - \frac{C_o}{A_o} \left(1 - \frac{A_o}{C_o} \right)^2 \sigma^2 \right]}$$

In this case, the accelerometers were mounted parallel to the principal inertia axis, making $\sigma = 0$, therefore C_o becomes

$$\frac{N_B}{\dot{r}}$$

where $\dot{r} = \frac{\Delta a_y}{x_1}$,

Δa_y difference between fore and aft accelerations

and x_1 distance between accelerometers

therefore

$$C_o = \frac{N_B x_1}{g \Delta a_y}$$

Corrections for yawing moments due to rudder and sideslip are negligible as the rudder was fixed and the sideslip angle was virtually zero. The damping term due to yawing velocity N , is also negligible as the yaw velocity r is very small at less than 1 degree per sec.

In this particular installation the accelerometers were mounted parallel to the principal axis of the aircraft which had been measured in previous tests. When the principal inertia axis of the aircraft has not previously been measured the accelerometers should be mounted parallel to the estimated inertia axis. Errors due to misaligned axes are calculated in Appendix II and show that a 1 degree error in axis alignment would produce a 3 per cent error in C_o for this aircraft.

7. Results and Discussion.

The results from the four flight tests are listed and compared with rig and estimated results below:

	Mass				Yaw inertia			
	Full		Empty		Full		Empty	
	lb	kg	lb	kg	slug ft ²	kg m ²	slug ft ²	kg m ²
Flight	5236	2375	4066	1844	—	—	16000	21693
Flight	5236	2375	4066	1844	—	—	17550	23795
Flight	5236	2375	4066	1844	—	—	16964	23000
Flight	5236	2375	4066	1844	—	—	16682	22618
Estimate	5057	2294	3887	1763	16630	22547	16400	22235
Rig	5057	2294	3907	1772	17670	23957	17380	23564

The four flight test results have been corrected to empty fuel tank conditions, and all results refer to a 182 lb (80 kg) pilot. The small discrepancy in the empty weights for rig and estimate is due to unusable fuel in the tanks.

At the time of the flight tests the empty aircraft mass was 159 lb (72 kg) more than at the time of the rig tests. This would mean that the inertia should be slightly larger, knowing that there had been no major redistribution of the equipment aboard since the rig tests. The comparison between the rig and flight results is thus somewhat surprising as the flight figures are about 3 per cent smaller than those achieved on the rig.

The mean flight result for yaw inertia is 16799 slug ft² (22776 kg m²) with reading accuracy of ± 2 per cent. The ± 4 per cent scatter on the results is most probably due to turbulence which makes it difficult to estimate with any confidence the accuracy of the accelerations. In the circumstances, it cannot be said whether the difference between flight and rig results is genuine or not.

Operating problems and possible improvements to the parachute system are discussed in Appendix III.

8. *Conclusions.*

A method of measuring the yaw inertia of the Handley Page HP 115 in flight has been tested. The yaw inertia was obtained by measuring the yawing acceleration of the aircraft caused by the step input of yawing moment at parachute jettison.

The mean result achieved from flights during which there was a low level of turbulence was encouraging and were only about 3 per cent lower than the results achieved in ground rig tests¹.

The test procedures were simple to operate and the design of the parachute was well suited to the tests and it flew with little oscillation. Some of the problems associated with the operation and suggestions for improving the system are discussed in Appendix III.

Generally the experiment was encouraging and indicated that measurement of yaw inertia in flight is possible, although a reasonably accurate knowledge of the inclination of the principal inertia axis is necessary. In this case the principal axis was already known from ground tests, but an uncertainty of 1 degree in axis inclination would have introduced an error of about 3 per cent in the measured yaw inertia. It seems that both roll and pitch inertia might be measured in a similar fashion with some prospect of success. Roll inertia could be measured by jettisoning wing-tip ballast and pitch inertia by jettisoning either a fin tip parachute or nose ballast.

LIST OF SYMBOLS

A_o	Principal rolling moment of inertia
A	Rolling moment of inertia in body axes
Δa_y	Difference in fore/aft accelerations
C	Yawing moment of inertia in body axes
C_o	Principal yawing moment of inertia
E	Product of inertia
L_B	Rolling moment in body axes
N_B	Yawing moment in body axes
P_x	Load in longitudinal, X , direction
P_y	Load in lateral, Y , direction
P_z	Load in normal, Z , direction
g	Acceleration due to gravity
\dot{p}	Roll acceleration
\dot{r}	Yaw acceleration
x	Chordwise distance between yoke and CG
y	Spanwise distance between yoke and CG
ε	Inclination of the principal axis to the body axis, +ve nose up, (-4 degrees)
θ	Inclination of post to direction of load
ψ	Strop angle
σ	Angle between principal and accelerometer axes

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-

APPENDIX I

Derivation of Equation for Principal Yaw Moment of Inertia, C_o .

