A MODEL OF THE BAFR FLIGHT TEST AIRCRAFT INCLUDING PROPELLER SLIPSTREAM EFFECTS

by

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Summary

The present work was carried out in the context of an Independent Flight Test Facility (IFTF) in Portugal, based on international (AGARD, NRL, DLR, BTU) and national (FAP, JNICT, OGMA, IST) cooperation; the flying element is the Basic Aircraft for Flight Research (BAFR), a CASA 212 Aviocar twin-turboprop light transport, fitted with a flight test instrumentation FTI system, from which smaller dedicated FTIs were developed for several aircraft. The present paper describes a part of one of the research projects carried out with BAFR, viz. a linear longitudinal stability model, including propeller splistream effects (§2-3); the model is reduced from 3x5 - form to a 4x4 - autonomous system of differential equations, from which the frequency and damping of the phugoid and short period modes are determined (§4-5). The results presented here are a part of a larger set including control and simulation studies, mentioned briefly in the conclusion (§6).

List of symbols

c	mean aerodynamic chord
$\bar{e}_x, \bar{e}_y, \bar{e}_z$	unit vectors in x, y, z -directions
g	acceleration of gravity
j	dimensionless acceleration of gravity (24b)
m	aircraft mass
q	pitch rate
s	variable in Laplace transform
u	longitudinal velocity perturbation
w	transverse velocity perturbation
x	longitudinal coordinate
y	transverse horizontal coordinate
z	transverse coordinate in vertical plane
A_{ij}	3x5 stability matrix in dimensional form (14a)
B_i	3-control vector in dimensional form (14b)
C_D, C_L	drag and lift coefficients
C_{ij}	3x5 stability matrix in dimensionless form (24a, 25)
D_i	3-control vector in dimensionless form (22)
$\bar{F}$	total force
$\bar{G}$	gravity force
H_{ij}	4x4 stability matrix in autonomous system
$I_{x,y,z}$	principal moments of inertia
$\bar{L}$	angular momentum
$\bar{M}$	moment of forces
N_i	4- control vector in autonomous system
S	reference area
T	decay time to half-amplitude
U	total longitudinal airspeed
U_0	longitudinal airspeed in steady state
W	total transverse airspeed
X_j	vector of 5 independent dimensional variables (2)
$\overline{X}_j$	vector of 5 independent dimensionless variables (19)
Y_i	vector of 3 dependent dimensional variables (1)
$\overline{Y}_i$	vector of 3 dependent dimensionless variables (20)
Z_i	4-vector of autonomous system (26)
$\tilde{Z}_i$	Laplace transform of Z_i
Z'_i	time derivative of Z_i
α	angle-of-attack
δ_e	angle-of-deflection of elevator
δ_{ij}	identity matrix
μ	reduced mass (23a)
ν	reduced inertia (23b)
ω	frequency
$\bar{\Omega}$	angular velocity
ξ	damping
τ	period
X_{ph}	quantity X for phugoid mode
X_{sp}	quantity X for short-period mode

§1 - Introduction

The present paper is related to the creation (Figure 1) in Portugal, of an independent flight test facility (IFTF) initially based on the BAFR (Basic Aircraft for Flight Research). The latter (Figure 2) is a CASA 212 Aviocar, of the Portuguese Air Force, converted to flight test aircraft, using instrumentation offered by the NLR in Amsterdam, and coming from the Fokker F.27 Friendship twin-turboprop, and F.28 Fellowship twin-jet airliner, and the Dutch-Canadian Northrop NF-5 freedom fighter program. The project was managed by the Aeronautics Laboratory of Instituto Superior Técnico, at Lisbon Technical University, and was supported by the group of Professor Gunther Schänzer, at the Institüt für Flugfuhrung, of Braunschweig Technical University. The project is a good example of international, and national cooperation, e.g. many of the contacts were made through the Flight Mechanics Panel (FMP) of AGARD (Advisory Group for Aerospace Research and Development), and the installation in the aircraft was performed by OGMA (Oficinas Gerais de Material Aeronaútico), which is Portugal's largest aerospace company.

