NINTH EUROPEAN ROTOCRAFT FORUM

Paper No. 68

ANALYSIS AND DESIGN OF HELICOPTER DIGITAL AUTOPILOT WITH DECOUPLED LONGITUDINAL STATE VARIABLES

A. DANESI
Aerospace Department, Rome University
Rome, ITALY

September 13-16, 1983

Associazione Italiana Industrie Aerospaziali
Associazione Italiana di Aeronautica ed Astronautica

ANALYSIS AND DESIGN OF HELICOPTER DIGITAL AUTOPILOT WITH DECOUPLED LONGITUDINAL STATE VARIABLES

Achille Danesi *

The University of Rome - Aerospace Department

Rome, Italy

Abstract

The feasibility of a flight control system making the helicopter longitudinal attitude in forward flight to be changed without involving simultaneously vertical velocity component variations, is afforded in this study. The proposed F.C.S. allows the helicopter decoupled attitude to be modified, as required in tracking a specified flight path, by use of a single control, the cyclic pitch, while the collective pitch is employed to control the decoupled vertical velocity component. The F.C.S. is conceived as a digital multifeedback structure where a microprocessor, on line with the servo units, is employed to compute the decoupling and control algorithms.

The digital simulation proves that the flight tracking precision can by sensibly improved by the decoupling control strategy with a reasonable provision of pilot monitoring effort relaxation.

Nomenclature

A	state matrix
B	control matrix
C	output matrix
K	feedback decoupling matrix
K_s	scalar or matrix forward gain
K_f	feedback vector
F_o	feedback matrix
	forward decoupling matrix
d_c	cyclic displacement
d_{cc}	collective displacement
f	decoupling function
g	element of the forward decoupling matrix
k	element of the feedback matrix
p	roll rate
r	element of the extern al forcing function vector or yaw rate
$\hat{u}$	forward velocity component
u	element of the input forcing function vector
v	element of the modified input forcing function vector
w	vertical velocity component
x	state variable vector
y	output vector
β	sideslip angle
ϑ	longitudinal attitude
φ	lateral attitude

* Professor, Servosystem Aerospace Engineering

1. Introduction

The requirements to conform to precise flight profiles become a stringent necessity for both military and commercial VTOL operations; all the aircraft maneuvering capabilities supported by an adequate flight control characteristics must be considered to achieve the required mission objectives involving often precise tracking of three dimensional trajectories including rapid and frequent profile changes. One of the more representitive case at this regard is the VTOL operations in Microwave landing (M.L.S.) procedures where spatial curvilinear trajectory has to be followed to comply with the Air Traffic Regulations (A.T.R.) Category 3 (Zero visibility) takeoffs and landings. In such operations any difference between the desidered and actual spatial coordinates must be corrected to bring, within small acceptable errors under all possible operating conditions, the actual trajectory into coincidence with the desidered one. The achievement of satisfactory control characteristic will require a flight control system capable of a direct and effective flight path control not involving, in manual or assisted pilot actions, excessive demand upon human pilot capability.

In forward flight the guidance errors are appearing as an heading error in the horizontal plane and an attitude error in vertical plane. These errors can be controlled regulating the intensity and direction of the aircraft velocity vector. The flight path corrections in the vertical plane can be carried out performing changes in the aircraft orientation about its pitch axis which produce changes of the orientation in respect to the flight path.

The resulting incremental change in aerodynamic lift force, acting in the aircraft plane of simmetry and directed normal to the flight path, will cause an acceleration normal to the velocity vector and an angular velocity which continues until the force equilibrium in the vertical plane is reached. Finally as a result of changing of the aircraft attitude, an altitude rate and altitude variation, are obtained. In this study, apart from the collective-power coordination to compensate changes in aerodynamic drag, no change in power or in powerplant performances are supposed to change on the hypothesis of relatively small altitude variations.

In a flight control system providing essentially an attitude control, a step input command proportional to the desidered attitude change yields, in stationary conditions, a constant pitch attitude proportional to step forcing function and a proportional change in the lift force component with a resulting linear velocity variation. Four helicopter state variables (u, w, q, ϑ) are essentially involved in guidance error corrections in the vertical plane and analogous considerations show that other four state variables (β, p, r, φ) must be considered in controlling, in coordinated maneuvers, the heading angle as required to carry out the guidance error corrections in the horizontal plane. In conclusion, four degree of freedom, two angular attitudes and two linear velocity components must be measured and controlled by a flight control system in order to perform a precise trajectory tracking. In order to reduce the pilot fatigue and improving his flight path monitoring in attaining the required precision in manual or assisted tracking task, various flight control system configurations have been proposed in the past, all tending to assist the pilot workload with a centralized or decentralized stability augmentation systems for the helicopter fundamental modes, leaving to the pilot the required authorithy in controlling the guidance errors in respect to the desidered trajectory.

To reduce the pilot burdening and improve the flight path tracking precision, a new control strategy is proposed in the present study; this is based on the availability, as a part of a digital flight control system, of a real time, high speed microprocessor as a computing unit; this is employed to solve, from the data measured by conventional gyroscopic and inertial autopilot sensors, a numerical algorithm decoupling some of the state variables directly involved in fligh path control. Furthermore employing the microprocessor output data, the necessary informations to implement a direct flight path control become available to be used as well for a flight path visualization in the cockpit. The conventional longitudinal flight control system configuration is maintained as the basic structure for the proposed F.C.S., made powerfull by the added on line computer capabilities which allow to improve the flight path tracking precision and the pilot monitoring proficiency, still maintaining its authorithy in the control loop.

In Section 2 the essential concepts on the proposed control strategy are described. In Section 3 a summary on the state variables decoupling theory is summarized. The results of the theory are applied to a conventional transport helicopter and the computed design data for the proposed flight control system are shown in Section 4. The digital implementation and simulation results are treated in the following sections.

