



EH101 - AUTOMATIC FLIGHT CONTROL SYSTEM :
AUTOPILOT CABLE HOVER MODE COMPUTER AIDED
DESIGN AND ASSESSMENT

BY

G.P. BENEDETTI
AGUSTA SISTEMI
Via Isonzo 33
21049 TRADATE (VA)
ITALY

FIFTEENTH EUROPEAN ROTORCRAFT FORUM

SEPTEMBER 12 - 15, 1989 AMSTERDAM

THIS PAGE IS INTENTIONALLY LEFT BLANCK

**EH101 - AUTOMATIC FLIGHT CONTROL SYSTEM:
AUTOPILOT CABLE HOVER MODE COMPUTER AIDED
DESIGN AND ASSESSMENT**

Author: Gian Pietro BENEDETTI
AGUSTA SISTEMI (AGUSTA S.p.A)
Via Isonzo,33 21049 Tradate (VA) - Italy

ABSTRACT

This work describes the activities performed to design the Cable Hover autopilot mode of the EH-101 helicopter Automatic Flight Control System (AFCS) {E.H. Industries is a joint company of Agusta (I) and Westland (UK)}. The AFCS is a digital, dual redundant stability augmentation and autopilot system using multiple microprocessors in all axes; the AFCS implements many autopilot modes.

Cable Hover is provided on the Marina Militare Italiana (MMI - Italian Navy) aircraft variant. Cable mode provides control of the cable angle of a submersible sonar to data set by the pilot. Two models (running on a VAX 8550 computer) were developed to simulate the Aircraft (helicopter + AFCS) Winch Cable Sonar System (AWCSS); all physical data are input parameters to the program. Once designed, the cable hover control law was linked to the AWCSS model. The model was tested through the simulation programme and a Flight Dynamic Simulator.

1. INTRODUCTION

Computer aided design technique has been successfully used to design the Automatic Flight Control System (AFCS) mounted on the E.H. Industries Ltd. (E.H.I.) EH101 helicopter: an easily handled helicopter for long duration missions. E.H. Industries Ltd. is a joint company of Agusta of Italy and Westland of the U.K..

The AFCS is a full digital, multiprocessor, dual redundant equipment enabling a pilot passive mode of operation in the following roles: anti-submarine and anti-ship warfare for the Royal Navy (RN) and the Marina Militare Italiana (MMI - Italian Navy), commercial transport and utility.

The AFCS facilities are:

- AUTOMATIC STABILIZATION EQUIPMENT (ASE) FUNCTIONS:
 - stabilization in PITCH, ROLL and YAW axes; provision has been made to incorporate any stabilization in the COLLECTIVE axis
 - Attitude and Heading Hold
 - Turn Coordination
 - Autotrim
- AUTOPILOT (AP):
 - Barometric Altitude Hold
 - Radio Altitude Hold
 - Airspeed Hold
 - Heading Acquire
 - Vertical Speed Acquire
 - Navigation
 - Transition Up
 - Transition Down
 - Hover Hold
 - Hover Trim
 - Cable Hover
 - Approach
 - Back Course
 - Go Around
- SYSTEM INTEGRITY:
- FLIGHT DIRECTOR:
 - Commands are provided to drive flight director cues for engaged autopilot modes.
- SUPPORT FUNCTIONS:

- ASE first failure
 - ASE second failure
 - AP first failure
 - Autotrim first failure
 - Subsequent failure
 - Combined failure
 - BUILT IN TEST (BIT):
 - Requested BIT: Pre Flight Maintenance
 - Automatic BIT: Continuous: Scheduled Soak Up
- Power Up

A complete Computer Aided Design and Assessment (CADA) technique has been used intending to:

- get a "satisfactory standard" for the flight system to be used in the first flight;
- consider the flight trials as a mean for the fine tuning of the system.

To apply the CADA technique it was necessary to develop a complete mathematical model of the Helicopter + AFCS. Westland Helicopter Ltd. (WHL) developed the mathematical model of the aircraft; Smiths Industries (SI) developed the mathematical model of the ASE and 13 autopilot control law and the link to the aircraft model; Agusta Sistemi (AS) developed the mathematical model of the Winch / Cable / Sonar System (WCSS), the autopilot Cable Hover Hold Control Law and the link to WHL and SI models.

The helicopter + WCSS + AFCS model has been developed and fully tested by means of a simulation program (TSIM - Cambridge Control) in the mixed continuous/discrete time domain (i.e. taking into account sampling and delay of any signal). The Helicopter + WCSS + AFCS model has been also assessed on the "pilot in the loop" EH101, 6 degree of freedom, full force, Flight Dynamic Simulator (FDS) (at WHL).

This paper deals with all the activities performed at Agusta Sistemi.

1.1 Acknowledgment

The author wishes to thank:

- Agusta S.p.A.
- Cambridge Control
- Smiths Industries - Aerospace & Defense Systems
- Westland Helicopter Ltd.

which have made this work possible.