The creation of the IFTF was motivated by pratical needs concerning aircraft testing, modification and certification, and has been supported by a fundamental research programme on dynamics of flight in perturbed atmospheres and non-linear airplane stability. We started with an outline of the research activities, which were started in advance of availability of the aircraft, i.e. in parallel with the design of the flight test instrumentation system; in this way, as soon as the installation of the latter was completed, its was possible to implement both practical application and fundamental research programmes. Starting with the latter three areas of research, of current interest, have been adressed: (i) concerning flight in perturbed atmospheres[1-3], an disturbance intensity indicator[4] has been applied to aerodynamic[5] and flight[6-7] data; (ii) concerning aircraft stability[8-10], non-linear[11-12] and unsteady[13-15] theories have been developed, and compared with flight test data[16-19]; (iii) the more conventional approach to linear, steady-state airplane stability, using Laplace transforms[19-20], has also been used, and a small part of our results is reported here.

§2 - Force and Momentum Balance

For linear stability, the transverse and longitudinal motions decouple, and the latter are specified by the variations in longitudinal F_x and normal F_z force, and pitching moment M_y:

$$i = 1,2,3: \quad Y_i \equiv \left\{\Delta F_x, \Delta F_z, \Delta M_y\right\}. \tag{1}$$

The independent variables would normally be also three, viz. the variations in longitudinal U and normal W velocity and in pitch angle θ:

$$j = 1,2,3,4,5: \quad X_j = \left\{\Delta U, \Delta W, \Delta W', \Delta\theta, \Delta\theta'\right\}, \tag{2}$$

but for a propeller-driven airplane, adequate modelling of slipstream effects, requires also the time derivatives of the latter two $W' \equiv dW/dt$, $\theta' \equiv d\theta/dt$.

If we take for reference state, straight and level flight at uniform airspeed U_0:

$$U(t) = U_0 + u(t), \qquad W(t) = w(t), \tag{3a,b}$$

the vertical velocity is related to angle-of-attack α

$$W = U_0 \Delta\alpha, \qquad W' = U_0 \Delta\alpha', \tag{4a,b}$$

and likewise for time derivatives (4b), so that:

$$X_j = \left\{\Delta u, \Delta\alpha, \Delta\alpha', \Delta\theta, \Delta\theta'\right\}, \tag{5}$$

is the state vector, with the five independent variables.

Turning now to the dependent variables, i.e. moment $\bar{M}$ and force $\bar{F}$, we consider[21-23] first the latter:

$$\bar{F} = m\left(\bar{u} + \bar{\Omega} \wedge \bar{U}\right), \tag{6}$$

including the acceleration due to translation and rotation:

$$\bar{U} = U_0 \bar{e}_x, \qquad \bar{\Omega} = q\,\bar{e}_y, \qquad \bar{u}' = u'\bar{e}_x + w'\,\bar{e}_y. \tag{7a,b,c}$$

Thus the longitudional (8a) and normal (8b) components of force are given by:

$$F_x = m\ u', \qquad F_y = m\left(w' - U_0 q\right). \tag{8a,b}$$

Concerning the rotation, we write the angular momentum L_k in terms of angular velocity Ω_k and principal moments of inertia I_k:

$$\left\{L_x, L_y, L_z\right\} = \left\{I_x, \Omega_x, I_y\Omega_y, I_z\Omega_z\right\}, \tag{9}$$

and note, on account of (7b), that only pitching inertia is relevant here:

$$I \equiv I_y: \quad \bar{L} = I\,q\,\bar{e}_y. \tag{10}$$

The Euler equation for the moment of forces:

$$\bar{M} = \bar{L}' + \bar{\Omega} \wedge \bar{L} = I\,q'\,\bar{e}_y, \tag{11}$$

specifies the third dependent variable in (1), viz:

$$Y_i = \left\{m\ u',\ m\left(w' - U_0 q\right), I\,q'\right\}, \tag{12}$$

with the other two coming from (8a,b).

