Computer Model of a Fully Deployed Parachute

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A computer model of a parachute system based upon a six-degree-of-freedom analysis is described. Its current limitations are discussed and an outline of the analysis and computer program is given. This is followed by a brief description of some comparisons made with real drops and the input data currently considered necessary to simulate the behavior of a real parachute. The paper concludes with a look at possible investigations which could lead to improvements to the model. The program is capable of ready adaptation to cope with a parachute system symmetrical about a plane through its longitudinal axis. The main assumptions are: the payload is rigidly connected; the aerodynamic forces on both canopy and payload are determined solely by the instantaneous angle of attack of the oncoming airstream; the apparent and included inertias of the system are constants, but are dependent upon the direction of the acceleration. A feature of the model, in addition to those just outlined, is an ability to simulate parachute behavior in a turbulent wind.

Introduction

IN order to complement other research at the University of Leicester into the behavior of fully deployed subsonic parachutes, an extremely flexible computer program, or model, has been designed and tested against the limited full-scale data available. The differences between this model and that due to White and Wolf[1] are discussed later.

Essentially, the model is an application of Newton's Laws of motion to a body with six degrees of freedom, together with the necessary trigonometrical relationships, in order to relate the body-centered coordinate system to an origin fixed in space.

In addition to a physical description of the parachute system being modeled, three types of input are required: the initial conditions for any given drop, i.e. velocities and attitude; the aerodynamic characteristics of the canopy and payload, i.e. lift, drag, and moments; the inertial characteristics of the system due to included and apparent air masses. The model itself is sufficiently adaptable to be able to accept a wide range of these input parameters. Determination of the aerodynamic characteristics of a given canopy shape formed a major part of the research program as a whole, and the techniques used, together with a discussion of the inertial characteristics of a parachute system, have been described by Cockrell et al.[2] However, a brief statement as to those adopted for the model/full-scale comparisons described herein is included in the selection entitled "Inputs to the Model."

Limitations

At the time of writing the basic assumptions which limit the model are as follows:

1) The system consists of two rigidly connected parts falling freely under the influence of gravity. These are a canopy which can experience lift, drag, and a pitching moment about a specified point, and a payload, or store, which creates drag but negligible lift force. This system is symmetrical about an axis joining the canopy centroid to the payload. The restriction to an axisymmetric system in this context is not as harsh as might appear at first sight. It applies only to the geometry of the system and not to its aerodynamic characteristics. The existence of drive slots would be of importance in this context only insofar as they affect the symmetry of the system's moments of inertia. Furthermore, an extension to plane symmetry about the xz plane only (see Fig. 1) involves no major modifications of the model.

2) The aerodynamic forces and moments on the canopy and payload are functions of the translational velocities, including therefore the angles of incidence, evaluated at the centroid, of each component. These translational velocities take into account both the translation and the rotation of the system as a whole, but any moments that would arise as a result of pure rotation of either component are not included. Experiments currently are being designed to determine the magnitude of rotational effects; should these be significant, the program will be modified to allow for them.

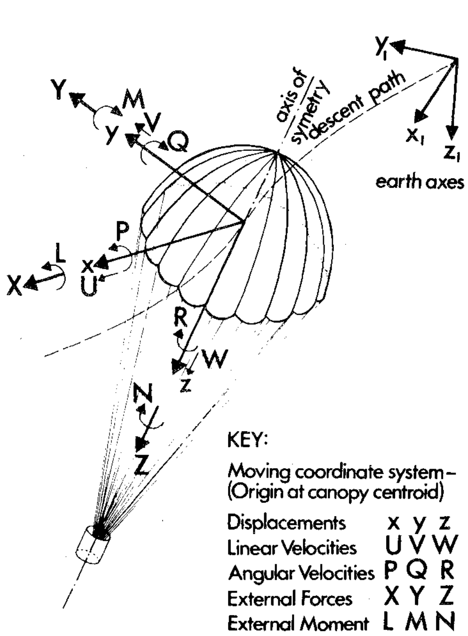

Fig. 1 System of axes.

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3) The model will only accept axisymetric aerodynamic data. It is an easy task to modify the program to overcome this limitation. However, this will necessitate supplying data as a function of two angles of attack and this in itself is a formidable problem.