2. MATHEMATICAL MODELS OF THE HELICOPTER-WINCH-CABLE-SONAR SYSTEM

The cable + sonar system is simulated by means of both a discrete and a lumped model. The use of a discrete model of threads describing the cable dynamic and a 6 degree of freedom model describing the sonar body dynamic involves the following problems:

- it is hard to deal with the most general form of the dynamic equations of threads;
- the necessary boundary conditions would come from the full force dynamic model of the helicopter and from the dynamic equations of the sonar body;
- the sonar body could not have a simple shape;
- the level of detail obtainable from the model would be too high compared with the capability to represent all physical contributions in a suitable way (e.g. sea surface, sea currents, wind, etc...);
- the computing time required to solve this type of model could be excessive thinking to the use of the model.

However, under simplifying conditions it is easy to deal with the steady state form of the discrete model; so, to take advantage of the opportunity

to have a good landmark in steady state conditions, the steady state form of the discrete model was developed.

The lumped model for both steady and dynamic conditions was developed under some drastic assumptions; as it will be shown, this model gave steady state results very close to those obtained with the steady discrete model. Once this fact was stated a sensible performance of the lumped model was identified in dynamic conditions (e.g. looking at the cable angle trend following an helicopter maneuver); after that the lumped model was linked to the helicopter + AFCS model and completed with the winch model and at last with the cable hover control law. The lumped model can simulate the following:

- helicopter by itself;
- helicopter + WCSS being:
 - the sonar either emerged or submerged;
 - the helicopter stationary over the sea and cable either partially or completely unreeled;
 - the helicopter moving and cable either partially or completely unreeled;
 - the helicopter moving while cable is unreeling;
- helicopter + WCSS + cable hover control law being the helicopter under the same conditions as above.

2.1 Discrete model

The following assumptions have been made:

- the cable is perfectly flexible;
- the drag forces due to wind and sea currents acting on cable and sonar body do not affect the dynamic equations of the helicopter model (in other words the helicopter is thought as fixed in space);
- the vertical forces (drag), acting on cable and sonar due to helicopter vertical velocity, are neglected;
- the cable position can be characterized by means of the steady state form of the threads equations written in $X Z$ and $Y Z$ planes:
$$\begin{matrix} h & h & h & h \\ h & h & h & h \end{matrix}$$
- the cable is unreeled (the scope is constant);
- the sea surface is flat;
- the sea currents are constant along the vertical axis;
- the cable/sonar junction is frictionless;
- the wind speed is constant along the vertical axis except in an air layer (H_0 meters height) over the sea surface. Within the air layer the classical cubic vertical wind profile is assumed;
- the reference systems used within WHL aircraft model are adopted to write the cable and sonar model equations.

2.1.1 cable

The vectorial equations of threads are projected on the earth axes X , Y , Z obtaining:

$$\begin{matrix} h & h & h \end{matrix}$$

$$F_i + \frac{d T_i}{d s} = 0$$

$$T_i - T * \frac{d i}{d s} = 0$$

$$T - \sqrt{\frac{T_x^2}{h} + \frac{T_y^2}{h} + \frac{T_z^2}{h}} = 0$$

being:

$$i = \frac{X}{h}, \frac{Y}{h}, \frac{Z}{h}$$

T the total pull in each cable stretch.

F the constant force per unit length acting on each cable stretch either emerged or submerged; F is the sum of three components:

- the weight of the cable,
- the drag forces due to either the wind or the sea current (they are assumed to be depended upon the square of the relative velocity between the cable and either the water or the air),
- the buoyancy;

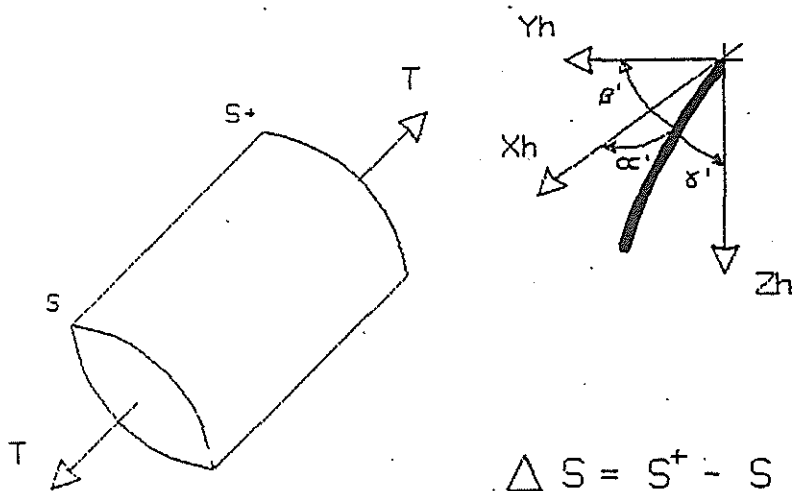
at cable/sonar junction the same components due to the sonar body are added.

The space discretization of the previous equations gives for each stretch of cable (see Fig. 2.1.1) :

- the position,
- the pull along the earth axes direction,
- the total pull along the cable,
- the director cosines,

being known the boundary conditions at the cable/sonar junction obtained from the sonar equilibrium equation.