§3. Linear Stability Theory

The basic empirical assumption of stability theory is a linear relation between independent (5) and dependent (12) variables:

$$Y_i = \sum_{j=1}^{5} A_{ij}x_j + B_i\,\delta_e\,, \tag{13}$$

where A_{ij} is a 3x5 response matrix (14a):

$$A_{ij} \equiv \partial Y_i / \partial X_j\,, \qquad B_{ij} \equiv \partial Y_i / \partial \delta_e\,, \tag{14a,b}$$

and the control vector B_j (14b) relates to elevator deflection δ_e. The 3-components of the control vector:

$$B_i \equiv \left\{\partial F_x / \partial \delta_e\,,\ \partial F_z / \partial \delta_e\,, \partial M_y / \partial \delta_e\ \right\}, \tag{15}$$

have to be identified from flight test data, as well as 12 linear stability derivatives:

$$A_{i1} \equiv \partial Y_i / \partial u\,, \quad A_{i2} \equiv \partial Y_i / \partial(\Delta\alpha), \quad A_{i3} \equiv \partial Y_i / \partial(\Delta\alpha')\,, \ A_{i5} \equiv \partial Y_i / \partial(\Delta\theta')\,; \tag{16a,b,c,d}$$

the remaining 3 components A_{i4} of the 15 elements of the stability matrix, can be calculated from the longitudinal and normal components of weight (Figure 3):

$$G_x = -m\,g\,\sin\theta\,, \qquad G_z = m\,g\,\cos\theta\,, \tag{17a,b}$$

which are the only dependet variables influenced by pitch angle:

$$A_{14} = \partial F_x / \partial\theta = \partial G_x / \partial\theta = -m\,g\,\cos\theta\,, \tag{18a}$$

$$A_{24} = \partial F_z / \partial\theta = \partial G_z / \partial\theta = -m\,g\,\sin\theta\,, \tag{18b}$$

$$A_{34} = \partial M_y / \partial\theta = 0. \tag{18c}$$

Thus the mathematical model of linear longitudinal stability (13), has 15 parameters to be determined (15; 16a,b,c,d).

We can write the system in dimensionless form, starting with the five independent variables (5), using airspeed U_0 and mean aerodynamic chord c:

$$\overline{X}_j = \{u / U_0, \Delta\alpha, c\,\Delta\alpha' / U_0, \Delta\theta, c\,\Delta\theta' / U_0\}\,; \tag{19}$$

concerning the dependent variables (1), forces are made dimensionless dividing by dynamic pressure $\frac{1}{2}\rho\,U_0^2$ times reference area S:

$$\overline{Y}_i = \left\{2F_x / \rho U_0^2 S,\ 2F_z / \rho U_0^2 S,\ 2M_y / \rho U_0^2 S\,c\right\}, \tag{20}$$

and for the moment we use the chord as well.

The linear longitudinal stability system (13) now becomes:

$$\begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} \delta_e = \begin{bmatrix} -C_{11} & -C_{12} & -C_{13} & -C_{14} & -C_{15} & \mu & 0 \\ -C_{21} & -C_{22} & \mu - C_{23} & -C_{24} & -\mu - C_{25} & 0 & 0 \\ -C_{31} & -C_{32} & -C_{33} & -C_{34} & -C_{35} & 0 & j \end{bmatrix} \cdot \begin{bmatrix} u / U_0 \\ \Delta\alpha \\ c\Delta\alpha' / U_0 \\ \Delta\theta \\ c\Delta\theta' / U_0 \\ u'c / U_0^2 \\ c^2\Delta\theta'' / U_0^2 \end{bmatrix}, \tag{21}$$

where: (i) the D_i relate the dimensionless forces and moments (20) to elevator deflection:

$$\{D_1, D_2, D_3\} = \left(2 / \rho U_0^2 S\right) \left\{\partial F_x / \partial\delta_e\,, \partial F_z / \partial\delta_e\,, c^{-1}\,\partial M_y / \partial\delta_e\right\}; \tag{22}$$