2. The state variable decoupled control strategy

The state variable vector:

$$\underline{x} = \left[u,\ w,\ q,\ \vartheta\right] \qquad (1)$$

describes the longitudinal behaviour of a rotary wing aircraft modelled by a first order, constant coefficients system state equation:

$$\dot{\underline{x}}\ (t) = A\ \underline{x}\ (t) + B\ \hat{\underline{u}}\ (t) \qquad (2)$$

where the elements of the state matrix A and control matrix B are expressed in terms of the kinematic, inertial and aerodynamic quantities characterizing the helicopter considered in the study. The longitudinal cyclic (d_c) and the collective pitch (d_{cc}) control commands are the elements of the control vector $\hat{\underline{u}}$:

$$\hat{\underline{u}} = \left[d_c\ ,\ d_{cc}\right] \qquad (3)$$

To change the helicopter orientation in respect to the flight path, as required in tracking the desiderided trajectory in the vertical plane, an automatic attitude control system (A.C.S.) is commonly employed to provide, in stationary conditions, attitude changes proportional to the amount of the applied control command. The primary state variable selected by the equation:

$$y(t) = C\ \underline{x}\ (t) = \left[0\ 0\ 0\ 0\ I\right]\ \underline{x}\ (t) = \quad \vartheta(t) \qquad (4)$$

is controlled by the A.C.S. applying a proportional plus derivative control law to the cyclic pitch channel:

$$\dot{u}(t) = d_c\ (t) = K_s\ \left[r(t) - K_f^T\ \underline{x}\ (t)\right] \qquad (5)$$

where K_s and K_f are respectively the A.C.S. forward gain and the feedback gain vector regulated to obtain a satysfactory attitude transient response.

As shown by the equation (2), the application of any one of the two controls will develop an helicopter dynamical behaviour where all the state variable (1) are involved; specifically a commanded change in helicopter attitude will result in not directly controlled changes in vertical velocity component which require corrective actions employing the collective pitch control. To reduce the complexity of the simultaneous control of the various helicopter degrees of freedom both in manual and automatic flight operations, a decoupling process applied to the fundamental state variables involved in the flight path control, is proposed in this study; this process consists in the solution of a decoupling algorithm, discussed in the next section, using a real time, high speed microprocessor at the input bus of which have direct memory access the data informations of all helicopter state variables measured by the gyroscopic and inertial sensors, commonly employed in advanced helicopter flight control unit. In order to assign to the cyclic and collective pitch channels the independent functions in controlling respectively the helicopter attitude (ϑ) and the vertical velocity component (w), a decoupling process transforming the original system (2) in two decoupled subsystems:

$$S_{11} = (d_c, \vartheta) \qquad (6)$$
$$S_{12} = (d_{cc}, w\ )$$

is required. The decoupling process is obtained solving the algorithm having the general expression:

$$f\ (t) = K\ \underline{x}\ (t) + G\ \underline{v}\ (t) \qquad (7)$$

where K and G are the state and control decoupling matrices defined by the theory; all the measurable state variables included in the state vector $\underline{x}$ (t) defined in (1) are involved as input data informations needed in the algorithm computational routine while the modified input vector $\underline{v}$ (t) is the external forcing function vector applied to the decoupled system. Assimilating the decoupling function f (t) to a control law applied to the original system (2), this will be transformed in the constituent decoupled subsystem (6) the dynamic of which, when evaluated in the frequency domain, are represented by a number of integrator poles at the complex plane origin. Since the state (K) and control (G) decoupling matrices in (7) are respectively the feedback and forward matrices for the decoupling process developed in closed loop fashion around the controlled system (2), each of the decoupled subsystems can be modeled as a closed loop system in the form:

$$\underline{x}\ (t) = A_d\ \underline{x}\ (t) + B_d\ v\ (t) \qquad (8)$$

where the state (A_d) and the control (B_d) matrices are the closed loop matrices derived in the next section; the external control function applied to each of the decoupled subsystems is indicated as the scalar v (t). The output equations:

$$y_1\ (t) = C_1\ \underline{x}\ (t) = \begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix}\ \underline{x}\ (t) = \vartheta\ (t)$$

$$y_2\ (t) = C_2\ \underline{x}\ (t) = \begin{bmatrix} 0 & 1 & 0 & 0 \end{bmatrix}\ \underline{x}\ (t) = w\ (t) \tag{9}$$

will select the decoupled state variables at the subsystems output. The transient behaviour of the decoupled helicopter attitude and vertical velocity component must be regulated, for satisfactory responses, by a proper choose of the forward and feedback gains in the feedback loop enclosing the decoupled subsystems (6). The regulating control law:

$$v(t) = K_s \left[r\ (t) - K_f\ \underline{x}\ (t) \right] \tag{10}$$

is applied to each decoupled subsystem, resulting in the decoupled and regulated closed loop subsystems described by the state equation:

$$\underline{x}\ (t) = A_{dr}\ \underline{x}\ (t) + B_{dr}\ r\ (t) \tag{11}$$

The equations (11) and (9) are modeling the helicopter states decoupled flight control system.

Since the output variables (9) are directly correlated to the flight path angle in the longitudinal plane, a direct flight path control can be obtained, as indicated in the bock representation in Fig.1. Comparing the attitude and vertical velocity component actual values to the correspondent reference datum, i.e. fixing the external forcing function r (t) in Eq. (11) to the values

$$r_1\ (t) = \vartheta_{ref}\ (t) \qquad r_2\ (t) = w_{ref}\ (t) \tag{12}$$

These reference data, applied by the trajectory computer or, in manual operations, by the pilot, to the channel input summers, may be time variant, as will be the case of the M.L.S. curvilinear trajectory tracking. The proposed flight control system configuration is structurally suited for both automatic and assisted manual actuactions with various authority levels of the pilot in the loop. In the next section the basic theory for the formulation of the decoupling algorithm is summarized.

3. The state variable decoupling algorithm

The theory on the state variabled decoupled systems (Ref.I) has been applied to decouple the helicopter longitudinal attitude and vertical velocity component following the procedure indicated in the preceding section. A generalized computer program has been prepared to design a flight control system with decoupled state variables and the basic theoretical equations involved in it are summarized in the following.