Figure 2.1.1 Space discretisation of the cable



2.1.2 Sonar

See section 2.2.2 .

2.2 Lumped model

The following assumptions have been made:

- the effects of drag forces due to wind and sea currents acting on the cable and sonar body are taken into account in the dynamic equations of the helicopter model (in other words the helicopter can be dragged by the sea or wind through the cable and sonar); the drag forces are supposed dependent on the square of the relative velocity between the body and the fluid;
- the cable/sonar system is considered as a system made of a "double pendulum " connected by means of an ideal spherical hinge; the weight of each stretch of cable (part I = emerged part; part II = submerged part) is supposed concentrated at the bottom;
- the dynamic effects of winds and sea currents are taken into account separately by writing the model using two dynamic equations: the first equation deals with the emerged part of the cable and the second one deals with the submerged part of the cable;
- the cable/sonar system moves in a viscous environment;
- the vertical (inertial and drag) forces acting on the WCSS due to vertical movements of the helicopter are neglected;
- the cable motion can be described by means of time dependent equations written in X Z and Y Z planes;
- the wind and sea currents can be strong but they are always characterized by weak gradients;
- the wind speed is constant along Z except in an air layer (H₀ meters height) over the sea surface; within the air layer the classical cubic vertical wind profile is assumed;
- the winch can be set at any distance from the origin of the A/C datum axes;
- the sea currents are constant along Z ;
- the sea surface is flat.

2.2.1 Helicopter-winch-cable

The aircraft dynamic equation system (force and moment balance) are modified to take into account the effects of the cable pull on the helicopter dynamic. The "winch" model consists of a set of simple equations giving the unreeled cable length (cable scope) as a linear function of time being assigned the cable unreeling velocity either greater or less than zero. To compute cable angles (fore/aft and lateral) from the absolute vertical the following equations are used:

fore/aft:

$$M_{tot} * L_{ce} * \frac{d^2 \alpha_1}{dt^2} = -T_{totz} * \sin \alpha_1 + T_{totx} * \cos \alpha_1 - K_1 * L_{ce} * \frac{d \alpha_1}{dt}$$

$$M_{II} * L_{cs} * \frac{d^2 \alpha_2}{dt^2} = -T_{IIz} * \sin \alpha_2 + T_{IIx} * \cos \alpha_2 - K_2 * L_{cs} * \frac{d \alpha_2}{dt}$$

lateral:

$$M_{tot} * L_{ce} * \frac{d^2 \beta_1}{dt^2} = -T_{totz} * \sin \beta_1 + T_{toty} * \cos \beta_1 - K_1 * L_{ce} * \frac{d \beta_1}{dt}$$

$$M_{II} * L_{cs} * \frac{d^2 \beta_2}{dt^2} = -T_{IIz} * \sin \beta_2 + T_{IIy} * \cos \beta_2 - K_2 * L_{cs} * \frac{d \beta_2}{dt}$$

The computed cable angles at helicopter (α_1 , β_1) can be lagged to simulate a smoothing filter applied to source of cable angles (cable angle sensor). The cable angles values at helicopter are limited to simulate the exit funnel from the helicopter.

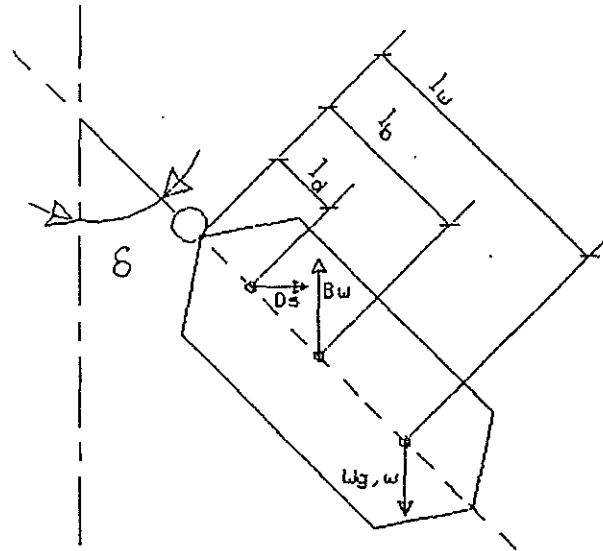
2.2.2 Sonar

To compute the tilt of the sonar body from the absolute vertical the following assumptions are made:

- the wind does not affect the sonar equilibrium because of both the higher viscosity of water than air and the very low ratio between the dry and wet cable length during standard operating conditions;
- quasi-steady model is used considering that:
 - this is a preservative hypothesis in terms of the computed sonar tilt due to the effects of drag forces onto it;
 - there is no need for a detailed description of the sonar dynamic in view of the particular use of the WCSS model;
 - there are some difficulties to make a full dynamic description of a sonar body because it has not yet been defined and, besides, at the moment the available MMI provisional sonar data indicate a fully articulated structure.