(ii) we have made the mass m and moment of inertia I_y dimensionless, by introducing the specific mass μ and specific inertia ν:

$$\mu = 2m / \rho\,S\,c\,, \qquad \nu \equiv 2I_y / \rho\,S\,c^2\,; \tag{23a,b}$$

(iii) of the coefficients C_{ij}, three (18a,b,c) are determined"a priori".

$$\{C_{14}, C_{24}, C_{34}\} = j\{\cos\theta, \sin\theta, 0\}, \quad j \equiv 2mg / \rho U_0^2 S = \mu g c / U_0^2\,; \tag{24a,b}$$

where we introduce the dimensionless gravity j; (iv) the remaining 12 coefficients involve stability derivatives:

$$\begin{aligned}
C_{11} &\equiv (2 / \rho U_0 S)\,\partial F_x / \partial u, \\
C_{12} &\equiv \left(2 / \rho U_0^2 S\right) \partial F_x / \partial(\Delta\alpha), \\
C_{13} &\equiv \left(2c / \rho U_0^3 S\right) \partial F_x / \partial(\Delta\alpha'), \\
C_{15} &\equiv \left(2c / \rho U_0^3 S\right) \partial F_x / \partial(\Delta\theta'), \\
C_{21} &\equiv (2 / \rho U_0 S)\,\partial F_z / \partial u, \\
C_{22} &\equiv \left(2 / \rho U_0^2 S\right) \partial F_z / \partial(\Delta\alpha), \\
C_{23} &\equiv \left(2c / \rho U_0^3 S\right) \partial F_z / \partial(\Delta\alpha'), \\
C_{25} &\equiv \left(2c / \rho U_0^3 S\right) \partial F_z / \partial(\Delta\theta'), \\
C_{31} &\equiv (2 / \rho U_0 Sc)\,\partial M_y / \partial u, \\
C_{32} &\equiv \left(2 / \rho U_0^2 Sc\right) \partial M_y / \partial(\Delta\alpha), \\
C_{33} &\equiv \left(2 / \rho U_0^3 S\right) \partial M_y / \partial(\Delta\alpha'), \\
C_{35} &\equiv \left(2 / \rho U_0^3 S\right) \partial M_y / \partial(\Delta\theta').
\end{aligned} \tag{25}$$

to be identified from flight tests.

$4 - Identification of Model Parameters

The system[21] appears as a 3x7 matrix, but it can can be written as a 4x4 autonomous system of ordinary differential equations[24-26]. For this purpose we choose as independent variables the longitudinal velocity perturbation u, the change in angle-of-attack $\Delta\alpha$, the change in pitch angle $\Delta\theta$, and the pitch rate or angular velocity in pith $q \equiv \Delta\theta'$:

$$i = 1,2,3,4: \quad Z_i = \{u, \Delta\alpha, \Delta\theta, q\}. \tag{26}$$

The autonomous system specifies the time rates of the variables in terms of the variables:

$$Z_i' = \sum_{j=1}^{4} H_{ij}\ Z_j + N_i\ \delta_e, \tag{27}$$

where: (i) because $q = \Delta\theta'$, one row of the matrix H_{ij} is a unit vector:

$$H_{31} = H_{32} = H_{33} = 0 = N_3,\ H_{34} = 1, \tag{28}$$

and one component of N_i as well; (ii) the remaining components of the vector N_i are:

$$N_1 \equiv \left(U_0^2/c\right)\{D_2\ C_{13} + D_1(\mu - C_{23})\}/\{\mu(\mu - C_{23})\},$$

$$N_2 \equiv (U/c)\,D_2/(\mu - C_{23}),$$

$$N_3 \equiv \left(U_0/c\right)^2 \{D_2\ C_{33} + D_3(\mu - C_{23})\}/j; \tag{29a,b,c}$$