The equations for yawing and rolling moments in accelerometer axis are:—

$$N_B = C\dot{r} - E\dot{p}$$

and

$$L_B = A\dot{p} - E\dot{r}.$$

If the difference between the inclination of principal inertia axis and accelerometer axis is σ then, with the accelerometer axis nose-up relative to the principal axis,

$$E = (C_o - A_o) \cos \sigma \sin \sigma \simeq C_o \left(1 - \frac{A_o}{C_o}\right) \sigma \text{ if } \sigma \text{ small,}$$

$$C \simeq C_o$$

and

$$A \simeq A_o + C_o \sigma^2 = C_o \left(\frac{A_o}{C_o} + \sigma^2\right)$$

therefore

$$N_B = C_o \dot{r} - C_o \left(1 - \frac{A_o}{C_o}\right) \sigma \dot{p}$$

and

$$L_B \simeq C_o \left(\frac{A_o}{C_o}\right) \dot{p} - C_o \left(1 - \frac{A_o}{C_o}\right) \sigma \dot{r}.$$

In order to eliminate \dot{p} these become:—

$$N_B \left(\frac{A_o}{C_o}\right) = C_o \dot{r} \left(\frac{A_o}{C_o}\right) - C_o \left(\frac{A_o}{C_o}\right) \left(1 - \frac{A_o}{C_o}\right) \sigma \dot{p}$$

and

$$L_B \left(1 - \frac{A_o}{C_o}\right) \sigma = -C_o \left(1 - \frac{A_o}{C_o}\right)^2 \sigma^2 \dot{r} + C_o \left(\frac{A_o}{C_o}\right) \left(1 - \frac{A_o}{C_o}\right) \sigma \dot{p}$$

therefore

$$N_B \left(\frac{A_o}{C_o}\right) + L_B \left(1 - \frac{A_o}{C_o}\right) \sigma = C_o \left\{ \left(\frac{A_o}{C_o}\right) - \left(1 - \frac{A_o}{C_o}\right)^2 \sigma^2 \right\} \dot{r},$$

$$N_B + L_B \left(\frac{C_o}{A_o}\right) \left(1 - \frac{A_o}{C_o}\right) \sigma = C_o \left\{ 1 - \left(\frac{C_o}{A_o}\right) \left(1 - \frac{A_o}{C_o}\right)^2 \sigma^2 \right\} \dot{r},$$

$$C_o = \frac{N_B \left[1 + \frac{L_B C_o}{N_B A_o} \left(1 - \frac{A_o}{C_o}\right) \sigma \right]}{\dot{r} \left[1 + \frac{C_o}{A_o} \left(1 - \frac{A_o}{C_o}\right)^2 \sigma^2 \right]}$$

and

$$C_o = \frac{N_B}{i} \frac{\left[1 + \frac{L_B}{N_B} \left(\frac{C_o}{A_o} - 1 \right) \sigma \right]}{\left[1 - \frac{C_o}{A_o} \left(1 - \frac{A_o}{C_o} \right)^2 \sigma^2 \right]}.$$

APPENDIX II

Errors in C_o Due to Aligning the Accelerometers at an Angle to the Principal Inertia Axis.

In the case of the HP 115 the manufacturer's estimated principal inertia axis inclination is 1.1 degrees different from the axis measured in Ref. 1. If the accelerometers had been aligned on the estimated axis, the value for C_o would have been in error. From Appendix I

$$C_o = \frac{N_B \left(1 + \frac{L_B}{N_B} \left(\frac{C_o}{A_o} - 1 \right) \sigma \right)}{\dot{v} \left(1 - \frac{C_o}{A_o} \left(1 - \frac{A_o}{C_o} \right)^2 \sigma^2 \right)}$$

for the HP 115,

$$\frac{C_o}{A_o} \approx 13$$

and

$$\frac{L_B}{N_B} \approx -\frac{1}{6}.$$

Measured inclination of the principal inertia axis is -4 degrees.

