PAPER Nr. 26

A129 - AUTOMATIC FLIGHT CONTROL SYSTEM :

DESIGN AND OPTIMIZATION OF A FULL DIGITAL FOUR AXIS AUTOPILOT

BY

E. MAJORI

AGUSTA SISTEMI
TRADATE (VA) - ITALY

FIFTEENTH EUROPEAN ROTORCRAFT FORUM

SEPTEMBER 12 - 15, 1989 AMSTERDAM

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A129 - AUTOMATIC FLIGHT CONTROL SYSTEM:
DESIGN AND OPTIMIZATION OF A FULL DIGITAL FOUR AXIS AUTOPILOT

Author: EMILIO MAJORI
Software team leader for A129 IMS
AGUSTA SISTEMI (AGUSTA S.p.A.)
Via Isonzo,33 21049 Tradate (VA) -Italy

ABSTRACT

The automatic flight control system of the A129 AGUSTA anti tank helicopter is presented.

The activities carried out to optimize the design and tuning of several autopilot modes are described.

The steps followed, starting from the helicopter model identification and simulation through AFCS parameters selection to flight test and data recording, reduction and analysis, are illustrated.

The principal aspects for optimization of different autopilot modes are analysed.

In particular, the digital implementation topics are treated, discussing the signal characterization, filtering and frequency requirement for control algorithms.

Finally, the integration of a strapdown platform is described, showing how the experience accumulated allowed the specification of a better requirement and the successful coupling of a new attitude and heading reference system to the AFCS.

1. ACKNOWLEDGMENT

The author wishes to thank:
- Agusta S.p.A.
- Harris Corporation - Government Aerospace System Division
both of which have made this work possible.

2. A129 INTEGRATED MULTIPLEX SYSTEM

A brief description of the Integrated Multiplex System (IMS) is mandatory to better understand the A129 AFCS architecture. The IMS consists of the following units:
- 2 Master Units (MU) containing processors (four Z8001), memory, 1553B bus controller and aircraft equipment interface circuits (Local Units),

- 2 Remote Units (RU) containing aircraft equipment interface and symbol generator circuits,
- 2 Multifunction Keyboards (MFK) for crew control and information display,
- 2 (with provision for 3) Multifunction Displays (MFD) for crew control, selection and display of information.

A dual redundant architecture provides the capability to reconfigure the system for a first critical function failure (i.e., AFCS, Hydraulics control). The two MU's perform identical tasks at the same time, and while the real master generates all the output controls, the other one (slave) works in a backup mode preparing its own outputs for a cross check.

A 1553B military standard data bus transfers all the information between IMS units and other interfaced avionic systems (i.e., Remote display units, radios, radar doppler). The bus controller, providing clock interrupts, is responsible for processor synchronization and task scheduling.

The IMS provides control and monitoring for all the following subsystems: AFCS, Fly-by-wire, Navigation, Communications, Fuel, Hydraulics, Engine monitoring, Transmission, Electrical, Visionic, and Weapons. It gives the crew all the information to perform the proper actions and to satisfy the mission requirements.

The A129 provides a primary Fly-by-wire (FBW) control of the tail rotor with a triple redundant analog system. The electronic circuitry is contained in three separated boxes (two RU's and one LU) of the IMS. The software provides a fourth channel model for surviving at a second failure automatic reconfiguration. The tail rotor AFCS contribution, after a proper authority limitation, is summed with the pilot pedal command directly by analog circuitry before being sent to the actuator.

Primary control for the main rotor is mechanical with a dual redundant backup FBW control. The main rotor FBW is a digital control, and the summation and authority limitation of the AFCS contribution is performed by software.

During AFCS flight test activities no FBW configuration was experimented; therefore the control of the tail rotor was temporarily modified by inserting a mechanical link. For AFCS yaw control an electromechanical actuator was installed.