(iii) the remaining components of H_{ij} are:

$$\mu(\mu - C_{23})\{H_{11}, H_{12}, H_{13}, H_{14}\} =$$

$$= \left\{\left(U_0/c\right)[C_{13}\ C_{21} + C_{11}(\mu - C_{23})],\right.$$

$$\left(U_0^2/c\right)[C_{13}\ C_{22} + C_{12}(\mu - C_{23})], \tag{30a}$$

$$\left(U_0^2/c\right)[-C_{13}\ C_{24} - C_{14}(\mu - C_{23})],$$

$$\left.U_0\,[C_{13}\,(\mu + C_{25}) + C_{15}\,(\mu - C_{23})]\right\},$$

$$(\mu - C_{23})\{H_{21}, H_{22}, H_{23}, H_{24}\} =$$

$$= \left\{C_{21}/c, \left(U_0/c\right)C_{22},\right. \tag{30b}$$

$$\left.-\left(U_0/c\right)C_{24}, -C_{25} + \mu\right\},$$

$$j(\mu - C_{23})\{H_{41}, H_{42}, H_{43}, H_{54}\} =$$

$$= \left\{\left(c^2/U_0^3\right).\left[C_{33},\ C_{21} + C_{31}(\mu - C_{23})\right],\right.$$

$$\left(c/U_0\right)^2\left[C_{33},\ C_{22} + C_{32}(\mu - C_{23})\right], \tag{30c}$$

$$\left(c/U_0\right)^2 C_{33},\ C_{24}, \left(c/U_0\right)$$

$$\left.\left[C_{33}\ (C_{25} + \mu) + C_{35} + (\mu - C_{23})\right]\right\}.$$

The values of the parameters for our aircraft lead to the matrix H_{ij} and vector N_i:

$$H_{ij} = \begin{bmatrix} -0.024 & 12.385 & -19.118 & 0 \\ -0.00225 & -1.16 & 0 & 0.987 \\ 0 & 0 & 0 & 1 \\ 0.0004 & -2.928 & 0 & -0.709 \end{bmatrix},$$

$$N_i = \begin{bmatrix} 0 \\ -0.0576 \\ 0 \\ -2.796 \end{bmatrix}, \tag{31a,b}$$

in the system(27). This data was obtained from a collaborative parameter identification work between DLR and INTA. It was used as initial estimate in our parameter identification work, in a procedure which consisted of the following steps: (i) obtaining Bode diagrams, to determine the frequency ranges allowing higher accuracy in the identification of parameters; (ii) designing control schedules, whose spectra have larger amplitude in these frequency ranges, to be used a inputs for flight tests; (iii) sampling the flight test data, and using a parameter identification routine, to obtain the parameters of the mathematical model; (iv) using the mathematical model, with these parameters, to reconstruct the flight manouevers flown, and compare with flight data records, as a vallidation. The vallidated mathematical model was used to design control systems, for pitch and altitude, taking into account the full fourth-order control system, with short-period and phugoid modes, or a reduced second-order system. Since we have no space to detail all this work here, we conclude with a discussion of the two longitudinal modes, from the data given before.

§5 - Frequency and Damping of Longitudinal Modes

Since we have a linear autonomous system of ordinary differential equations with constant parameters, it is convenient to use the Laplace transform[27-29]:

$$\tilde{Z}_i(s) = \int_0^\infty Z_i(t)\ e^{-st}\ dt, \qquad (32)$$

which leads from the system of differential equations(27), to a linear algebraic system of equations:

$$Z_i(0) - s\tilde{Z}_i(s) = \sum_{j=1}^{4} H_{ij}\ \tilde{Z}_j(s) + s^{-1}N_i\delta_e. \qquad (33)$$

In the absence of control inputs or initial disturbances, the system is homogeneous:

$$\delta_e = 0 = Z_i(0): \quad \sum_{j=1}^{4} \left(H_{ij} + s\,\delta_{ij}\right)\ \tilde{Z}_j(s) = 0, \qquad (34)$$

where we have introduced the identity matrix:

$$\delta_{ij} = \begin{cases} 0 & \text{if} \quad i \neq j \\ 1 & \text{if} \quad i = j. \end{cases} \qquad (35)$$

