Biodynamics of Ejection-A Resume of Applied Studies at Institute of Aviation Medicine

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The forces developed during the firing of ejection guns are discussed based on the trajectory traced by the ejection seat and the requirement for safe clearance of the seat from aircraft structure. Assessment of ejection characteristics of seat packs and comfort cushions assume significance in view of the high magnitude of these forces. Testing of these properties is possible by recording the damped oscillatory motion of the seat pack or cushion after an impact force.

Theory and developmental details of strain gauge accelerometers and anthropomorphic dummies alongwith their use in the evaluation of ejection cartridges are discussed.

Introduction

Ejection is the accepted mode of escape for aircrafts having speeds higher than 200 m.p.h. It is well understood that above this speed the force of the slip stream will be too high, that an aircrew trying to leave the aircraft will be pushed back into the seat. It is, therefore necessary to assist the subject to escape by means of an ejection seat which is given an upward velocity 'V_S' by firing the ejection cartridges.

Trajectory of Ejection Seat

Determination of the ejection seat trajectory with respect to the aircraft is of great importance to ensure that the seat-man combination does not foul with any part of the abandoned aircraft. The equation for the trajectory can be worked out[2] and is given by :

$$Y = \left[\frac{V_1^2}{g} \frac{V_S}{V} f_1 - \frac{V_1^2}{V^2} f_2 + \frac{1}{2} \frac{C_L}{C_D} f_1^2 \right]$$

where Y is the vertical distance with the aircraft cockpit as the origin, V_1 the terminal velocity of the seat at the ejection altitude, V_S the ejection velocity, C_L and C_D are coefficients of lift and drag and g acceleration due to gravity f_1 and f_2 are functions depending on the factor $\frac{gx}{V_1^2}$ where x is the horizontal distance on the the X — axis. The equation shows the dependence of the trajectory on the drag produced on ejection. The trajectory becomes flatter and flatter as the drag increases with the speed of the aircraft at which ejection takes place. The only available method therefore to ensure safe ejection is to increase the value of 'V_S'

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requiring higher velocity cartridges for high speed ejections.

Human Tolerance to Ejection Accelerations

The tolerance limit laid down[3 & 6] for the short duration acceleration of the type met with in ejection, and acting along the vertical axis of the spine is in the range of 300 g/sec rate of onset and 25 g maximum peak. However, the design criteria of ejection cartridges have to be lower than this because the forces experienced by the human subject could be higher than that produced by the cartridges as a result of the internal dynamics of the man-seat system. One of the important factors which contribute to dynamic overshoot of acceleration is the type of the seat pack. When a force is applied rapidly to an elastic mass, such as the seat pack-subject, a dynamic response is initiated in the mass. It is observerd by Watts et al[8] that the peak acceleration at a given point in a system depends on the time of application of force, natural frequency and damping of the system.

Assessment of Ejection Characteristics

Good correlation has been established between the seat pack characteristics (compressibility, damping and natural frequency) and acceleration experienced by the subject[1]. Assessment of the seat pack characteristics are carried out using the experimental arrangement shown in Figure 1.

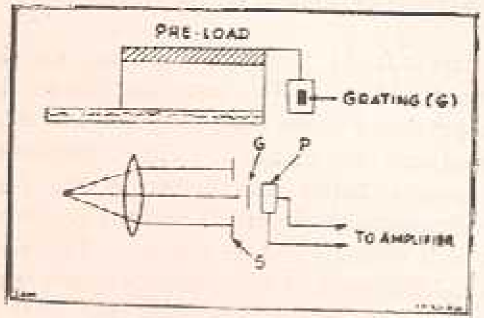

Fig. 1 The experimental arrangement

Oscillatory motion of the pack is initiated by applying an impulse force. Mechanical oscillations are transduced by using a special grating with wedge shaped elements[6]. A beam of intense light is admitted through a narrow slit S and then passed through the grating G. The emergent rays fall on a photocell P. The lamp-slit-photocell arrangement is set on an adjustable platform and the centre of the slit is made to coincide with the centre of the grating which is attached to the preload. The amplified output of the photocell is recorded.

Equivalent Dynamic System

The equivalent circuit of the experiment adopted is that of a mass M_1 (Pre-load) suspended from a spring of mass M_2 (seat pack) and a displacement given to M_1, the system moving through a viscous medium.