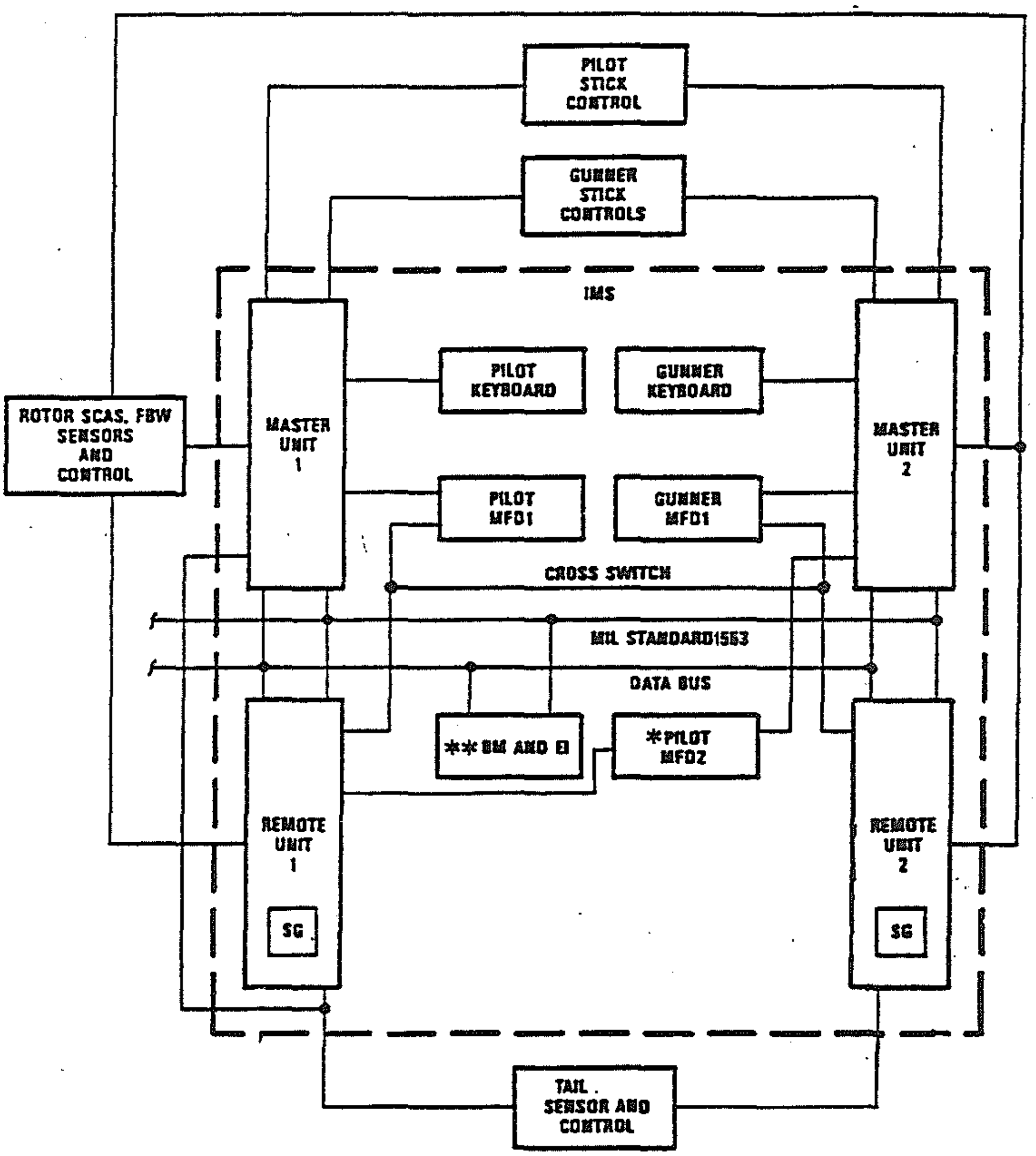


Fig. 3.1 IMS Hardware Flight Control System Configuration

3. A129 AFCS ARCHITECTURE

The IMS h/w flight control configuration is shown in fig. 3.1. The crew commands for AFCS mode selection are entered via the two MFK, the cyclic, and the collective sticks switches.

Aircraft information and cautions are presented on the two multifunction displays. The bus controller loads all the input data, provided by different sensors, into a global memory area accessed by the AFCS processor and sends the computed outputs to the actuators' interfaces. Four CPU boards are inside each master unit; one of these is completely dedicated to AFCS functions.

The AFCS actuators for the main rotor are integrated into three main rotor boosters. The flight control has, however, to perform an electronic mixing for pitch, roll and collective commands. Main rotor AFCS actuators are mechanically limited to +/- 10% authority of the main rotor ram movement. Considering the pilot command excursion (cyclic and collective), the maximum AFCS authority for each axis will be:

AFCS pitch cmd. = +/- 10% of longitudinal command
AFCS roll cmd. = +/- 16% of lateral command
AFCS collective cmd. = +/- 10.5% of collective command

The temporary electromechanical tail rotor actuator provides a command limited to +/- 6.7% of the pilot pedal command.