The system (34) has non-trivial solution:

$$\left\{\tilde{Z}_i(s), \tilde{Z}_2(s), \tilde{Z}_3(s), \tilde{Z}_4(s)\right\} \neq \{0, 0, 0, 0\}, \qquad (36)$$

if and only if the determinant of coefficients vanishes:

$$0 = \mathrm{Det}\left(H_{ij} + s\,\delta_{ij}\right) = \sum_{n=0}^{4} a_n s^n, \qquad (37)$$

leading to a polynomial of the fourth-degree, ,with coefficients:

$n = 0, 1, 2, 3, 4$:

$a_n = 0.00637, 0.00527, 0.179, 0.0895, 0.0473.$ (38)

Note that -s are the eigenvalues of the matrix H_{ij} (31a), and hence the roots of (37, 38).

The polynomial (37) may be factorized:

$$0 = a_4\left(s^2 + 2\xi_{ph}s + \omega_{ph}^2\right)\left(s^2 + 2\xi_{sp}s + \omega_{sp}^2\right), \qquad (39)$$

emphasizing the damping ξ and natural frequency ω of the phugoid and short-period modes[30-32]. In the present case, the phugoid has frequency (40a) and period (40b):

$$\omega_{ph} = 0.191\,s^{-1}, \quad \tau_{ph} = 2\pi / \omega_{ph} = 32.8\,s, \qquad (40a,b)$$

and damping (41a) and decay time (41b):

$$\xi_{ph} = 0.0314, \; T_{ph} = 0.693 / \omega\xi = 116\,s, \qquad (41a,b)$$

where the latter is the time for the amplitude to decay to half the initial value. The frequency and period are one order of magnitude apart from those of the short-period mode:

$$\omega_{sp} = 1.903\,s^{-1}, \qquad \tau_{sp} = 3.30\,s, \qquad (42a,b)$$

and the damping and decay time:

$$\xi_{sp} = 0.467\,s^{-1}, \qquad T_{sp} = 0.780\ s, \qquad (43a,b)$$

show even greater contrast.

§6 - Conclusion

The present paper has described Part I of a linear, longitudinal stability study of BAFR, viz. the mathematical model. In this conclusion we mention briefly related work on parameter estimation (Part II) and control system design (Part III).

The study of parameter identification (Part II) comprised several stages: (i) the use of Bode diagrams to select the frequency range of optimum identifiability; (ii) the comparison of several excitation signals, such as the step, doublet and 3211 inputs, as regards power spectral density at various times; (iii) aspects related to data handling, like choice of sampling rate, calibration and offsets, high-frequency noise and low-frequency perturbation; (iv) the carrying out of the flight test manouvers, and use of the data record for parameter identification by the maximum likelihood[33] method; (v) the validation of the mathematical model, by reconstruction of the responses to manouevers recorded in flight.

We do not go into detail in either this or Part III concerning control system design. The latter used state space methods in several application: (i) control of the full fourth-order system using either pitch rate or pitch angle in the feedback loop; (ii) altitude control by choice of eigenvalues in the closed-loop system; (iii) comparison of the fourth-order phugoid+short period mode model with the reduced short period-only second-order system, again for pitch rate or pitch angle feedback; (iv) optimal altitude control using a quadratic merit function; (v) control using a Luneberg observer; (vi) response to simulated atmospheric turbulence represented by a Dryden spectrum. This work is not complete, since aspects such as Kalman filtering, flight path reconstruction[34] and handling qualities[35] are yet to be considered.

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Legends for the Figures

Figure 1 - Bar chart of major tasks in setting up IFTF

Figure 2 Location of sensors in BAFR (Basic Aircraft for Flight Research)