The equation of motion is :

$$M\frac{d^2x}{dt^2} + Sx + 2r\frac{dx}{dt} = 0$$

where S is the force required to produce unit extension and $2r$ is the force per unit velocity.

If $\frac{r^2}{M} < S$, the solution of the equation is

$$X = e^{-\frac{r}{M}t} \left\{ A_1 e^{i\sqrt{\frac{S}{M} - \frac{r^2}{M^2}}\,t} + A_2 e^{-i\sqrt{\frac{S}{M} - \frac{r^2}{M^2}}\,t} \right\}$$

where A_1 and A_2 are constants

This represents an oscillation of decreasing amplitude of period,

$$T = \frac{2\pi}{\sqrt{\frac{S}{M} - \frac{r2}{M^2}}}$$

and logarithmic decrement,

$$D = \frac{\pi}{\frac{r}{M}\sqrt{\frac{S}{M} - \frac{r^2}{M^2}}}$$

Actual record from a typical survival pack is given in Figure. 2.

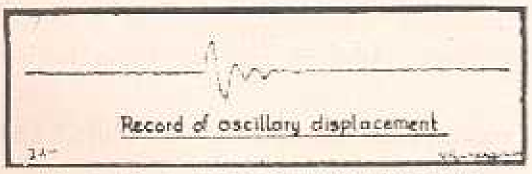

Fig. 2 Record of oscillary displacement

Choice of the contents of Personal Survival Packs for their ejection characteristics have to be based on the values obtained for damping and compressibility.

Such a technique is currently followed in the I.A.F.

Recording of Accelerations during Ejection

Since accelerations produced by currently used ejection cartridges are quite close to the human tolerance level, recording of accelerations on the ejection seat as well as at the hip and chest level of the subject are resorted to in the assessment of ejection cartridges, survival packs and comfort cushions. Accelerations with linear response upto 50 g which can give continuous record of 'G' for short duration (0.2 sec) are required for this purpose. During our studies on biodynamics of ejection we had to develop accelerometers for physiological recording since the central purchase of these items from Statham Laboratories did not materialise.

Design of the Accelerometers

Our design is based on recording of the strain in a Cantilever beam with a weight at one end, produced by the effective increase in weight caused by the accelerative forces (Fig. 3) similar to the principle used for

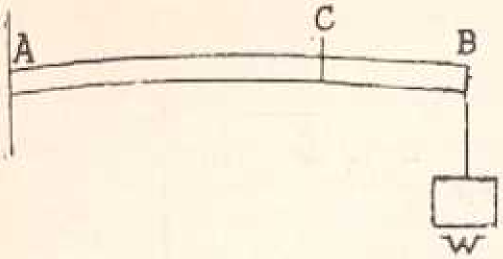

Fig. 3 Cantilever with load

accelerometer developed by the Cramp Shipbuilding Company and U.S. Naval Air experimental station[4]. Since high frequency response upto 100 C. P. S. is required for ejection studies our design has to be significantly different from the thin beam-heavy weight used by the Naval Station.

When a beam is strained by the action of a weight W, equilibrium of forces is established by the internal forces and the effect of the load W. For any section through a point such as 'C' the bending moment $W \times CB$ is balanced by an internal couple. The depression δ at the point 'B' caused by W is given by the equation :

$$YAK^2\delta = \frac{L^3}{3}\left(W + \frac{3}{8}W'\right)$$

where Y is the Young's modulus, AK^2 is moment of intertia, L is the length of the beam and W^1 is the weight of the beam.

If we consider a layer DE of the bar which is above the neutral surface by a value 'Z' (Figure 4) and if PN is drawn parallel to DM, then the extension of the layer 'ds' $= PN\theta = Z\theta$ where θ is the angle PNE. θ will also be the angle subtended by the neutral surface MN at its centre of curvature. If 'S' is the length of the unextended element along the neutral axis, then $S = R\theta$