Estimated inclination of the principal inertia axis is -5.1 degrees.

Thus alignment of the estimated axis would introduce an error in inclination, σ , of -1.1 degrees.

In this case the factor

$$\frac{1 + \frac{L_B}{N_B} \left(\frac{C_o}{A_o} - 1 \right) \sigma}{1 - \frac{C_o}{A_o} \left(1 - \frac{A_o}{C_o} \right)^2 \sigma^2} \approx 1.03,$$

i.e. approximately 3 per cent error in C_o for a 1.1 degree error in accelerometer axis alignment, with the measured value of C_o less than the true value when the accelerometer axis is nose down relative to the true principal axis ($\sigma - ve$).

APPENDIX III

Operating Problems.

Most of the problems during the flight tests concerned the operation of the explosive bolt. These difficulties came under four main headings:—

(1) Failure to detonate. The explosive bolt failed to detonate on two occasions out of thirty-six attempts. Both of these failures were caused by the detonating wires being severed by the motion of the yoke. These failures necessitated the aircraft being landed with the parachute streamed.

(2) Detonating unexpectedly. There was one flight where the parachute jettisoned after it had been deployed for some time. The apparent explanation of this is that the bolt was exploded by RF transmission, a known possibility, although steps had been taken to minimise the risk of this occurring.

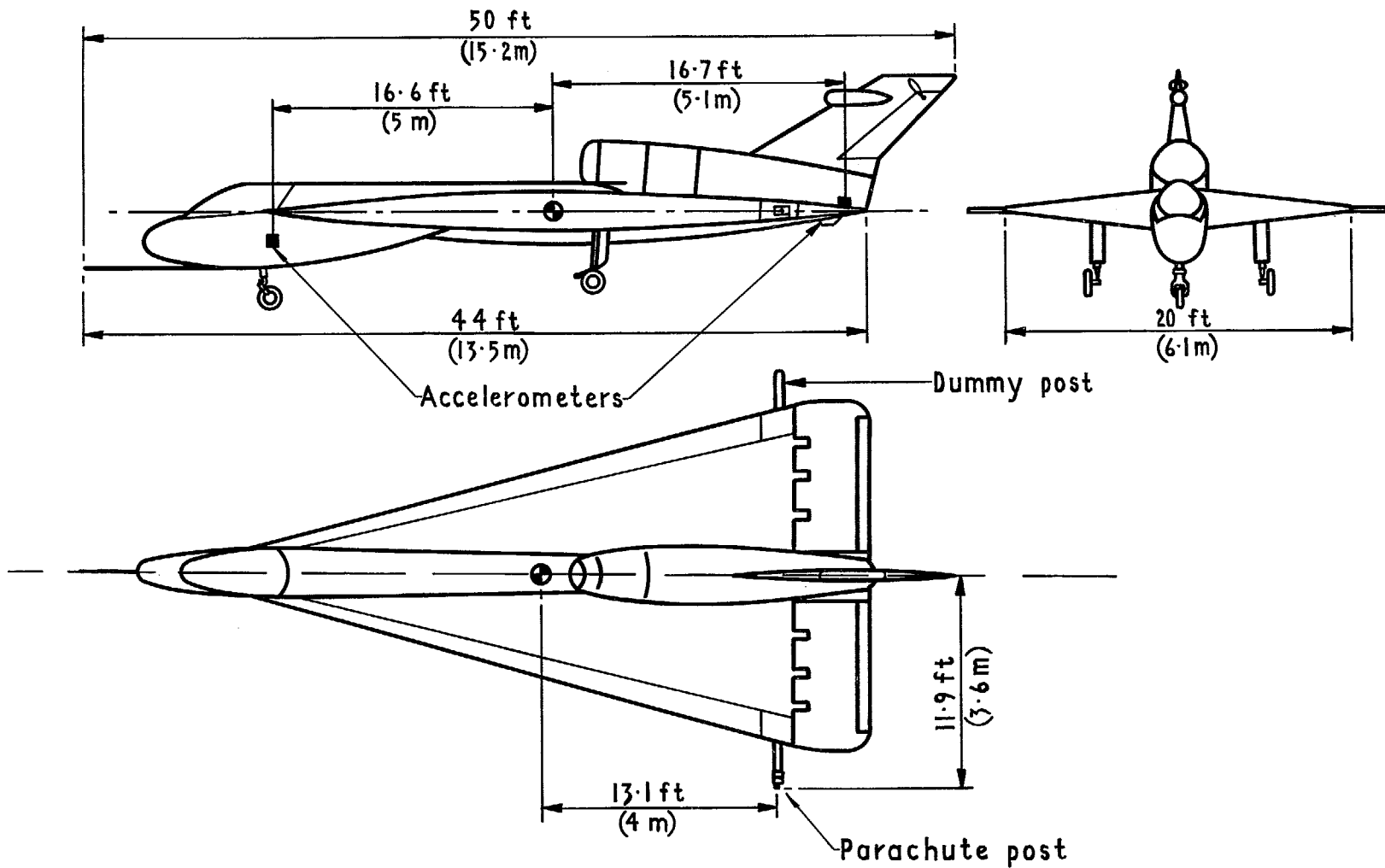
(3) Damage to nearby equipment. It was found that the explosion caused damage to the cable angle potentiometer which was necessarily close to the bolt. This was partially overcome by shielding, but the potentiometer was still subjected to occasional damage.