The tilt of the sonar body from the vertical is then computed using a moment balance of hydrodynamic and gravitational forces about the frictionless cable/sonar junction (See fig. 2.2.2):

Figure 2.2.2 Sonar body



2.3 Verification of the computed results in steady conditions

The results are obtained by means of the discrete and lumped model. Table 2.3-1 shows the computed results compared with those available in Agusta (for high Aircraft altitude hover, low sonar depth). In the fifth column the sea current velocity values are written; in the sixth column the wind velocity values are written. The results are relevant to the cable angle and sonar body tilt in the fore/aft direction. The first (1) column of the table shows the cable angle values computed using the discrete model; the second (2) column shows the cable angle values computed using the lumped model; the third (3) column shows the results available in Agusta; the fourth column shows the computed sonar body tilt. Table 2.3-2 shows a further comparison between reference results and those obtained by means of the lumped model. Table 2.3-2 shows the computed results compared with provisional MMI sonar data; columns (1) and (2) show the reference and the computed results relevant to the cable angle from absolute vertical at the helicopter; columns (3) and (4) show the reference and the computed results relevant to the sonar body tilt from absolute vertical. The sonar tilt does not change on different cable scopes because it depends only on the relative velocity between the water and the helicopter.

Table 2.3-1 Comparison between computed and reference (Agusta) cable angle values.

	CABLE ANGLE α (deg.)			SONAR TILT δ (deg.)	Vc (m/s)	Vw (m/s)
	(1)	(2)	(3)			
test case 1	0. 2.14 18.62	0. 2.18 18.73	0. 2.2 20.5	0.	0.	0. 10. 30.
test case 2	0.89 3.04 19.42	0.91 3.09 19.45	1. 3. 21.5	0.33	0.2	0. 10. 30.
test case 3	8.00 10.09 25.52	8.18 10.18 25.09	8. 11. 28.5	2.96	0.6	0. 10. 30.
test case 4	-15.35	-15.09	-17.	1.32	0.4	-30.

3. SIMPLIFIED AUTOMATIC STABILIZATION EQUIPMENT MODEL FOR GROUND RESONANCE TEST

In order to carry out an investigation into air and ground resonances it was required to Smiths Industries a simplified ASE transfer function equivalent to the full ASE control law transfer functions. Since there was no need for a use of the full AFCS model, the simplified ASE model has been efficaciously used to design the AP cable hover control law; obviously all actuator and ASE authority rate and position limits have been added to this simplified model so as to characterize the AP control law correctly. Figures 3-1 shows the total control loop.

Figure 3-1 Total control loop

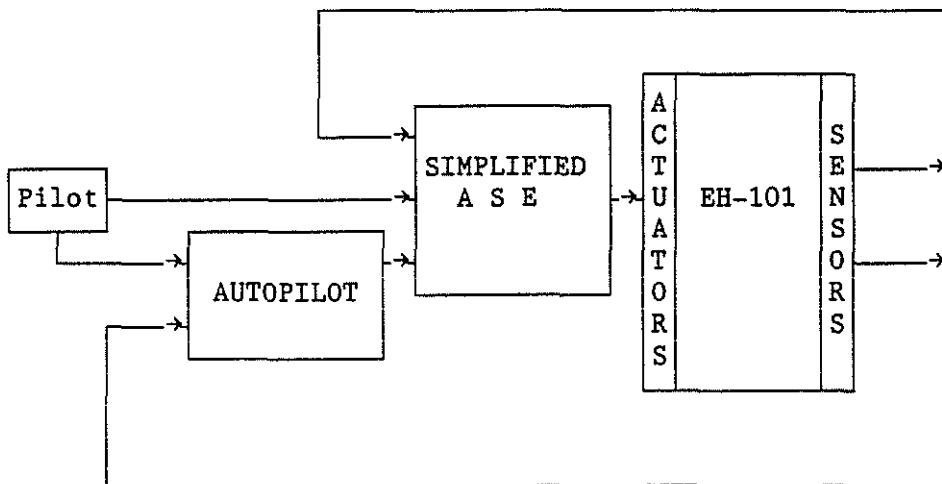


Table 2.3-2 Comparison between computed and reference (MMI) cable angle values.