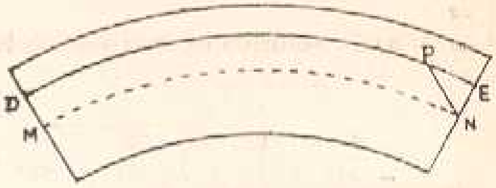

Fig. 4 Strain in a bent bar

Therefore $$\frac{ds}{S} = \frac{Z}{R}$$

The internal bending moment will be :

$$\frac{Y}{R}\sum \alpha Z^2 = \frac{YAK^2}{R}$$

where Y is the Young's modulus, α, the area of cross sections of the individual elements and A, the area of cross section of the bar. This must balance the moment of the external forces at the section considering the strain of a section distant 'd' from the fixed end of the cantilever and if 'l' is the distance of the weight 'W' from the cantilever, the external moment will be :

$$W(l-d) + W'\left(\tfrac{L}{2}-d\right)$$

Since $AK^2 = \frac{bt^3}{12}$ for beam having rectangular cross section with width b and thickness t

$$\frac{Ybt^3}{12R} = W(l-d) + W'\left(\frac{L}{2}-d\right)$$

So the strain of the section DE

$$\frac{ds}{S}=\frac{12Z}{Ybt^3}\left\{W\,(l-d)+W'(\tfrac{l}{2}-d)\right\}$$

The strain of the section will be maximum if it lies on the upper or lower surface of the beam and when the distance from the fixed edge is minimum. In the present design of the accelerometer four strain gauges are cemented close to the fixed edge, two on the upper R_1 and R_4 and two on the lower surface R_2 and R_3.

The gauges are connected in a Wheatstone network(Fig. 5) using a battery with a voltage 'E' and an amplifier–recorder assembly with resistance 'R_g'. The bridge is balanced when there is no strain on the gauges. Under 'G', when a change in resistance

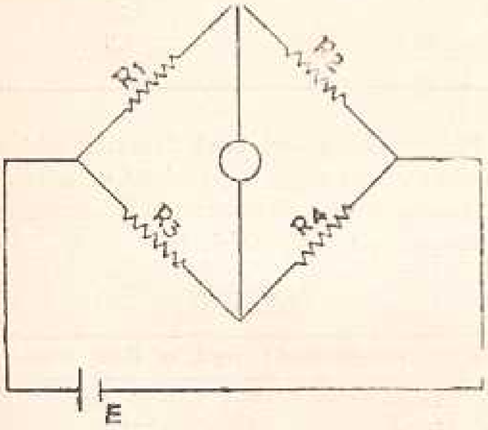

Fig. 5 Strain gauges in wheatstone net work

$$\triangle R=F.R.\frac{ds}{S}$$

is produced, F being the gauge factor, the bridge balance will be upset and there will be a current '$i\,g$' flowing through the galvanometer.

$$i\,g=\frac{E\triangle R}{\left\{R_g\;R+R^2-(\triangle R)^2\right\}}$$

Therefore $i\,g$ is linearly related to strain for change in resistance where the gauge factor remains unchanged.

Using flat grid strain gauge having resistance 120 ohms and gauge factor 2.8, our design aimed at 150µv output per 'g'

The accelerometer in its final assembled form and the Cantilever strain gauge arrangement are given inFigure 6.

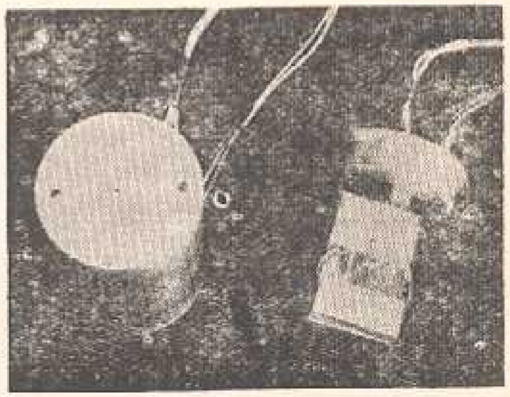

Fig. 6 Accelerometer

Calibration of Accelerometer

The exact unbalanced output potential per unit 'g' has to be estimated prior to the use of any accelerometer. This was carried out by using a Human Centrifuge. The accelerometer was mounted in the gondola, with the accelerometer axis along the vertical axis of the gondola which was on free gymbals. The Centrifuge was run for different 'g' values ranging from 5 g to 25 g. The records of bridge output obtained on a Grass Model III