4) The apparent mass and apparent moment of inertia of the system, referred to jointly as the apparent inertia, are constants but are dependent on the direction of motion being considered.

5) The density of the air is constant and the Earth is considered to be flat. Both of these were considered adequate for the current applications of the model, and will be removed in order to cope with deep turbulent shear layers.

Basic Equations

The feature that distinguishes a body moving in a fluid from one in free space is the apparent inertia which arises because of the acceleration of the fluid. The apparent inertia is dependent upon the direction of motion. Thus, when writing the equations of motion that are obtained by applying Newton's Laws, the mass and the moment of inertia of the system under consideration can be considered to be dependent upon the relevant component direction.

In these equations, therefore, mass is assumed to consist of three components: the actual mass of the system; the included mass, i.e. the mass of air that is assumed to be trapped by the canopy and rigging lines and thus to move with the system; and the apparent mass which is due to acceleration of the surrounding air. These component masses have moments of inertia about the origin.

The external forces and moments on the system arise from direct aerodynamic effects, i.e. lift, drag, and pitching moment of the canopy and payload, and the weight of these components. The included and apparent masses do not contribute to the weight of the system.

The reader is referred to Fig. 1 for a definition of the symbols used for forces and moments and the various motions of the moving coordinate system. The plane symmetry conditions referred to previously allow only one nonzero first moment of mass, and all inertial cross products are zero. Thus, we have the following equations of motion:

$$X=M_1(\dot{U}-RV+QW)+(RP+\dot{Q})A_3 \tag{1a}$$

$$Y=M_2(\dot{V}-PW+RU)+(RQ-\dot{P})A_3 \tag{1b}$$

$$Z=M_3(\dot{W}-QU+PV)-(P^2+Q^2)A_3 \tag{1c}$$

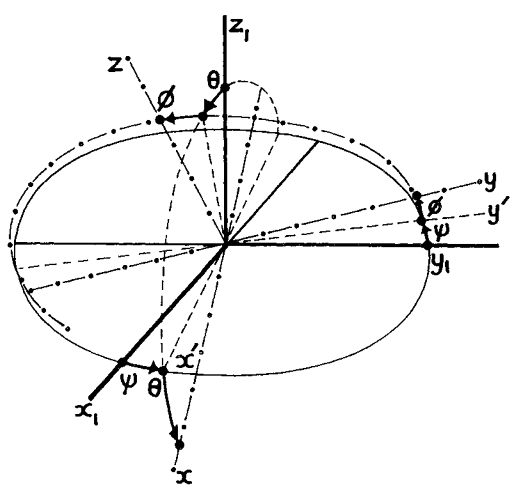

Fig. 2 Euler angles – x,y,z specified in relation to x_1, y_1, z_1 by an ordered sequence of rotations: a rotation about z_1 (x_1 moves to x', y_1 to y'); a rotation about y' (x' moves to x); a rotation about x (y' moves to y).

$$L=I_1\dot{P}-(\dot{V}-PW+RU)A_3-(I_2-I_3)QR \tag{1d}$$

$$M=I_2\dot{Q}+(\dot{V}-RV+QW)A_3+(I_1-I_3)RP \tag{1e}$$

$$N=I_3\dot{R}+(I_2-I_1)PQ \tag{1f}$$

where M_1 and M_2 are effective masses in directions x,y, and z; I_1, I_2, and I_3 are moments of inertia about axes x,y, and z; and A_3 is a first moment of mass, the moment arm being measured along the z axis.

Since the origin has been chosen to be at the canopy centroid, at which point the included and apparent masses are assumed to act,

$$A_3=lm_p \tag{2}$$

m_p being payload mass and l distance of payload from canopy centroid.

Since one of the external forces is that due to gravity, it is necessary to relate the orientation of the moving coordinate system to fixed Earth axes. Also, if other factors such as wind speed or air density are dependent upon altitude, the position of these axes must be established. The equations necessary to achieve this are

$$\dot{\theta}=Q\cos\phi-R\sin\phi \tag{3a}$$

$$\dot{\phi}=P+Q\sin\phi\tan\theta+R\cos\phi\tan\theta \tag{3b}$$

$$\dot{\Psi}=(Q\sin\phi+R\cos\phi)\sec\theta \tag{3c}$$

$$\dot{x}_1=U\cos\theta\cos\Psi+V(\sin\phi\sin\theta\cos\Psi-\cos\phi\sin\Psi)+W(\cos\phi\sin\theta\cos\Psi+\sin\phi\sin\Psi) \tag{3d}$$