The first step in decoupling the two subsystems (6) is to define the subsystems order:

$$p_i = d_i + 1 \tag{13}$$

where d_i is the decoupling index:

$$d_i = \underset{j}{\mathrm{Min}}\ (j:\ C_i\ A^j\ B); \quad i=1,2; \ j = 0,1,2,3 \tag{14}$$

The decoupling process applied to the system (1) will be based on the control law:

$$f(t) = K\ \underline{x}\ (t) + G\ \underline{v}\ (t) \tag{15}$$

where $\underline{v}(t)$ is an imput vector applied externaly to the decoupled system. The (2x2) input matrix G and the (2x4) feedback matrix K are defined in the following form:

$$G = \bar{B}^{-I} \qquad\qquad K = -\ \bar{B}\ A^{-} \tag{16}$$

$$\bar{B} = \left[C_I\ A^{d_I}\ B \quad \vdots \quad C_2\ A^{d_I}\ B \quad ^T \right]$$

$$\bar{A} = \left[C_I\ A^{d_I + I} \quad \vdots \quad C_2\ A^{d_2 + I} \quad ^T \right]$$

The control law (15) solves the decoupling problem if and only if the matrix $\bar{B}$ is not singular. In Fig.2 is given the feedback structure of the control system allowing the two state variable ϑ and w to be regulated indipendently respectively by the cyclic and collective pitch controls. The closed loop representation of the decouples subsystems, in the form ready given in (8), is defined by the state and control matrices:

$$A_d = A + B\ K \qquad\qquad B_d = B\ G \tag{17}$$

The integrator poles of the decoupled system must be now located to the desidered positions in the complex plane satysfying the transient response characteristics proposed in the design. This objective has been achieved in two steps; in the first one the system (6), by means of the linear transformation:

$$\underline{z}\ (t) = T\ \underline{x}\ (t) \tag{18}$$

is transformed in a system having the following state matrix:

$$A_t = \mathrm{diag}\left[(A_{11},\ A_{22})\ \vdots\ A_r^{\ T}\right] \tag{19}$$

where the submatrices A_{11} and A_{22}, in fase variable forms, are respectively, the state matrices of the subsystems S_{11} and S_{12} and A_r is an additional row resulting from the definition of the transformation matrix T having the same dimension of the state matrix A_d in Eq.(8):

$$T = \left[T_1 \vdots T_2 \vdots T_r\right]^T\ ;\ T_1 = C_1\ ;\ T_2 = \left[C_2\ \ \vdots\ \ C_2\ A\right]$$

The row T_r, not influencing the subsystem dynamic, is chosen to be linearly independent from the other rows avoiding as well the matrix singularity; a subroutine in the computer program will generate the transformation matrix T with such additional row. The structure of the transformed system becomes:

$$\dot{\underline{z}}\ (t) = A_t\ \underline{z}\ (t) + B_t\ \underline{v}\ (t) \tag{20}$$

$$\underline{y}\ (t) = C\ \underline{z}\ (t)$$

The feedback process applied to the transformed system (20) make easy task to program the integrator poles shift into the desidered locations in the complex plane. As result of this computational treatment which include the inverse transformation in the original coordinate $\underline{x}$, the control law for the decoupled system satysfying the desidered transient behaviour will be expressed by the equation:

$$\underline{v}(t) = K_s\left[\underline{r}(t)\ + F_o\ \underline{x}\ (t)\right] \tag{21}$$

where the (2x2) gain matrix K_s and the feedback matrix F_o are computed along with the poles positioning numerical process.

From the preceding equations it is apparent that the mathematical process yielding the regulation of the decoupled system modifies, as indicated in Fig.3, the gain and feedback matrices in Eq. (16) as follows:

$$G' = \left[g'\right] = K_s\ G \qquad\qquad K' = \left[k'\right] = K + G\ F_o \tag{22}$$

In terms of the new matrices G' and K' the control law for the decoupled and regulated system can be written as follows:

$$\underline{v}\ (t) = \left[v_1,\ v_2\right] = G'\ \underline{r}\ (t) + K'\ \underline{x}\ (t) \tag{23}$$

which allows to keep the same block representation given in Fig.2. Equation (22) can be developed in the following numerical scalar form:

$$v_1\ (t) = \sum_{j=1}^{4} k'_{1,j}\ \ x_j\ (t) + \sum_{i=1}^{2} g'_{1,i}\ \ r_i\ (t)$$

$$v_2(t) = \sum_{j=1}^{4}\ k'_{2,j}\ \ x_j(t) + \sum_{i=1}^{2}\ g'_{2,i}\ r_i\ (t) \tag{24}$$

Equation (24) indicated the requested control laws can be implemented as a sum of the partial products including the constant gains appearing as elements of the computed matrices G' and K', the external forcing functions and the whole set of the feedback state variables. As shown in Fig.3, a microprocessor is expected to generate the control function (24) processing the feedback and reference set point data. The numerical values of the constant coefficient g' and k' are stored in the microprocessor memories.

4. Basic Helicopter dynamics

For realistic evaluation of the dynamic characteristics obtainable with the proposed flight control system, a conventional tranport helicopter of the class of the Sikorsky S.55 has been considered in the following demonstrative numerical application. The chosen reference flight conditions are specified in a forward flight at sea level with an airpeed of 21.88 m/sec in a sub-horizontal flight path. On the basis of the available or predicted arodynamic derivatives, the state and the control matrices in the linear, constant coefficients state equation (1) are assumed as follows:

$$A = \begin{bmatrix} -0.0438 & 0.00513 & 30 & -9.8 \\ -0.0638 & -0.80 & 21.88 & 0 \\ 0.214 & -0.056 & -0.984 & 0 \\ 0 & 0 & I & 0 \end{bmatrix} \qquad B = \begin{bmatrix} 9.7536 & -0.9266 \\ 17.25 & -88.69 \\ -7.35 & 0.902 \\ 0 & 0 \end{bmatrix}$$

The characteristic polynomial is:

$D(s) = \left| s\, I - A \right| = s^4 + 1.8278\, s^3 + 0.988195\, s^2 + 0.24786\, s + 0.17.113$
showing a stable overdamped oscillatory motion and light instable oscillation developed in a longer time period.

5. The decoupled subsystems

The resulting decoupled system consists of two subsystems, a second order subsystem S_{11} and a first order subsystem S_{12}, defined in (6). The forward and feeback gains, *involved in the decoupling algorithm* expressed, neglecting the contribution of the regulating process, by the Eq. (24), are given in Table I, The prefilter and feedback controller structure are shown in Fig. 5.