Figure 3 - Components of aircraft weight for stability analysis

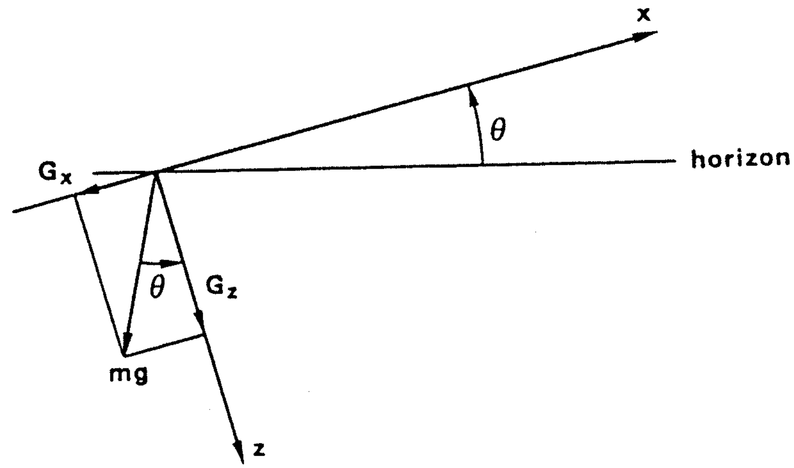

FIGURE 3

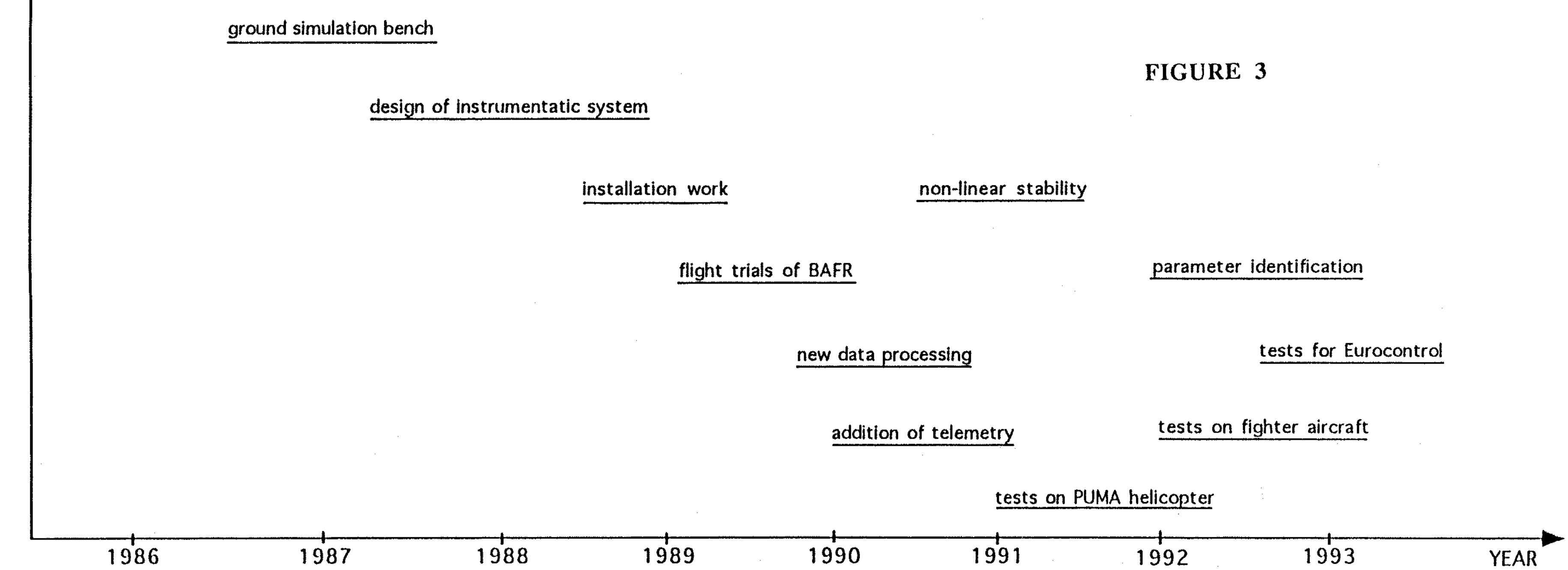

FIGURE 1

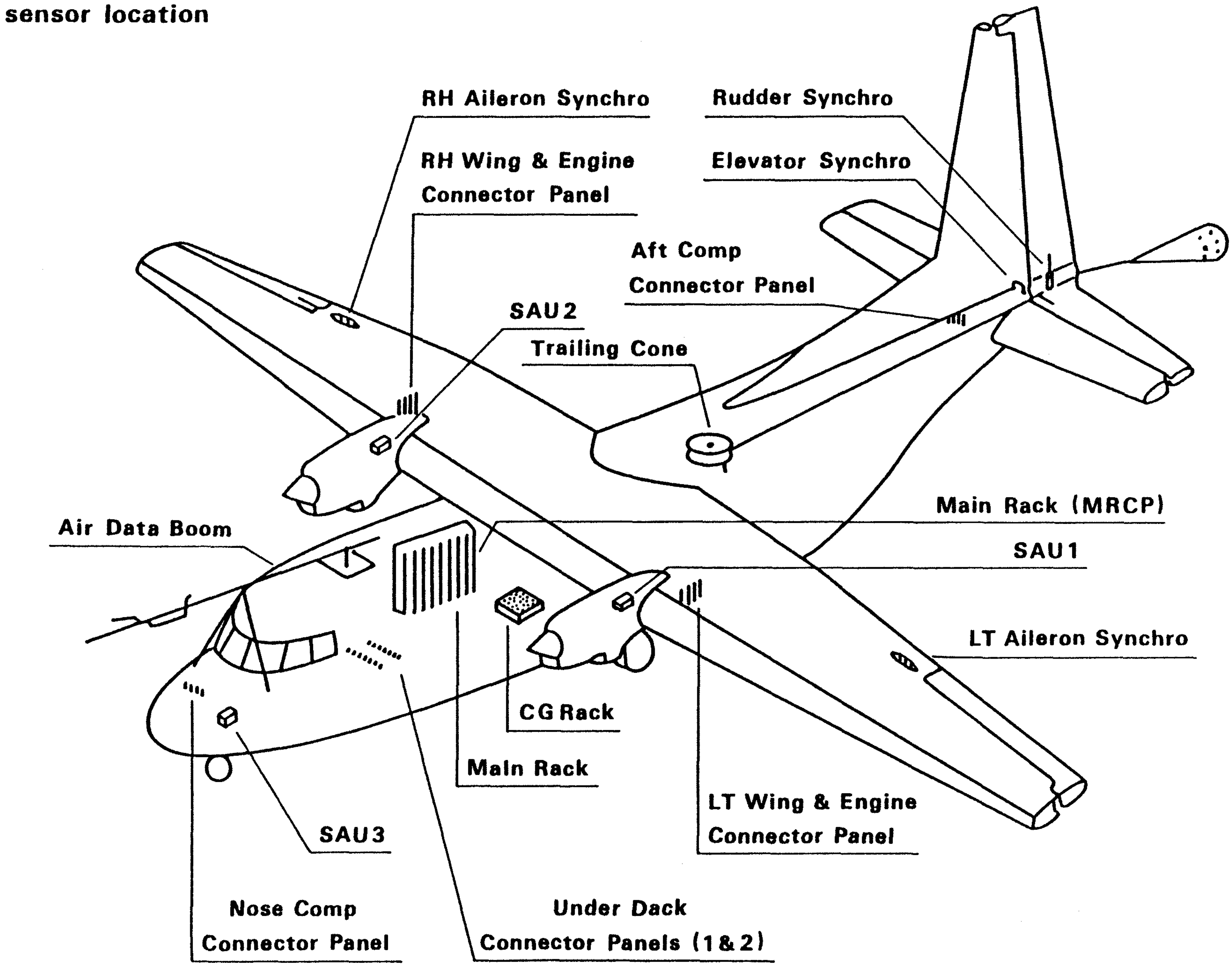
sensor location
RH Aileron Synchro
RH Wing & Engine Connector Panel
Rudder Synchro
Elevator Synchro
Aft Comp Connector Panel
SAU2
Trailing Cone
Main Rack (MRCP)
SAU1
Air Data Boom
LT Aileron Synchro
CG Rack
Main Rack
LT Wing & Engine Connector Panel
SAU3
Nose Comp Connector Panel
Under Dack Connector Panels (1&2)

FIGURE 2