Relative velocity between A/C and sea water (kts)	Cable Scope (m)	Cable Angle α (deg.)		Sonar Tilt δ (deg.)	
		(1)	(2)	(3)	(4)
0.25	475	2.3	2.3	0.43	0.42
0.50		9.2	9.0	1.68	1.68
0.75		19.5	20.0	3.77	3.80
1.00		32.2	33.0	6.65	6.70
1.25		44.4	45.4	10.24	10.36
1.50		58.2	55.6	14.40	14.75
0.25	415	2.0	2.1	0.43	0.42
0.50		8.1	8.3	1.68	1.68
0.75		17.7	18.2	3.77	3.80
1.00		29.6	30.4	6.65	6.70
1.25		41.4	42.5	10.24	10.36
1.50		51.5	52.8	14.40	14.75
0.25	315	1.7	1.7	0.43	0.42
0.50		6.6	6.8	1.68	1.68
0.75		14.5	15.1	3.77	3.80
1.00		24.8	25.6	6.65	6.70
1.25		35.6	36.8	10.24	10.36
1.50		45.8	47.1	14.40	14.75
0.25	215	1.3	1.3	0.43	0.42
0.50		5.0	5.2	1.68	1.68
0.75		11.2	11.7	3.77	3.80
1.00		19.4	20.2	6.65	6.70
1.25		28.7	29.9	10.24	10.36
1.50		38.0	39.6	14.40	14.75
0.25	115	0.9	0.9	0.43	0.42
0.50		3.4	3.6	1.68	1.68
0.75		7.7	8.1	3.77	3.80
1.00		13.4	14.2	6.65	6.70
1.25		20.4	21.5	10.24	10.36
1.50		27.9	29.6	14.40	14.75
0.25	45	0.6	0.6	0.43	0.42
0.50		2.3	2.4	1.68	1.68
0.75		5.1	5.4	3.77	3.80
1.00		9.0	9.6	6.65	6.70
1.25		13.7	14.8	10.24	10.36
1.50		19.2	20.8	14.40	14.75

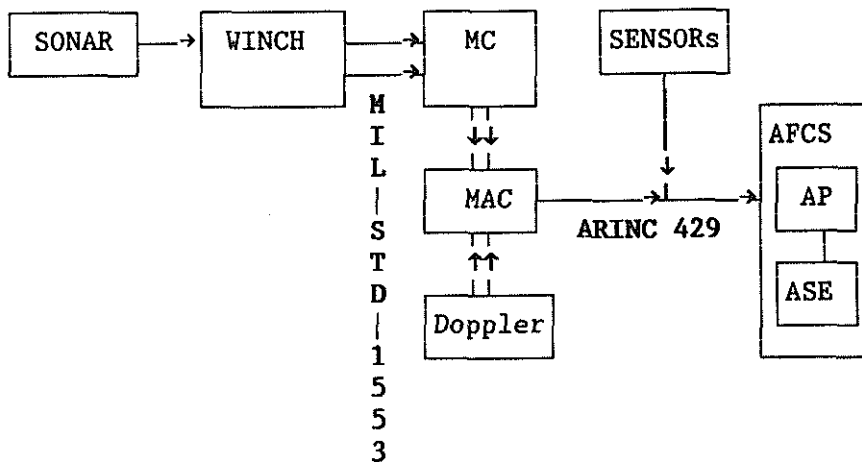
4. AUTOPILOT CABLE HOVER MODE

Autopilot cable hover hold mode is provided on the MMI naval variants of the EH101 helicopter. It is for use in the anti-submarine role with a submerged sonar transducer. This section shows the overall system configuration used as a basis to design the cable hover control law; the cable hover mode functionality and control law are also presented.

4.1 System configuration

The sonar and the other units are interfaced to the AFCS as shown in figure 4.1-1:

Figure 4.1-1 System configuration



where:

MC = Mission Computer
MAC = Management Computer
AFCS = Automatic Flight Control System
AP = AutoPilot
ASE = Automatic Stabilization Equipment

4.2 Cable hover mode functionality

The helicopter horizontal control is by cyclic pitch and cyclic roll axes. Vertical control is by collective axis. The radar altitude mode provides the control of the aircraft hover altitude. Directional control of the aircraft is through the yaw autostabiliser. The cable hover mode shall function at:

- wide range of aircraft hover height
- wide range of sonar depth
- full range of both sonar and aircraft operating conditions.

Assuming calm conditions, the cable hover mode at the engagement Rapidly establishes the helicopter hover at null cable angle with, at the most, one little overshoot. The cable hover mode complies with the following condition during operation:

- very small deviation of the cable angle with respect to the cable angle datum (Fore/Aft - Lateral)
- control action unaffected by a change of:
 - aircraft heading
 - aircraft altitude
 - sonar depth.

The mode can be engaged even if the ground speed signals are declared invalid. Cable hover mode engagement request occurs if:

- the pilot presses the CAB button on the front panel of the PCU (Pilot Control Unit);
- the radio altitude hold mode is engaged;
- either the doppler hover hold mode is engaged or the aircraft is in attitude hold mode.

After the request, the mode engages only if the following conditions are satisfied:

- valid cable angle and sonar signals;
- sonar pressure depth > 0.0 feet or sonar submerged;
- valid Fore/Aft earth axis acceleration signal;
- valid Lateral earth axis acceleration signal;
- small aircraft total horizontal ground speed being valid the ground speed validity signals;
- smoothed aircraft altitude within the operational range;
- small absolute vertical earth axis velocity.

Cable hover mode disengages following:

- sonar body emersion,
- loss of acceleration signals,
- pilot intervention.