TABLE I - Subsystems gains:

Helicopter Sikorsky S. 55
IAS = 21.88 m/sec.- S.L.

Gain	Variable	Sensor	Subsystem S_{11}	Subsystem S_{12}
g_{11}	d_c	Trx.	-0.139381	-
g_{12}	d_{cc}	"	$-1.4145\ 10^{-3}$	-
g_{21}	d_c	"	-	-0.02711
g_{22}	d_{cc}	"	-	-0.011551
k_{11}	u	I.V.M.S.	$2.89283\ 10^{-3}$	-
k_{12}	w	"	$-1.9145\ 10^{-3}$	-
k_{13}	q	R.G.	-0.106135	-
k_{14}	ϑ	V.G.	0	-
k_{21}	u	I.V.M.S.	-	$-1.568\ 10^{-4}$
k_{22}	w	"	-	$-9.39256\ 10^{-3}$
k_{24}	q	R.G.	-	0.22606
k_{34}	ϑ	V.G.	-	0

Trx = Trasm.; I.V.M.S. = Inertial Syst.; R.G. = rate gyro; V.G. = vert.gyro

The roots of the characteristic equation of the decoupled system expressed by the Eq. (8) are a real pole and a pair of complex conjugate poles which are located pratically at the origin of the complex plane, representing the dynamical behaviour of the subsystems S_{11} and S_{12} and a real pole relative to the residual dynamic effects inherent to the decoupling process which has been neglected in the present analysis.

6. Cyclic and collective channel regulation

The variable gains in Eq. (10) applied to the two decoupled subsystems, referred respectively as cyclic and collective channels, are regulated to obtain a satisfactory attitude and vertical velocity component time response to a step input forcing function. The attitude response was modelled essentially as a second order system response with a pair of complex conjugate poles yielding an underdamped oscillatory motion with a fairly fast initial raising and a small overshoot; the vertical velocity component time behaviour was established as a aperiodic mode with a dominant time constant proper to the desidered long term response. The main model time response characteristics for the two channels are indicated in Table 2.

TABLE 2 - Model step responses

Resp. Parameter	Dim.	cyclic channel	Collect.channel
Relative damp.	N.D.	0,48	-
Undamp.Freq.	rad/sec	2	-
Time constant	sec.	1,11	2.5
Time resolution	sec.	2.5	4.54
Rise time (63%)	sec.	1.0	0.9
Overshoot	%	15	-
Bandwidth	rad/sec.	6	-

In Table 3 are shown the values of the final gains defined in Eq. (22) providing a compact flight control system representation where the processes to decouple the helicopter attitude and vertical velocity component controls and regulate, as desidered, their transient behaviour, are combined.

TABLE 3 - Final channel gains

Gain	Variable	Gain value
g'_{11}	d_c	-0.558091
g'_{12}	d_{cc}	-0.14009
g'_{21}	d_c	-0.113058
g'_{22}	d_{cc}	-0.032889
k'_{11}	u	-0.695289
k'_{12}	w	-0.14005
k'_{13}	q	-0.25448
k'_{14}	ϑ	-0.55809
k'_{21}	u	-0.1461
k'_{22}	w	-0.04227
k'_{23}	q	-0.17289
k'_{24}	ϑ	-0.113058

7. Flight control system implementation

The flight control system block representation is depicted in Fig.6 where it is evident its resemblance to the conventional autopilot configuration; the only remarkable difference that may be observed is the presence of a digital processor as an on line controller which may be employed as a conventional compensator to solve the common control laws, as the proportional - derivative - integral algorithm required for the attitude control.

The processor taken into consideration in this application is an 8 bit word, 8K - PROM and 2K - RAM microprocessor with a 2 MHz internal clock; this microprocessor is capable to handle data from each buffered input at a sample rate of 4K-bits per second through a direct access channels and to execute an ADD/SUBSTRACT cycle in a time 15 μ sec. and a multiply time of 190 μ sec. A real time, high speed microprocessor of the new generation is expected to be employed for the specific case treated in that the drastic reduction in multiply time, predicted value 70-40 . μ sec and the increase in word lenght, allow to carry out the control process in considerably lower time and greater numerical resolution. The microprocessor considered in laboratory applications proves, however, to have, in this research feasibility stage, acceptable characteristic for satisfactory results.

The autopilot sensor output, together with the reference set point voltages are applied to a parallel-in-serial-out (8x1) analog multiplexer (MPX). Each of the MPX inputs are enabled to be traslated to the 8-bits analog-to-digital converter (ADC) under the adressing assignement given by a 3-bits preset counter. The data transfer from the MPX to the ADC and from the converter to the microprocessor data bus is carried out interely under the control of the software implemented as a part of the microprocessor interrupt program. Since the uncertainty in the control laws generation dependes predominantly on the uncertainty in the control gains assignement, particular attention was paid in choosing the lenght of the word representing a coefficient in the control algorithm. The criterion adopted at this regard was referred essentially to the maximum allowable percentage error (1%) in locating the integrator poles in the complex plane, as requested in the decoupling and regulating processes; this error was correlated to the minimum number of bits in the numerical representation of the closed loop control gains. For the case treated the minimum word lenght for the requested accuracy was evaluated in 13 bits. The coefficients in control algorithm are entered in the 8-bits microprocessor in two set of 8 bits each, representing respectively the most and the least significant bits. Since the measured state variables have a direct memory access in the microprocessor as an 8-bits data, the software implementing the control algorithms yields product of 16-bits multiplicand, transferred temporarely in couples of 8 bits registers, by an 8-bits multimplicator; the 8-bits partial products are entered into an accumulator as the multiplicator bits are shifted out. By means of an appropiate use of the memory stack, the sum of the partial products are made available in sequence in the accumulator at the end of the multiplication. The final result is traslated to the output port from the accumulator under the program control. The control algorithms required for each of the two subsystems constituent one channel, 6 multiplications and 6 additions. To perform the arithmetic and miscellaneous operations which include the interrupt and I/O sequences, a total time of 10 msec. is required.

The sampling time for the digital processing was chosen at the value of 0,02 sec.