(4) Danger to groundcrew. To minimise the danger to groundcrew, the detonating circuit was not primed until the aircraft was on the runway. The only other real problems were turbulence, non-deployment of the parachute on one occasion, and there were two auto-jettisons on streaming.

Some Suggestions for Improving the System.

The removal of the explosive bolt from the system would eliminate the bulk of the problems. The possibility of using a small bomb slip or cable cutter should be explored.

An improvement in the parachute storage and deployment would be to stow the canopy and shroud lines in a tube and blow the canopy out fully deployed, by compressed air. This would have several advantages over the system used in the HP 115. Firstly it would mean that the complicated release box would not be needed as only a tube and an electrically operated air bottle would be required. Secondly it would remove all air loads from the pack which would reduce the possibility of auto-jettisons. Thirdly it would mean that the parachute would automatically deploy as it would be stowed in the tube without being in the parachute bag. This system has been used in other tests with very good results.



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FIG. 1. General arrangement of HP 115.

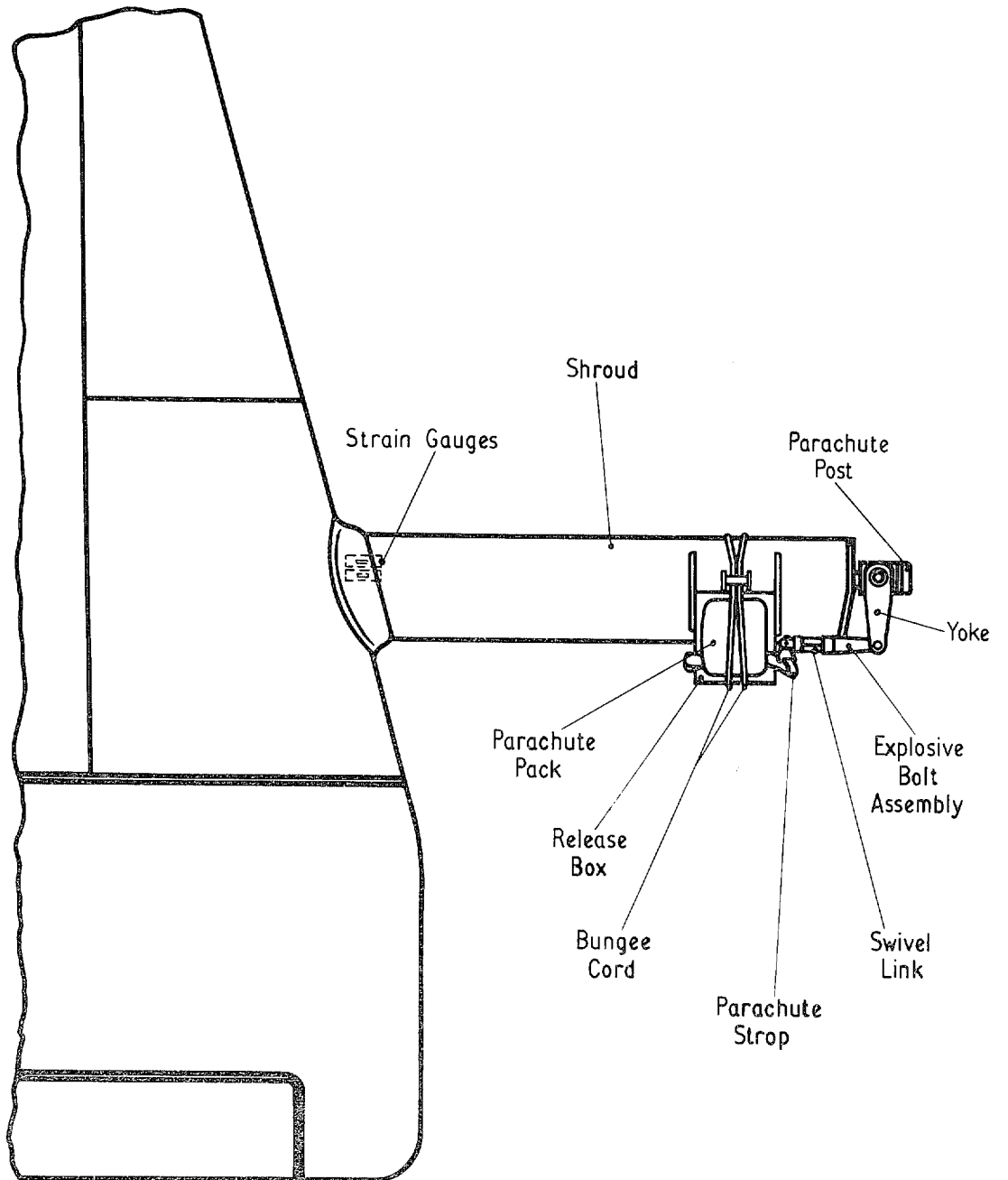


FIG. 2. View of parachute installation port wing tip.

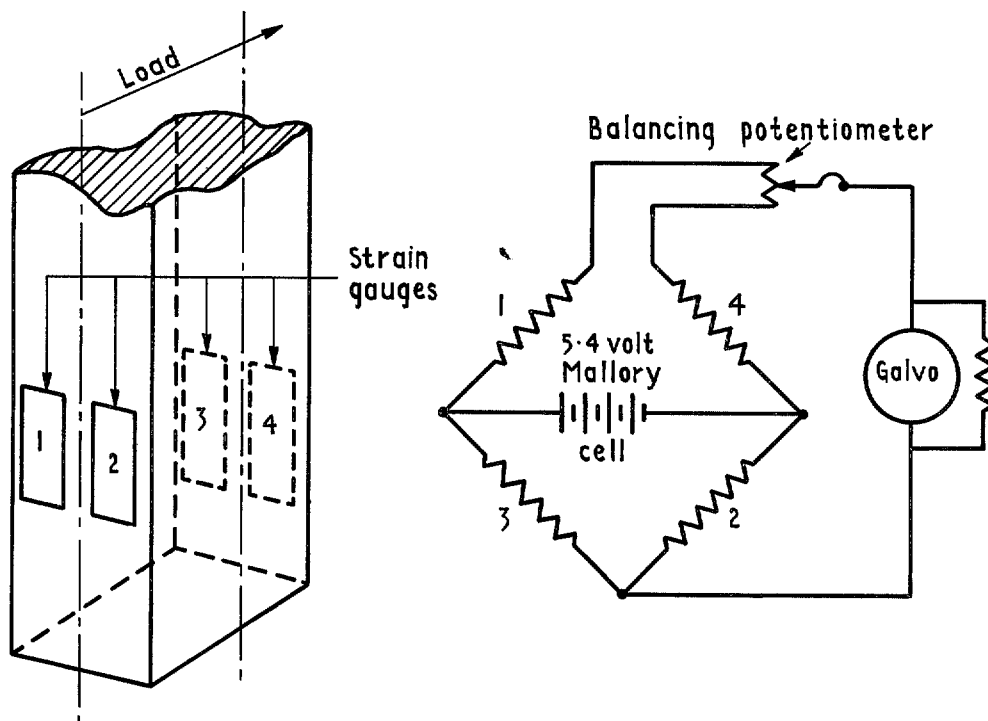


FIG. 3. Bridge circuit used to determine parachute loads.