4. AFCS FUNCTIONAL MODES

A brief description of the AFCS functional modes optimized on the A129 follows:

- SCAS (Stability and Command Augmentation System) provides a short term damping about the pitch, roll and yaw axis. It provides the augmentation of pilot inputs to enhance the handling qualities of the aircraft.
- ATTITUDE HOLD provides the capability to automatically hold a particular pitch or roll attitude.
- HEADING HOLD provides the long term retention of heading.
- ALTITUDE HOLD provides the long term retention of the barometric or radar (if HOVER HOLD mode is active) altitude.
- HOVER HOLD provides the long term retention of longitudinal and lateral position of the aircraft with respect to the ground.
- AIR SPEED and GROUND SPEED HOLD shall maintain the air speed (as measured by the air data system) or ground speed (as measured by the radar doppler) of the aircraft.
- VERTICAL SPEED HOLD shall maintain the rate of climb or descent of the aircraft as measured by the radar doppler.
- WINGS LEVEL provides aircraft wing level return.

- COURSE shall maintain course by generation of a roll command from both crosstrack error and heading error relative to a track on the ground.
- FLIGHT PLAN shall provide commands whereby the aircraft shall fly to pre-entered way-points.

5. AGUSTA ACTIVITIES FOR A129 AFCS

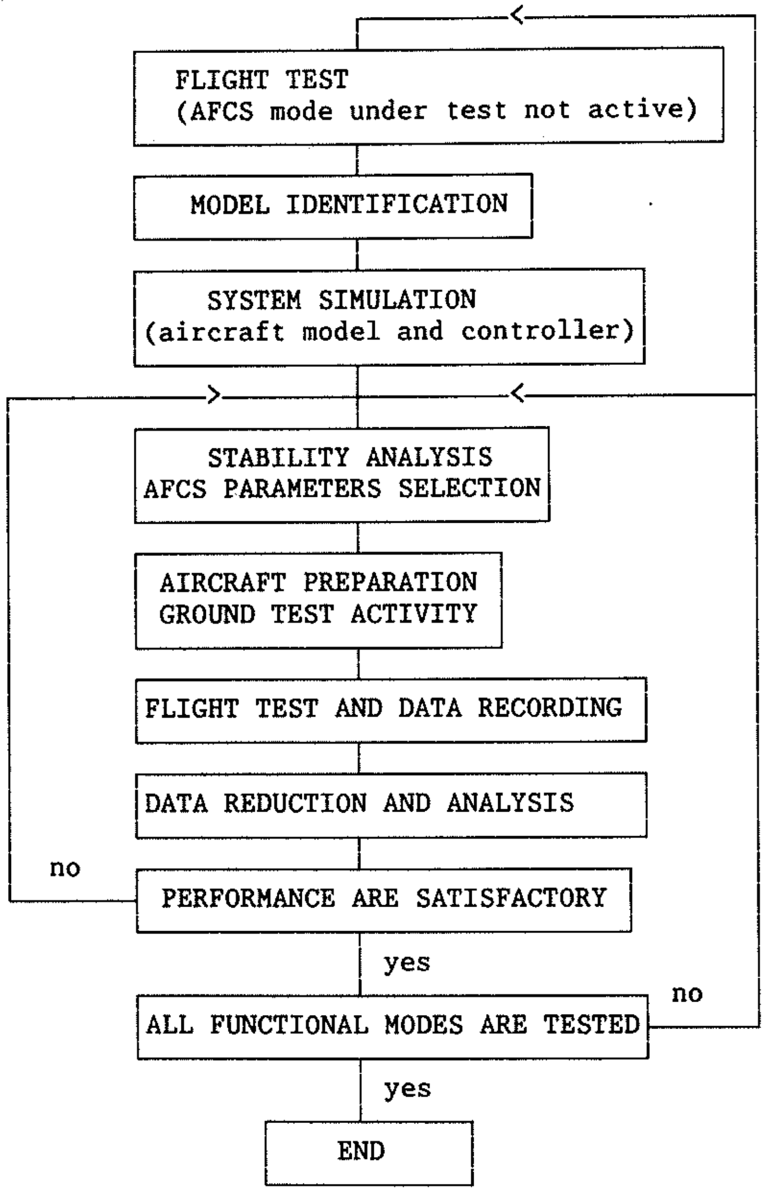
The A129 AFCS was the first undertaking carried out by Agusta to design and optimize an automatic flight control system. Previous knowledge on servo actuator application and avionic systems, together with the experience in integrating autopilots on different helicopters, was applied in designing the A129 AFCS architecture and in specifying the proper requirement for the IMS.