The control signals governing the decoupled channels are traslated from the latch register at the microprocessor output to the 8 bits-10 volts full scale voltage digital-to-analog converter (DAC); the conversion is performed at the rate of its internal clock (10 MHz) with a resolution compatible with the maximum admissible error in rotor blades pitch angular positioning and well within the precision capability of the overall digital system precision.

The autopilot servosystem consists of hydraulic actuators with servovalves regulated by means of variable reluctance stepping motors. The pulse train to the stator windings, is generated by an electronic controller which essentially a rate multiplier unit working on piece-wise constant analog voltages in the range from 10 to 38 mvolts and generating, at its output, pulse trains at a recurrence frequency varying between 100-1000 pulse per second; these pulse trains are properly sequenced, through the control logic unit, to the motor stator windings forcing the stepping motor in the slew range varying from 0,87 to 8.7 rad/sec.

8. Sistem simulation

The purpose of the system simulation was essentially devoted to test the process performed by the microprocessor employed in laboratory applications and programmed in its assembler linguage to solve the algorithms proposed to decouple and regulate the system state variables. The overall digital system was simulated in a UNIVAC 1100 computer employing a microassembler program allowing the control algorithms to be entered, for the part regarding the microprocessor simulation including all I/O operations, in assembler linguage while the Fortran programming was used for the discrete and continous part of the system.

The system simulation results are discussed in the next section.

9. Discussion of the simulation results

The forced time response to a longitudinal cyclic pitch step command of the helicopter with automatic F.C.S. disconnected is given un Fig.7; in Fig.8 the same case for a collective pitch step command is presented. In Fig.9 is shown the dynamical behaviour of the helicopter automatically controlled by the proposed flight control system with gains regulated as indicated in Table 3 in response to a step change in a signal (u_1) applied to the cyclic pitch channel with no command at the collective pitch channel input (u_2=0). A similar simulation was carried out for the case of a step actuaction of the collective pitch channel with zero command to the cyclic channel and the correspondent time response is given in Fig.10.

From these result is clearly apparent the satisfactory effects of the decoupling process and the acceptable approximation achieved in the reproduction of the desidered helicopter dynamical behaviour. In Fig.11 the capability of the helicopter under the automatic state variable decoupled F.C.S. to follow a general curvilinear trajectory, as requested in performing M.L.S. guided landing approach, is shown.

10. Conclusions and areas of future researches

The present study indicates the feasibility of an helicopter flight control system capable to decouple and regulate the longitudinal cyclic and collective pitch channels. The advantages achievable with the proposed flight control system are the improvement in flight path tracking precision and the reduction of pilot workload in assisted manual operations particularly in missions with established rigid flight path involving frequent and rapid profile changes.

Further author work in this research area are in preparation; the subjects treated are the provision of a multi-axes decoupling process with unconventional manual controllers allowing the pilot to perform longitudinal and lateral flight path corrections by regulating singularly the primary state variables and the collection of all data made available at the microprocessor output to implement a flight path visualization in the cockpit integrated with the data flow involved in the automatic control processes.

References

Falb, P.L. "Decoupling in the design and synthesis of multivariable control systems" - IEEE Transactions in Automatic Control - Vol. AC.12, pag.651-659. December 1967

Danesi, A. "Aerospace vehicle digital optimal control" - Paper n.206 Aerospace Research Center - Rome University, July 1981.

Aknowledgement

The author woull like to express his thanks to the M.S. Electronic Engineer Arturo Danesi who assisted in computer programming and collaborated in system electronic design.