$$\dot{y}_1=U\cos\theta\sin\Psi+V(\sin\phi\sin\theta\sin\Psi+\cos\phi\cos\Psi)+W(\cos\phi\sin\theta\sin\Psi-\sin\phi\cos\Psi) \tag{3e}$$

$$\dot{z}_1=-U\sin\theta+V\sin\phi\cos\theta+W\cos\phi\cos\theta \tag{3f}$$

Where θ, ϕ, and Ψ are Euler angles specifying rotations of an orthogonal set of axes x,y,z, in axes system x_1,y_1,z_1 (see Fig. 2).

This set of 12 linear ordinary differential equations, rearranged with the derivatives on the left-hand side, may be readily solved numerically given the necessary 12 initial conditions.

The attitude of the system, the inclination of the system to the vertical, may be obtained from the Euler angles via

$$\text{Attitude}=\cos^{-1}(\cos\theta\cos\phi) \tag{4}$$

Computer Program

The philosophy behind the construction of the program was that all discrete mathematically or physically identifiable features should be kept in separate subroutines. In Fig. 3 the name of each subroutine is shown in hierarchical diagram. A brief description of the functions of some of the various routines will indicate the techniques used and the potential of the model.

ADSBH, PARA, OUT

The operation of the model is controlled by subroutine ADSBH. This is an implementation of the Adams-Bashforth algorithm for solving a set of first-order ordinary differential equations by means of a forward and backward difference predictor and corrector technique.

Each of the 12 derivatives are computed in subroutine PARA using current values of all of the variables. The values of these variables at the end of the time interval are then predicted and compared with these obtained using the corrector routine. Providing the predicted and corrected

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MAIN                                        Entry point.
     INITL                                  Initialises model, reads data.
          UNTVCT                            Computes unit vectors at current attitude.
     ADSBH                                  Solves differential equations (see text).
          PARA                              Organises equations for ADSBH.
               UNTVCT                       See above.
               AIR                          Determines air movements relative to canopy and payload.
                    WIND*                   Supplies information on superimposed winds.
               FORCES                       Calculates all external forces on the parachute system.
                    CNF                     Computes normal force on canopy.
                         TRPL                                            } Aids for accessing
                              AITKEN                                     } tabulated data.
                    CTF                        "     tanjential " "    "
                         TRPL
                              AITKEN
                    CMF                        "     Pitching moment "  "
                         TRPL
                              AITKEN
                    CSF                     Computes drag on payload.
               DER                          Assembles right hand side of differential equations.
          OUT                               Print-out routine.
*A user supplied function.
The column in which a routine occurs denotes its position in a hierarchy, decreasing in status to
the right. A routine calls those of the next lower status listed below it until another routine
of equal status is encountered.
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Fig. 3 Computer program.

values lie within specified limits, the calculation is repeated for the next time interval. This process continues until a predetermined time has elapsed. Should the errors lie beyond the permitted limits, the time step is either halved or doubled, as appropriate, and the calculation repeated until these limits are satisfied. The values obtained are printed out using subroutine OUT at specified intervals. At present the output is in the form of tabulated values of Earth coordinates, Euler angles, and attitudes. In the near future it is likely that this information will be produced in graphical form.

AIR, WIND

In the first routine the air velocity and angle of incidence relative to the canopy and payload are determined. This involves the use of WIND which is a user-supplied routine specifying incident air velocities relative to the Earth axes. The wind, thus specified, may be a function of time or position; in this way for example, a turbulent boundary layer could be simulated.

FORCES

All external forces are computed using the air velocities determined in subroutine AIR in conjunction with user-supplied data for aerodynamic forces and moments.

INITL, CNF, CTF, CMF, CSF

Data for lift, drag, and pitching moment about the canopy apex are supplied, as inputs, at discrete angles of incidence. These data are converted once and for all in INITL into normal and tangential forces and moment about the canopy centroid. These converted values are interpolated for any required angle of incidence as the calculation proceeds. CSF, the drag on the payload is calculated assuming a constant drag coefficient appropriate to a short cylinder.