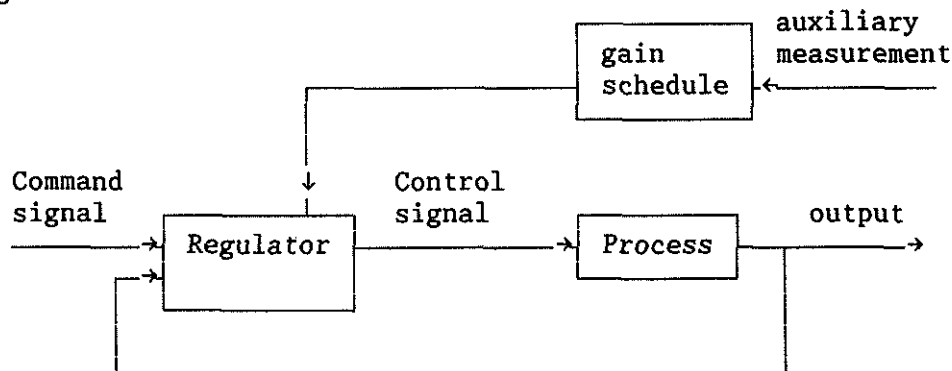
A "system beep trim" function is provided to enable the pilot to make small and accurate Fore/Aft and Lateral cable angle datum changes to cope with wind effects on the cable. This function operates through pitch axis using the Fore/Aft cyclic system beep trim switch and through roll axis using the Lateral cyclic system beep trim switch. The system beep trim function is limited to some degree.

The pilot is able to maneuver the aircraft with cable hover mode engaged by displacing the cyclic stick: the cable hover mode is now transparent to the pilot. When the cyclic stick is restored to the zero force position, the cable hover control law returns the aircraft to the previously trimmed cable angle datum.

4.3 Cable Hover Control Law

The cable hover control law is an "adaptive" control law; namely it makes use of a "gain scheduling" technique (there is a controversy in nomenclature concerning whether gain scheduling should be considered as an adaptive scheme or not, because the parameters are changed in open loop). Briefly this technique is shown in figure 4.3-1.

Figure 4.3-1 Gain schedule controller



The gain scheduling technique is adopted since:

- it was not possible to satisfy all the requirements with a unique control law;
- it should have been too much expensive in terms of developing and

computing time to use a more sophisticated adaptive control technique;

- it was possible to determine the regulator parameter over the entire flight envelope, simply by performing extensive, low cost simulations (i.e. time responses); the flight envelope is not so wide.

The cable hover control law provides the control of the aircraft horizontal position using as inputs:

- the Fore/Aft and Lateral cable angle from body axes which are used to compute the cable angles from absolute vertical;
- the longitudinal and lateral filtered ground speeds;
- the longitudinal and lateral earth axes accelerations (feet/s**2);
- the smoothed aircraft altitude (feet);
- the unreeled cable length (feet).

A block diagram of the pitch cable hover control law is shown in figure 4.3-1; a similar control law is used for the roll axis with different gains value.

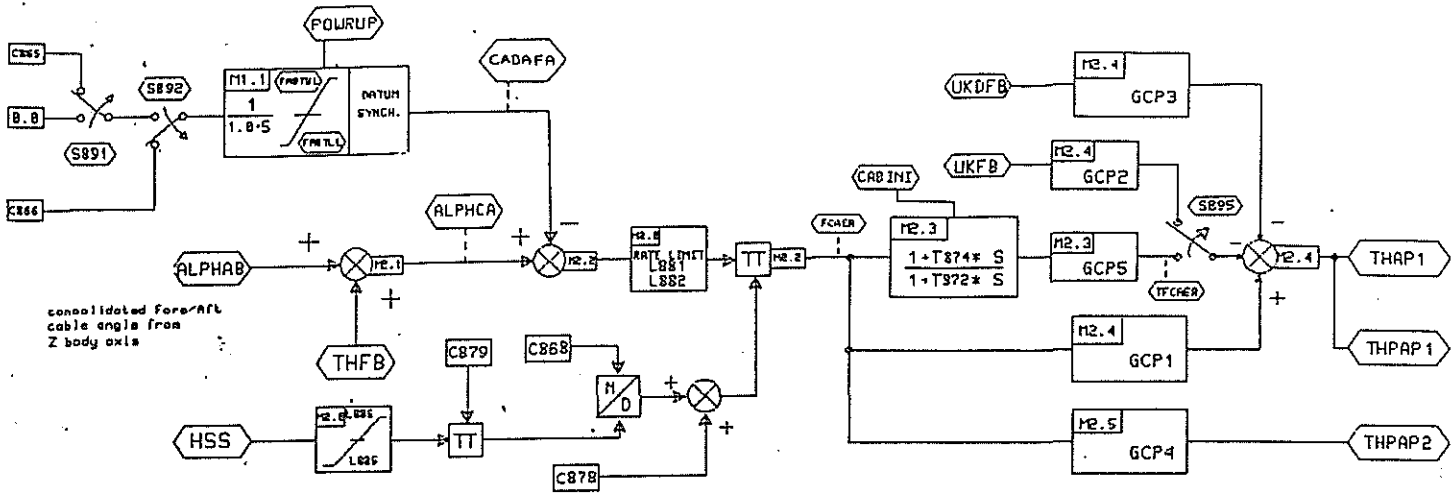


Figure 4.3-1 Pitch cable hover control law

5. SIMULATIONS

5.1 TSIM time responses

TSIM simulation program enables the users to simulate a mixed continuous/discrete (digital) system as it is the Helicopter + AFCS. TSIM at Agusta Sistemi runs on a DEC VAX 8550; the obtained time responses show the trend of the selected quantities (helicopter attitude and ground speed, cable angles etc...) upon miscellaneous inputs to the overall system. The following figures are 2 of more than 100 documented time responses performed to test the performance of the Helicopter + AFCS + Winch / Cable / Sonar / System.