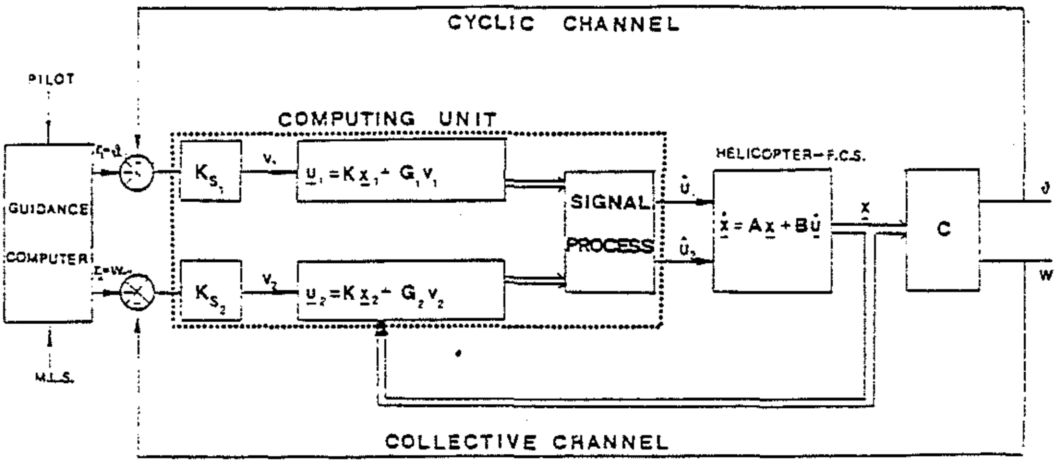


FIG.1 HELICOPTER TRAJECTORY CONTROL

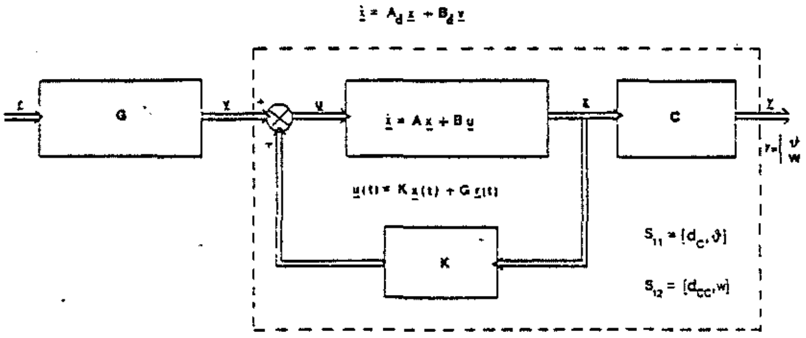


Fig. 2 - DECOUPLING PROCESS

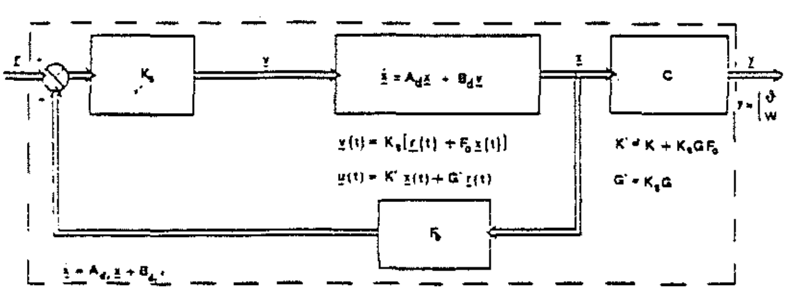


FIG.3 REGULATING PROCESS FOR THE DECOUPLED SYSTEM

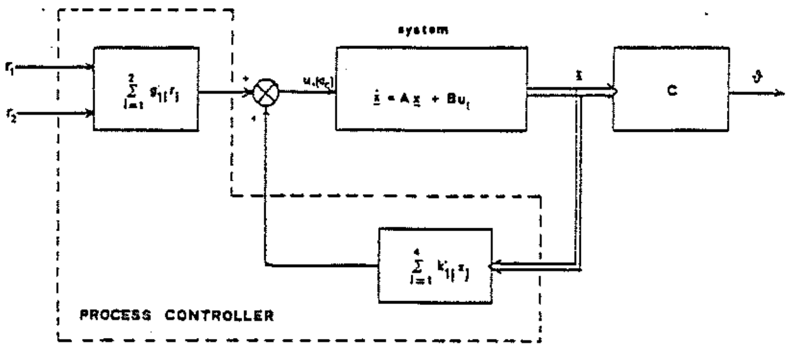


Fig. 4 - SYMBOLIC REPRESENTATION OF CONTROL PROCESS FOR THE SUBSYSTEM (d_c, ϑ)