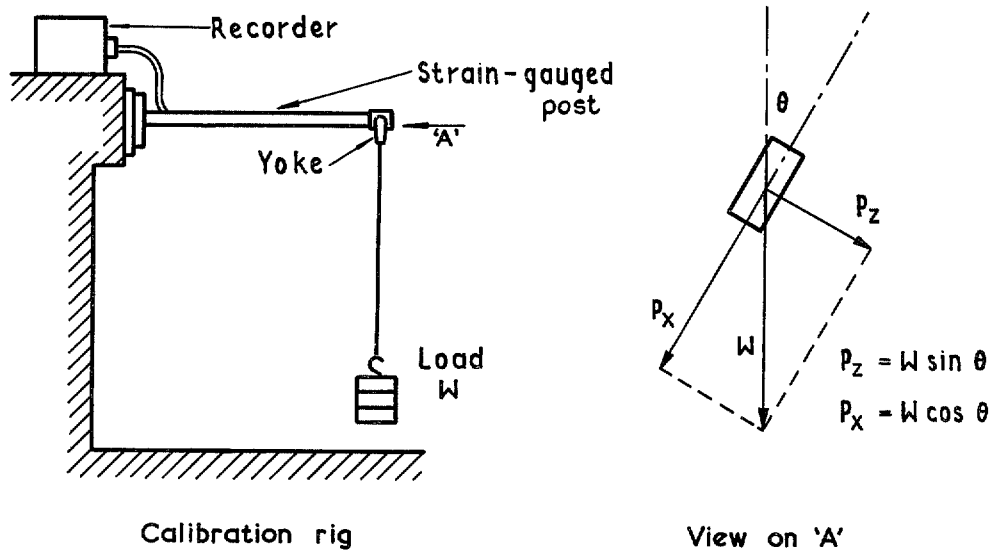


FIG. 4. Method of calibrating strain gauges.