Figure 5.1-1 Forward system beep trim to achieve -5.0 deg. of cable angle.

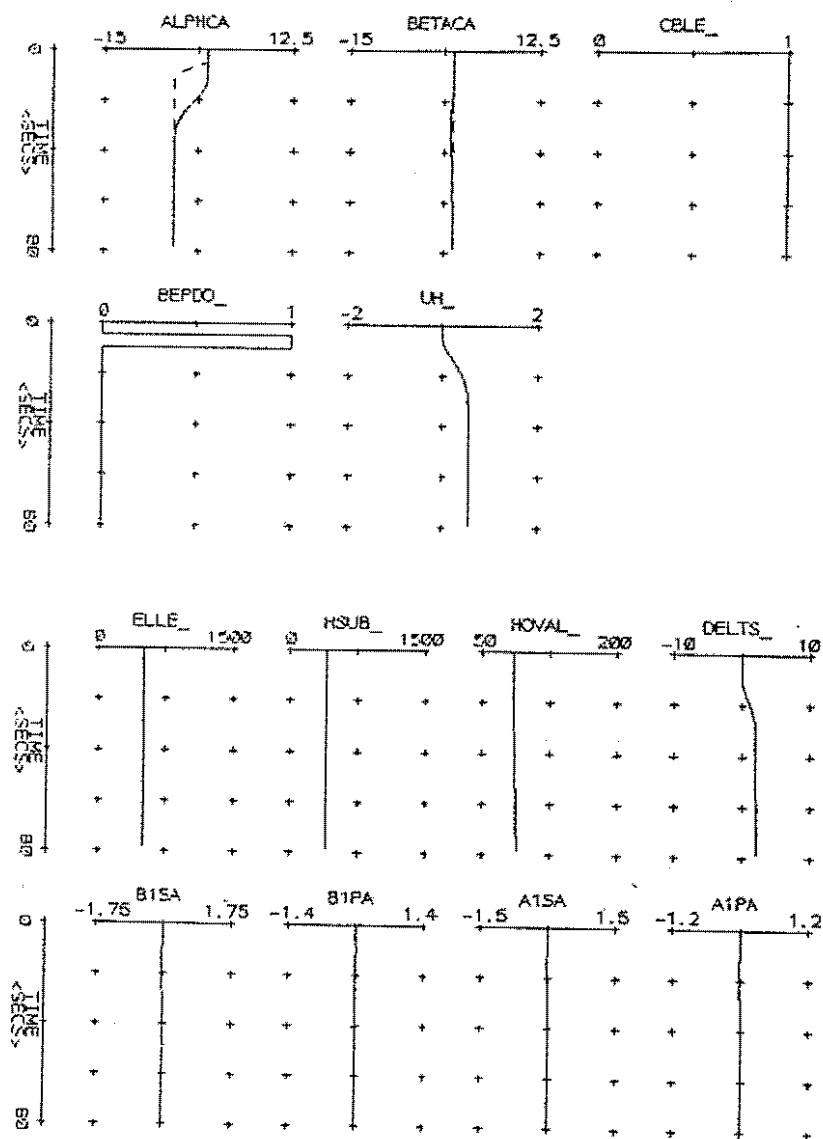
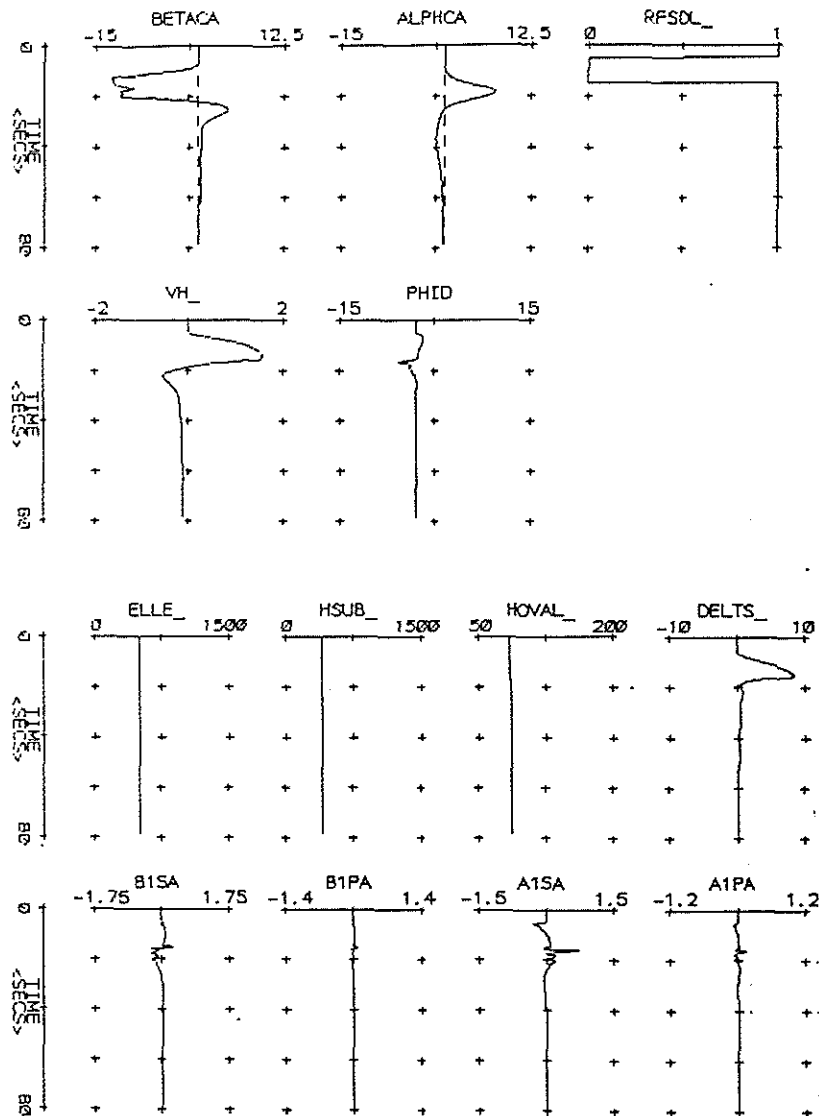