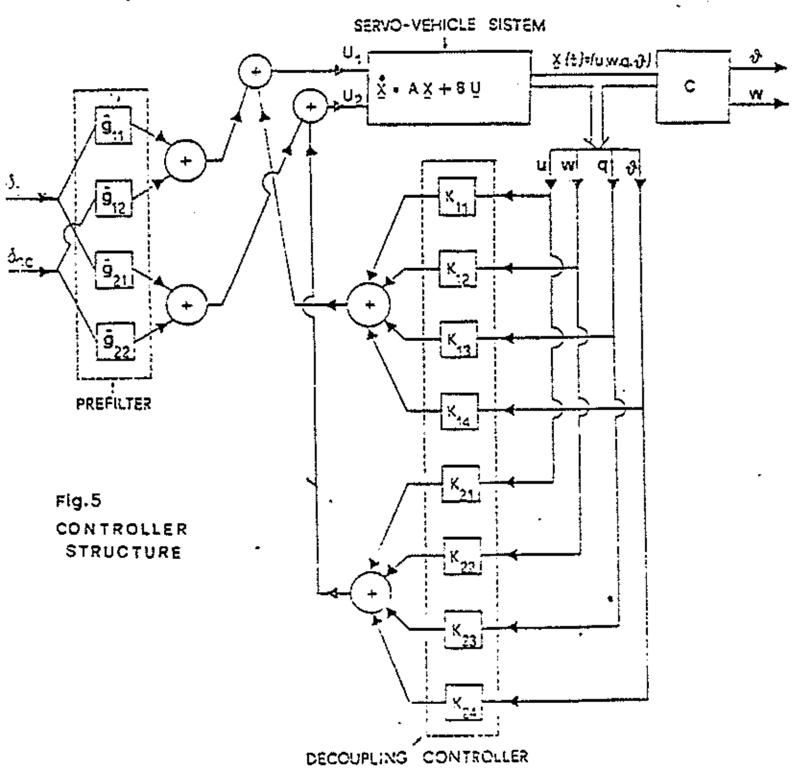


Fig.5
CONTROLLER STRUCTURE

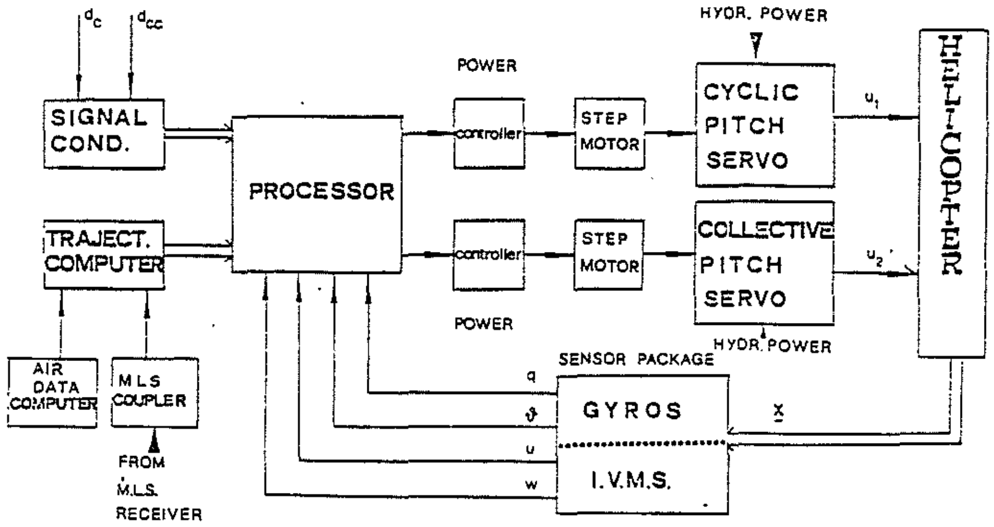


FIG.6a FLIGHT CONTROL SYSTEM IMPLEMENTATION

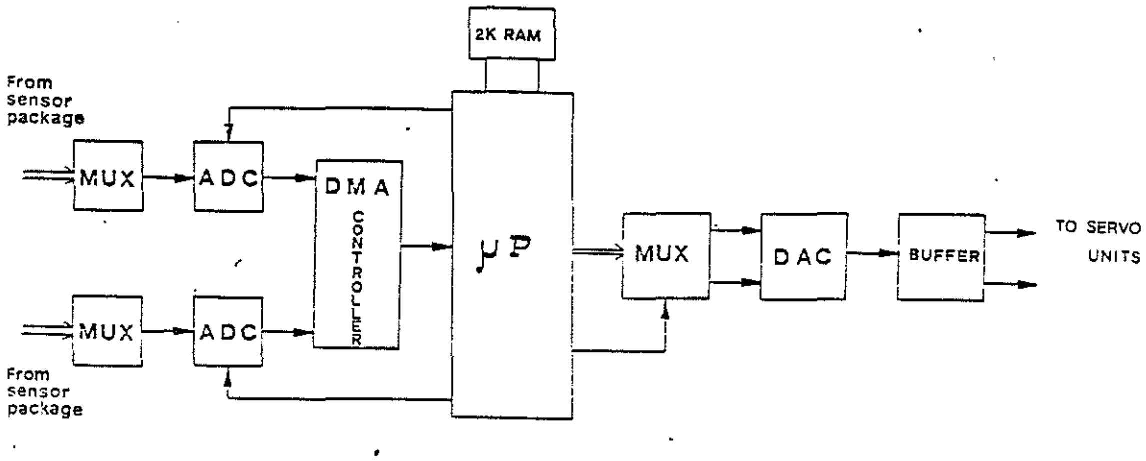


FIG.6b PROCESSOR INTERFACES

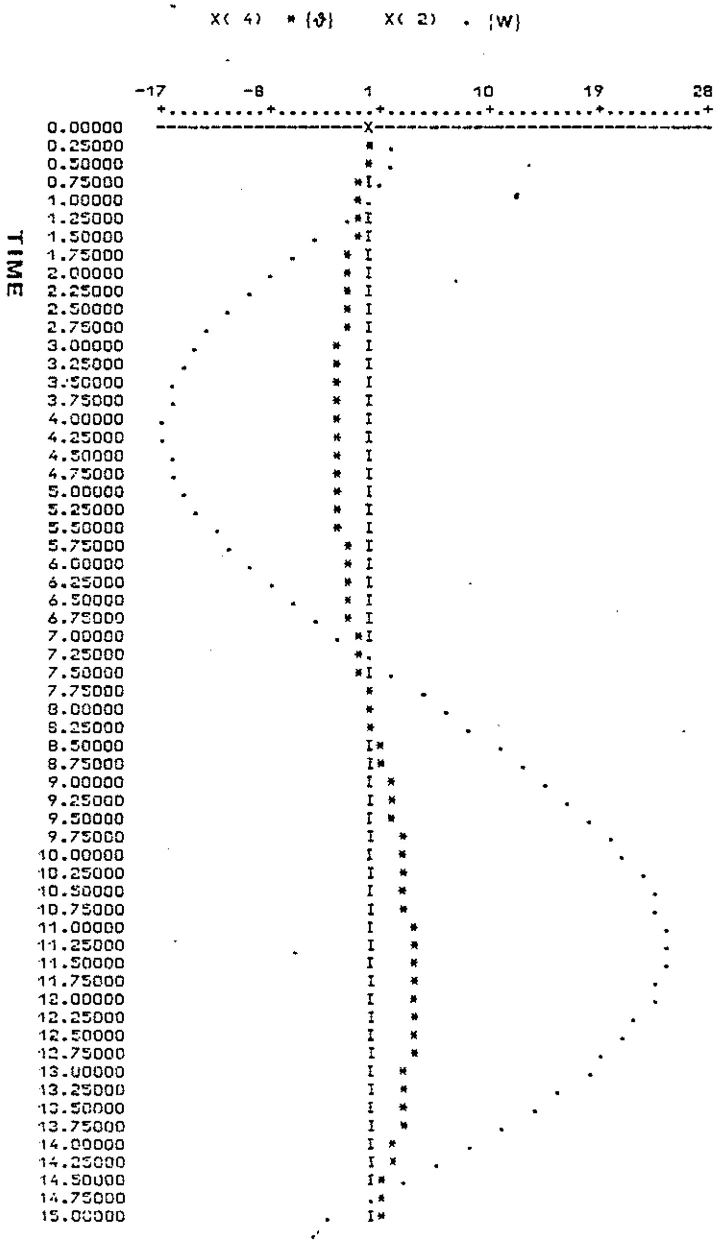


FIG.7 FORCED HELICOPTER RESP.s
NO AUTOMATIC FCS