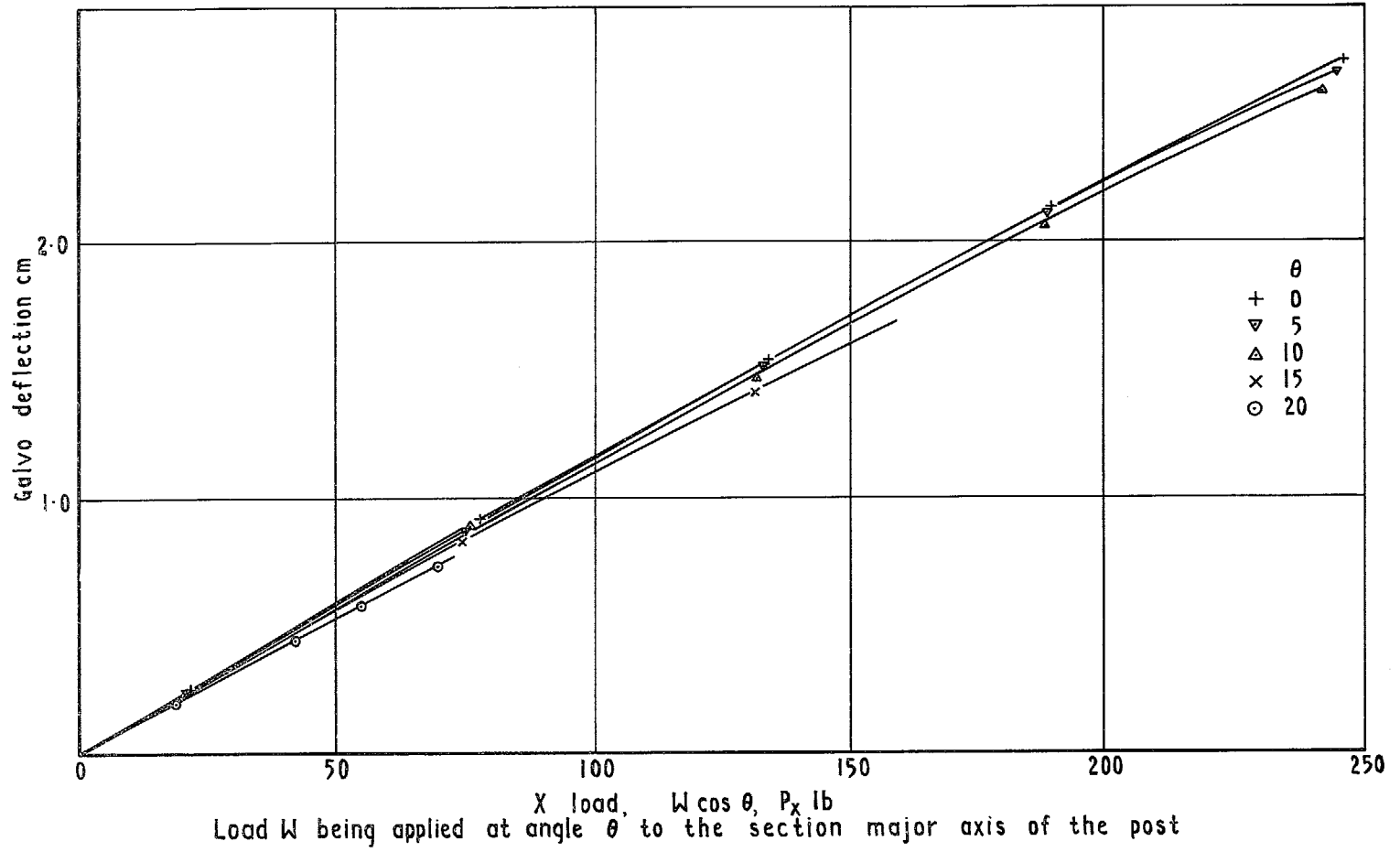


FIG. 5. X load calibration on aircraft.