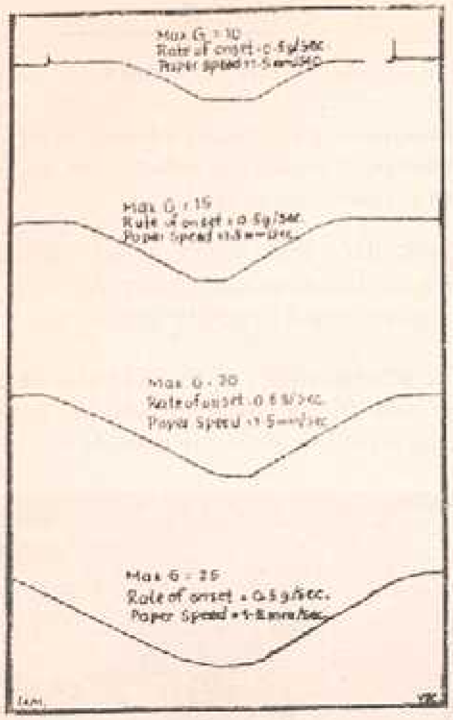

Fig. 7 Calibration Curves for Accelerometer

Polygraph are shown in Fig. 7. The accelerometer gave a linear response for all values upto 25 g as may be seen from the records.

Anthropomorphic Dummy

Because of the dynamic response characteristics of the human body, acceleration profiles obtained from a rigid structure such as ejection seat will not give the actual acceleration experienced by the human subject. Though it is ideal to record accelerations from the human subject by fixing accelerometers at the required sites, it is not advisable to have human subjects for trials because of the injury risk involved. Anthropomorphic dummies, with elastic and damping properties as close to the human subjects as possible, are used for such trials.

TABLE I

Weight Distribution of the Body

Body Component	Percentage of total weight
Head and Neck	8.3
Upper Trunk	27.2
Lower Trunk	15.5
Thighs	22.2
Legs and Feet	16.7
Upper Arms	5.6
Forearms and Hands	4.5

We have made two such dummies which have the same weight distribution of the limbs and body components as an average human subject (see Table I).

TABLE II

Weight, Height and Length of Body Parts	
Weight	65 Kg.
Height	171 cms
Leg Length	107.5 cms
Thigh Length	58.8 cms
Sitting Height	89.0 cms

The weight, height and length of body parts of the dummy were similar to those of the average I. A. F. Pilot (Table II). After trials on a number of materials, a plastic-rubber adhesive combination was chosen for fabrication of vertebrae with compressibility comparable to that of cadaver. Sample test results on lumbar vertebrae using Amsler testing machine is given in Table III

TABLE III

Load in Kg.	D. T. I. Readings Least count 0.01 mm.			
	Test — I		Test — II	
	Loading	unloading	Loading	unloading
0	0	0	0	0
400	164	223	151	236
600	220	257	206	273
800	262	279	273	296
1000	299	299	318	318

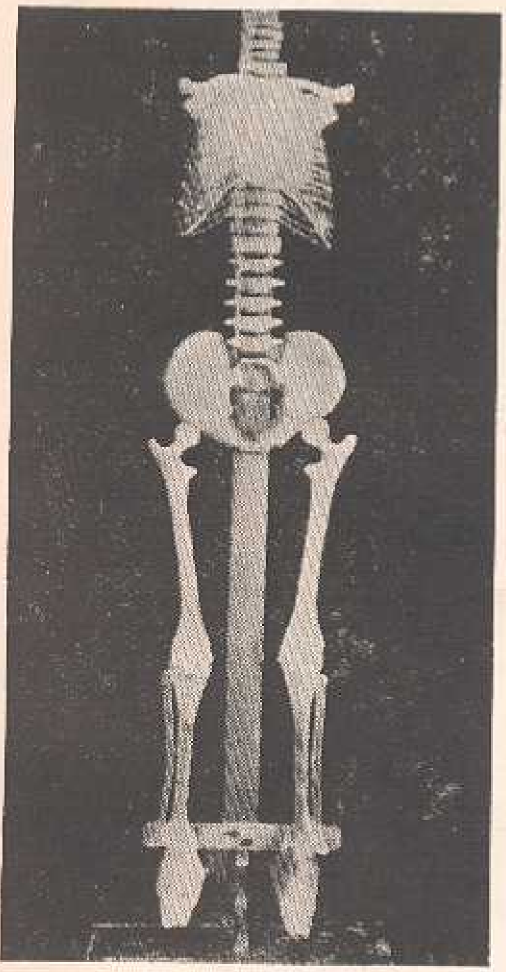

Fig. 8.
Skeleton for anthropomorphic dummy

Rib cage was prepared by heat treatment of perspex and shaping the perspex on a plaster of paris mould of the cage. The skeletal system was assembled with essential joint movements (Fig. 8)

Trials revealed that heat treated raw rubber corresponded in properties to that of muscle and tissues mass and foam rubber-crepe rubber combination came close to that of fat and skin.