STEP CYCLIC COMMAND

FIG. 8 FORCED HELICOPTER RESP. s
NO AUTOMATIC FCS
COLLECTIVE STEP COMMAND

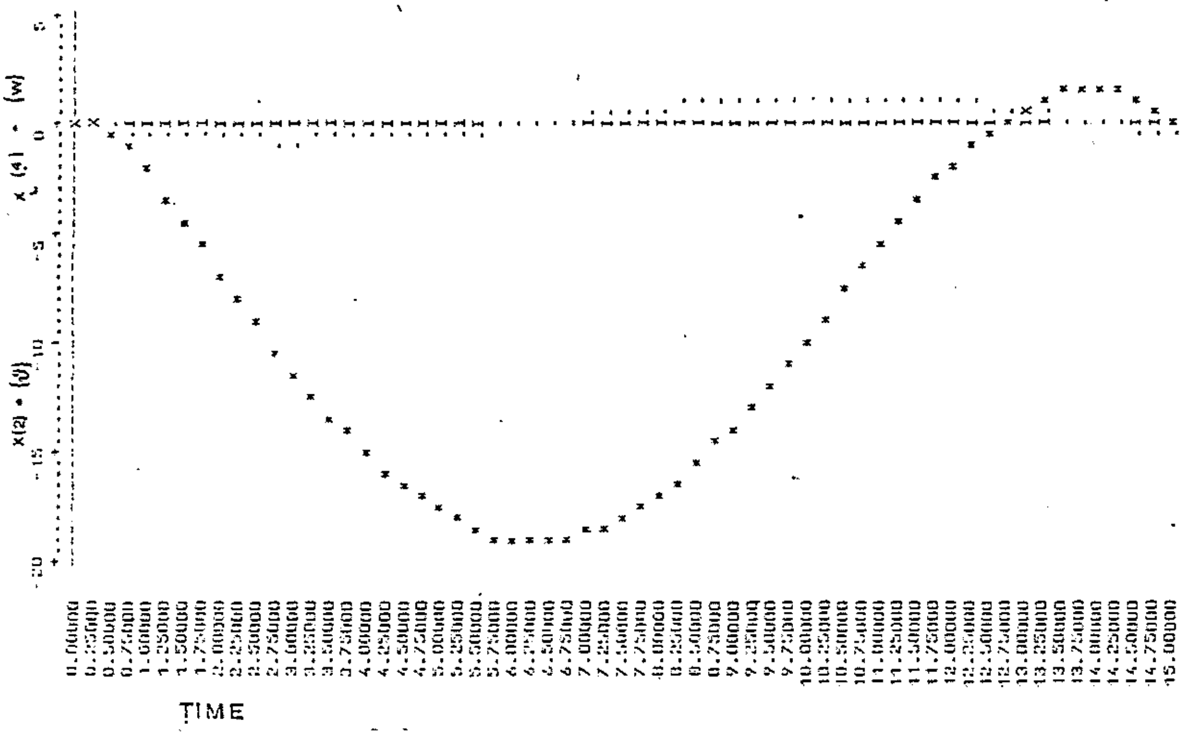


FIG. 9 FINAL AUTO-CYCLIC
STEP RESP. s

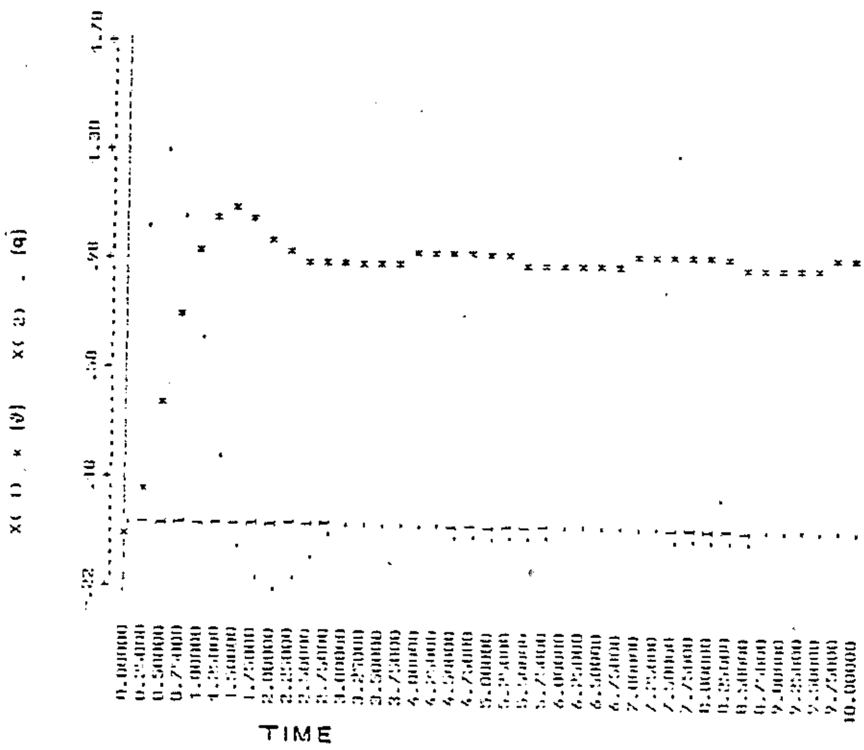
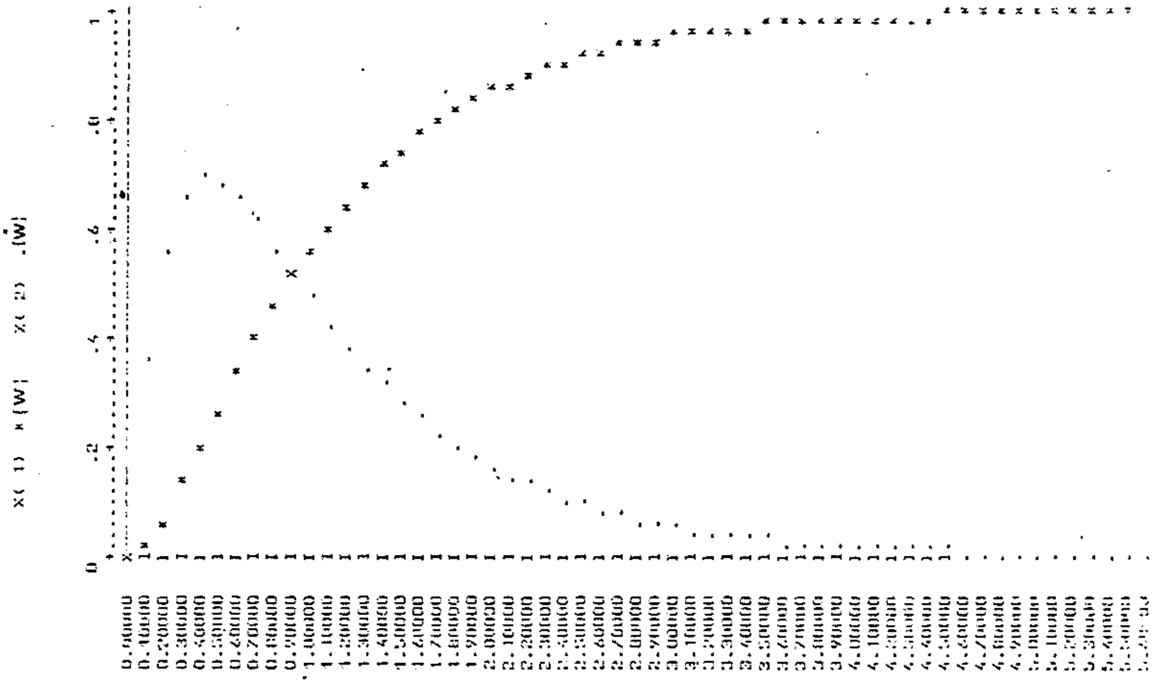


FIG. 10 FINAL AUTO-COLLECTIVE STEP RESP.s



TIME

FIG 11