Comparison with White and Wolf's Model

The current model removes several of the restrictions accepted by White and Wolf.[1] Extensions of their analysis permit 1) hydrodynamic forces on the payload to be included, 2) the system to have an additional degree of freedom, since it is free to roll about its longitudinal axis, 3) included and apparent mass to be tensors, and 4) wind effects to be included. Other features which make the authors model more adaptable include the following: 5) The analysis is carried out and the program written in units normally used by parachute designers. The nondimensional grouping adopted by White and Wolf has been avoided in order to reveal the essential simplicity of the mathematics. 6) By evaluating forces etc., in discrete steps, i.e. first determining relative air movement and then using the appropriate coefficients to obtain forces, simplicity is maintained.

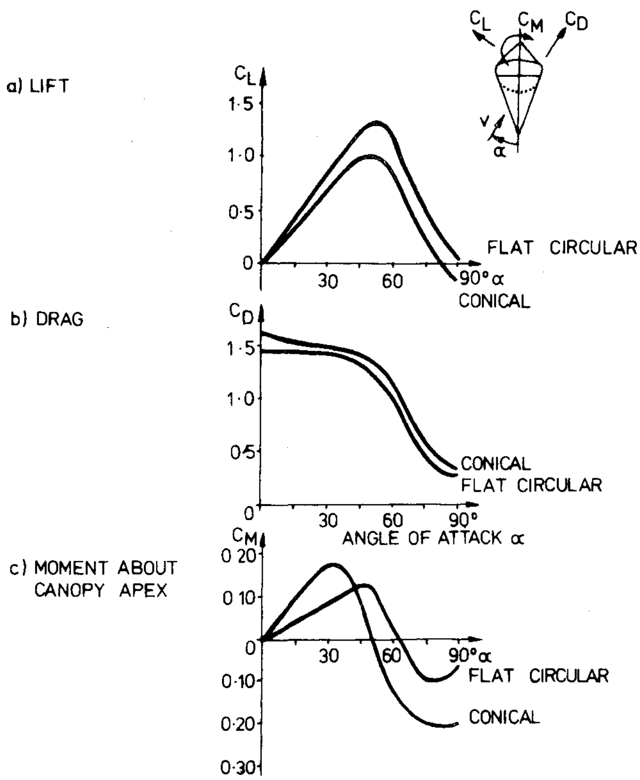

Fig. 4 Lift, drag, and pitching moment for flat circular and aeroconical canopies.

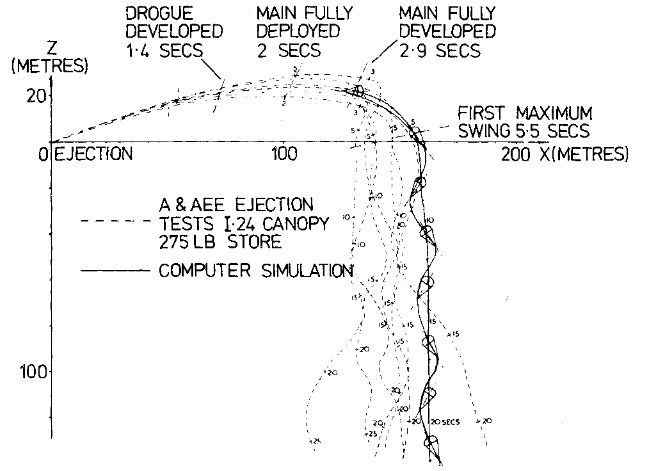

Fig. 5 Trajectories of model and flat circular canopies.

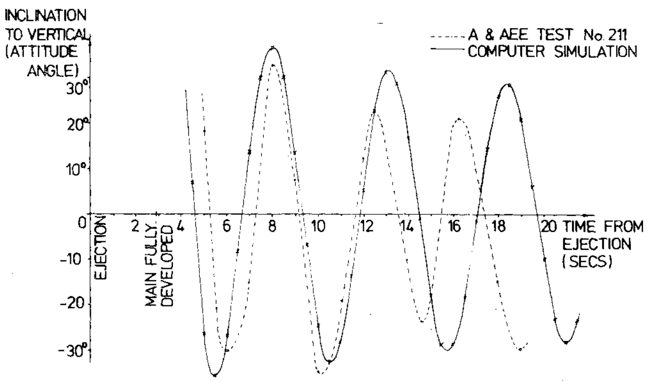

Fig. 6 Oscillatory behavior of model and flat circular canopies.