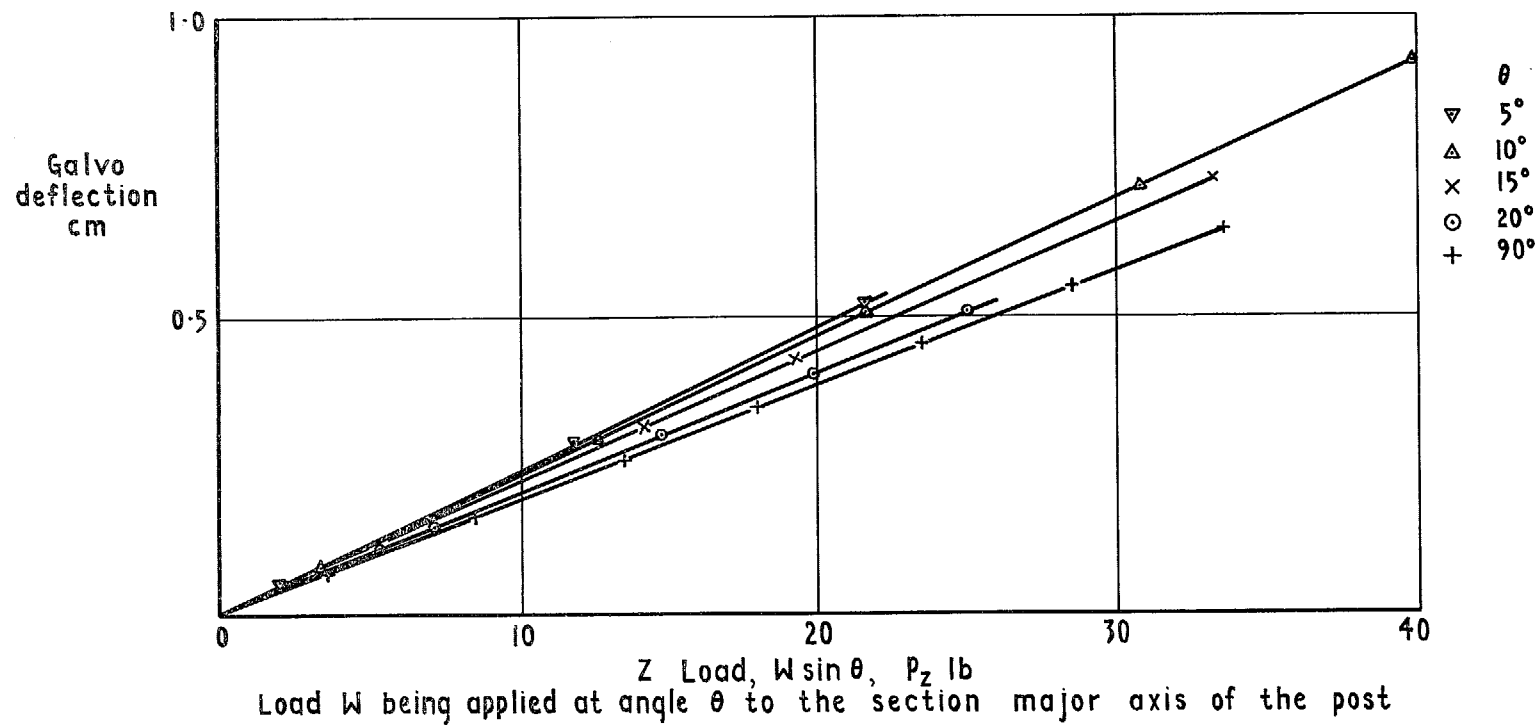


FIG. 6. Z load calibration on aircraft.