Figure 5.1-2 Lateral manual maneuver.



5.2 Simulation on flight dynamic simulator

The assessment of the cable hover hold control law and mode logic have been made by the AGUSTA and WESTLAND test pilots, on the EH101, 6 degree of freedom, full force, Flight Dynamic Simulator (FDS) at WHL. This assessment have been performed on the basis of a test instruction covering more than 60 different operating situations grouped into the following topics:

- mode engagement;
- pilot manual maneuver being the mode engaged;
- cable angle datum variation;
- aircraft altitude and sonar depth variation being the mode engaged;
- mode engagement and maneuvers being the doppler signal not valid;
- mode logic and display.

The cable hover hold mode has been assessed through the above mentioned test cases using more than 10 hours of flight on the FDS employing also the simulator motion facility; the test cases have also been used to verify whether or not the mathematical model of the cable were realistic. At the

end of the assessment it has been declared that:

- the Helicopter / Winch / Cable / Sonar model behavior is realistic,
- the cable hover hold control law meets the requirements,
- the cable hover hold control law gives a stable, smooth and tight control of the aircraft,
- the present configuration of the control mode is a 'satisfactory standard' for the first flight.

It is expected that during the flight trials it will be necessary a control law retuning mainly due to the fact that:

- up to today the sonar and cable hydrodynamic characteristics are not well known (the control law design is based on the most suitable informations being the sonar design still in progress),
- the flight dynamic simulator behavior could be in some way dissimilar from that of the real aircraft.

6. CONCLUSIONS

A computer aided design technique has been used to develop the Automatic Flight Control System (AFCS) mounted on the E.H.I. (Westland + Agusta) EH101 helicopter; one of the 14 autopilot mode, the cable hover hold mode and the related winch - cable - sonar mathematical model, has been designed by Agusta Sistemi. The adopted design technique has involved:

- the system model identification and tuning using a simulation program (TSIM - Cambridge Control);
- the simulations and system tuning using the EH101 "pilot in the loop" 6 degree of freedom, full force, Flight Dynamic Simulator (at Westland).

The high degree of standardization of the adopted design technique has allowed the developing of the AFCS by two companies: Smiths Industries (UK) and Agusta Sistemi (I). Flight trials are in progress to define the final AFCS parameter configuration. The trials are showing that the adopted design technique is reliable and correct; the use of simulation allows a safe, efficient and highly economical technique both to evaluate the aircraft performances while the avionic systems are developed and to increase the speed and thoroughness of pilot training.

7. NOMENCLATURE

F	force
K	equivalent viscosity coefficient
L	cable length
M	mass
s	line coordinate
t	time
T	pull
X,Y,Z	reference coordinates

subscript:

c	sea current, cable
e	emerged
h	earth axes
s	submerged

Greek letters:

α_1	fore/aft cable angle from absolute vertical at helicopter
α_2	fore/aft submerged cable angle from absolute vertical
β_1	lateral cable angle from absolute vertical at helicopter
β_2	lateral submerged cable angle from absolute vertical
δ	sonar tilt from absolute vertical
θ	pitch attitude
ϕ	roll attitude
ψ	heading