Inputs to the Model

The following describes the inputs which were supplied for the comparison with actual test drops described in the next section. This should serve to indicate both the nature of the inputs required and the current state of the modelling art at the University of Leicester.

Apparent and Included Inertias (Hydrodynamic Inertias)

Flow visualisation studies by Cockrell et al.[2] have supported the idea put forward by White and Wolf,[1] Heinrich,[3] and others, that there is a mass of air within and below the canopy which is virtually stagnant. A reasonable representation of the flow around a canopy may be obtained by considering it to behave as a planetary ellipsoid. This shape is circular in plan when viewed along the longitudial axis of the parachute system and elliptical, with the major axis equal to the maximum diameter of the inflated canopy, when viewed from the side. The ratio of the minor to major axes for a flat circular canopy is typically 1:2.

Lamb[4] derived expressions for the apparent inertias of ellipsoids of revolution moving in a potential fluid. From these expressions coefficients have been calculated to relate the apparent inertias to the mass of air displaced by the body. Assuming that the included mass, the air moving with the canopy, forms the planetary ellipsoid referred to earlier, we have the following equations defining the hydrodynamic inertias of the system:

$$m_i = (1 + k_i) m_e \qquad I_i = (1 + k'_i) I_{ie} \tag{5}$$

where i can take values 1, 2, and 3, and

m_i = hydrodynamic mass in direction of axis i
I_i = hydrodynamic moment of inertia about axis i

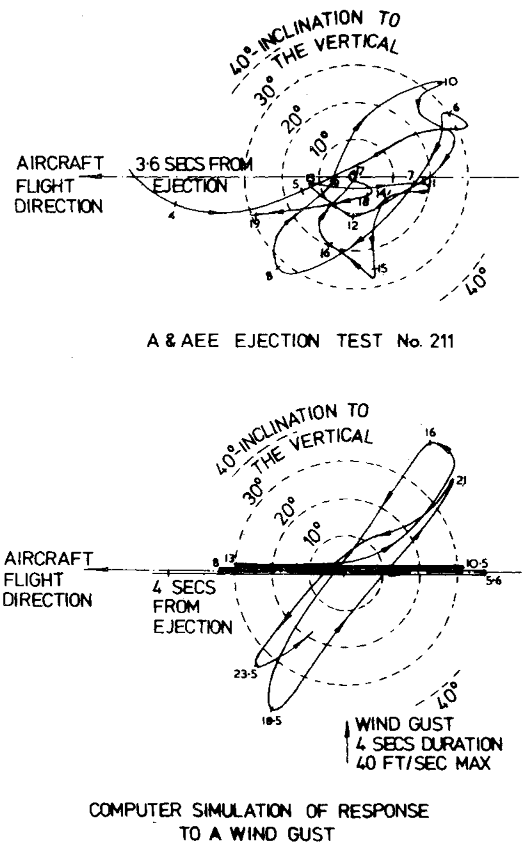

Fig. 7 Effect of gust on model of flat circular canopy.

m_e = mass of planetary ellipsoid of air
I_{ie} = moment of inertia of the planetary ellipsoid about axis i

To these hydrodynamic inertias must be added the normal masses and moments of inertia of the parachute system to obtain M_1, M_2, M_3, I_1, I_2, and I_3 in the equations of motion.

For a planetary ellipsoid with an aspect ratio of 1:2, we have

$$k_1 = k_2 = 0.31 \qquad k_3 = 1.12 \tag{6a}$$

and

$$k'_1 = k'_2 = 0.34 \qquad k'_3 = 0.0 \tag{6b}$$

Aerodynamic Forces and Moments

Values of lift, drag, and pitching moment measured about the canopy apex were supplied for 19 angles of incidence between 0° and 90°. These values were obtained from wind-tunnel tests carried out on 1/40th scale rigid imporous models in a wind tunnel. The models were mounted on a three-component balance and held rigidly at each angle of incidence. These tests were carried out at a Reynolds number of 2.5×10^5. See Ref. 2 for a discussion as to the implications of scale effect. The data used in the comparisons to be described are shown in Fig. 4.