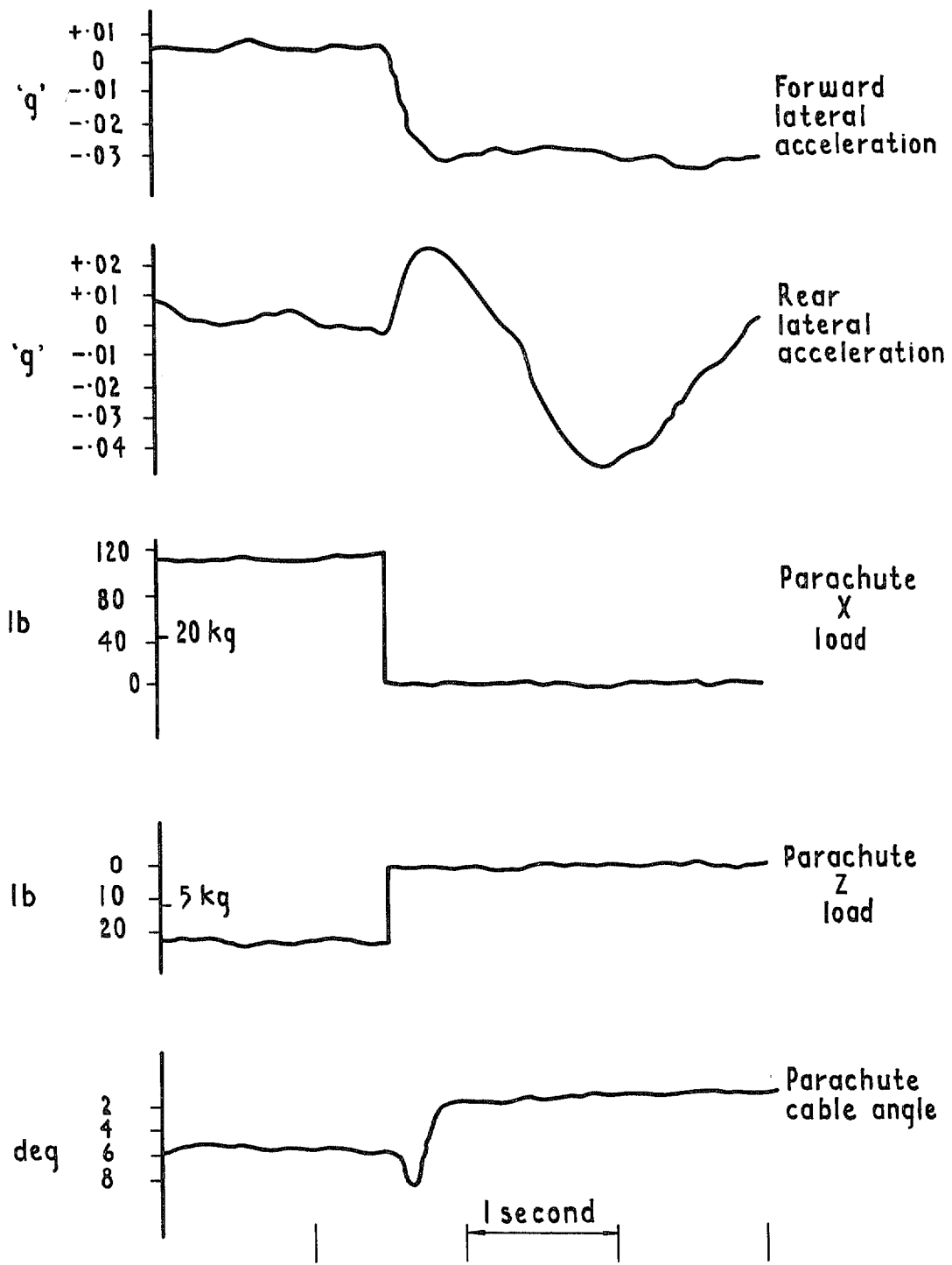


FIG. 7. Typical time history of parachute jettison
 ias 120 knots alt 2500 ft.

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