Headform was fabricated from specially chosen wood which matches the density and impact damping properties of the head.

For the analysis of impact damping, a special instrumentation set up was fabricated for shock absorption. (Fig. 9). This is now being used for testing of bone domes and helmets[7].

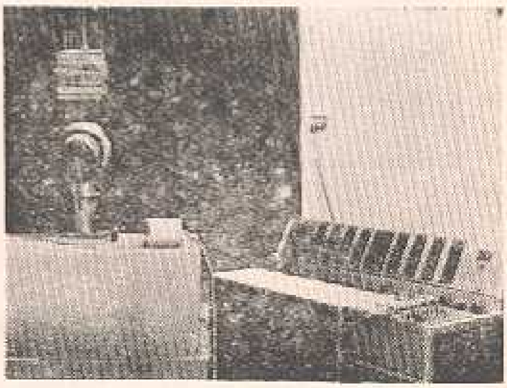

Fig. 9
Instrumentation set up for helmet testing.

This equipment included the development of a piezoelectric load gauge with x-cut quartz crystal ($1''x\frac{1}{4}''x\frac{1}{4}''$) mounted in a mild steel gauge body. The load gauge was mounted on a large concrete block weighing one ton. The output of load

Fig. 10a The Anthropomorphic Dummy

Fig. 10b The Dummy on the ejection seat

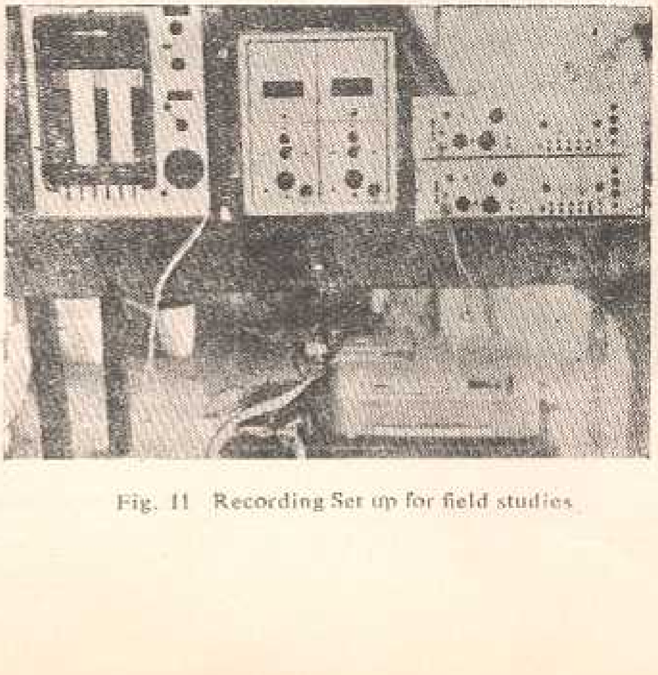

Fig. 11 Recording Set up for field studies

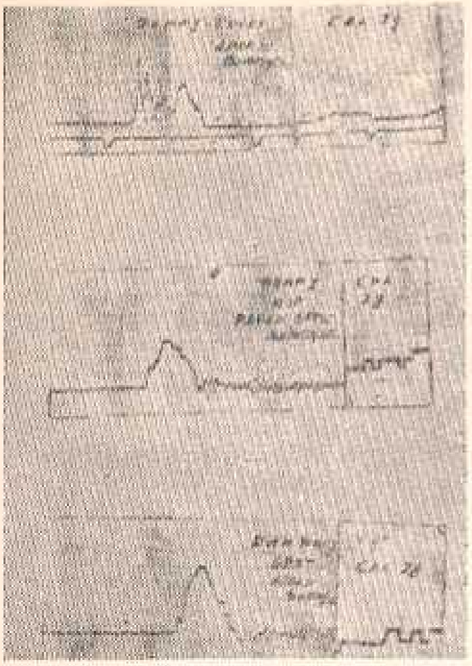

Fig. 12
Acceleration profile from ejection cartridge

gauge was fed to a recorder through an amplifier.

The dummy in the completed form is shown in Figure 10.

Ejection Test Rig Trials

I. A. M. accelerometers were used for trials using an ejection test rig and an instrumented anthropomorphic dummy. One accelerometer was fixed on the ejection seat and two on the dummy; one at the hip and the other at the chest. The accelerometers were connected by long cables to a three channel recording system (Fig. 11). Typical records from the dummy are given in Figure 12.

Acknowledgement

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