Comparison with Test Drops

The only useful data from test drops available to the authors were for flat circular and aeroconical canopies ejected from aircraft.[5] Since the model is restricted to fully deployed canopies, it was necessary to select a point on the trajectory where this state was reached and to use the velocities and attitude at the point as the initial conditions for the model.

Flat Circular Canopy

The actual drops were made with a standard Irvin I24 canopy and are compared with a simulated drop in Fig. 5.

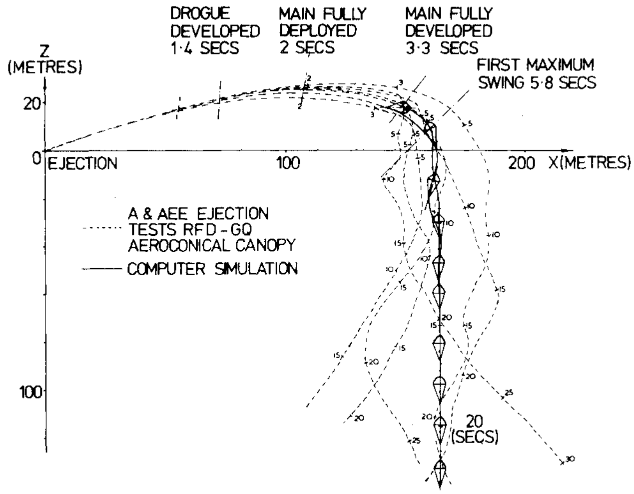

Fig. 8 Trajectory of model and aeroconical canopies.

Still-air conditions were assumed for the simulation; the live drop data were corrected for a steady wind, but it is likely that some turbulence was present.

The simulated drop exhibited oscillations of the order $\pm 30°$ with a period of 5 secs about an otherwise almost vertical descent. The plane of the oscillations was coincident with that of the trajectory. The actual drops were inevitably somewhat random but exhibit broadly the same period, although the rate of horizontal retardation is underestimated by the model. A direct comparison of the oscillatory behavoir is made in Fig. 6.

In order to assess the response to turbulence, gusts of varying intensity were applied to the model. These were single sinusoidal pulses of 4-sec duration applied at right angles to the flightpath 10 sec after the start of the simulation. Figure 7 shows the results of a 40-fps gust compared with an observed drop. Since no wind data for this drop are available, the apparent correlation could be entirely fortuitous. However, it demonstrates the potential of the model and suggests a field for further investigation.

Aeroconical Canopy

The test data were obtained from an RFD-GQ aeroconical canopy with drive slots. Since no aerodynamic characteristics were available for a canopy with drive slots, nor does the model in its present form handle nonaxisymmetric data, the comparison of trajectories is of little value insofar as descent paths are concerned, Fig. 8. However it can be seen that the stable nature of the aeroconical canopy is predicted well. Clearly much further work is also necessary here.

Further Investigations

There is a pressing need for more comparisons between full-scale drops and the computer model. This necessitates obtaining data from drops under controlled conditions, in both still and turbulent air. The instrumentation to provide an adequate description of the latter presents a major problem.

The model, inevitably, is only as good as its input data. However, it is possible to test the sensitivity of the performance of a parachute to the various factors on which it depends. A start has been made on this, and early results suggest apparent inertia is not such a critical parameter as has sometimes been suggested (see also Cockrell et al.[2]). A sensitivity analysis should indicate the relative importance of various possible lines of inquiry. The assumption that quasistatic aerodynamic forces and moments describe canopy behavior adequately also needs further investigation.

Future Developments of Model

With regard to the model itself, several minor extensions already have been mentioned – for example, further relaxation of the asymmetry constraints so as to be able to simulate the flight of canopies with drive slots. The problem here is more one of obtaining aerodynamic data than in modifying the computer program. It is intended to extend the output routines so as to produce graphical output, possibly in the form of animated displays. Since the program currently runs in real time on a second-generation computer, with a faster machine interactive control is a real possibility.

Acknowledgment

The authors wish to stress that the work described was part of that of the parachute Aerodynamics Team[2] in the Engineering department at the University of Leicester. Financial support for the work was largely from the Ministry of Defense and the Science Research Council, assisted in the early stages by the Royal Aeronautical Society. Collaboration with Irvin (GB) Ltd., RFD-GQ. Ltd., R.A.E., and A. and A.E.E. is greatly appreciated.

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