In 1982, a bread-board prototype of the AFCS was installed on an A-109 helicopter. The risk associated with the integration of a fully digital autopilot into IMS had yet to be explored. The platform stabilization and the optimization of some higher functional modes were achieved. This activity was useful to better understand the problems related to digital implementation of a controller. Some s/w and h/w requirement had to be modified, and the frequency of the control loop algorithms was redefined.

In 1986, the first IMS was installed on the A129 prototype. The first flight test activity was dedicated to checking the IMS monitoring and control for basic aircraft subsystems. During the AFCS testing, the built-in-test functions were activated and checked. Using the dedicated A129 prototype in a two year flight test period, the goal to optimize the AFCS, navigation, and built-in-test subsystems was achieved.

6. A129 AFCS MODES OPTIMIZATION

The different activities followed for AFCS optimization are shown in the next figure.



The previous activities carried out on the A-109 eliminated the risks associated with a digital integrated AFCS, but on the other hand showed the necessity for having a more sophisticated method for optimizing the AFCS gains. During this period, a special program (MOSTAB) was used to simulate the helicopter model. Starting from the physical characteristics of the A-109 aircraft, the coefficients of a stability derivative model were found. The reproduction of that model on an analog simulator allowed both the design of the control law algorithms and the selection the AFCS parameters for stability and control. The subsequent flight test phase showed the discrepancies between the simulated model and actual aircraft behaviour under different dynamic conditions, requiring the redefinition of the controller gains. On the A129, a different approach was used. A parametric identification of an AutoRegressive Moving Average model (ARMA) was applied. This statistical method minimizes the difference (with a minimum square root error approach) between the response of the actual system and the output of the model, given the identical input. For the sake of simplicity, the models identified were one-dimensional, without any cross-coupling between different aircraft axes. The order of the model (number of state variables) was not limited by the simulation program, but had to be selected before running the program.

For data recording, some dedicated flights were required. The typical pilot manoeuvre had to stimulate a single axis without perturbing the helicopter on other channels. Two initial step commands, followed by 15-20 seconds of steady input, reproduced the aircraft step response. A subsequent "sinusoidal sweep" (from about .1 HZ to the maximum allowed) characterized the frequency response. If the SAS and attitude hold functions were under test, the pilot command and aircraft attitude were recorded for model identification.

It was furthermore determined that as the the order of the model increased, it more closely followed the aircraft response. The improvement was evident up until at a certain limit (6-8); beyond that, differences were noted only during fast transients.

Having established the aircraft model, different methods were applied for AFCS gains definition (Bode, root locus, Nyquist).

System simulation was performed to validate the controller selection.

Several sets of different parameters were then prepared for each AFCS functional mode, and subsequently, flight test activity was ready to begin.

Data recording, reduction and analysis was necessary for the AFCS parameter tuning and definition.

7. PRINCIPAL ASPECTS OF AFCS DIGITAL IMPLEMENTATION

When dealing with digital signal processing, one must consider the problem of aliasing due to the sampling process. If the values of the frequency components of the sampled signal are greater than half of the sampling frequency, these components are reflected in the lower spectrum. To avoid this phenomenon, an analog pre-sampling filter for each signal should be used. The filter characteristics will be defined according to the signal frequency components and the system control loop bandwidth.

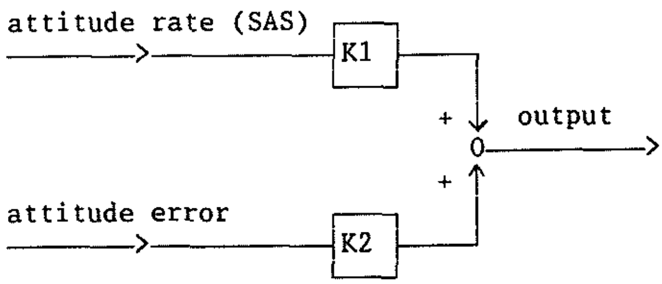
This approach cannot be used for special electrical signals like syncro and resolver, very common in avionic applications. Furthermore, in certain systems, some signals are provided directly in a digital format without a proper control of frequency components.

In the A129 AFCS, a vertical gyro is used for pitch and roll SAS and attitude control, while a directional gyro is the reference for heading control. The high frequency components and harmonics generated from the main and tail rotor revolution are the dominant vibrations on the A129 (23 Hz is the four per turn of the main rotor, and 27 Hz is the two per turn of the tail rotor). When computing the derivative of the attitude signals to obtain the rates, an amplification of noise is inevitable. During the first flights test, without applying any filtering, the commands generated by the AFCS saturated the actuators. Due to the aliasing effect of the 23 Hz from the main rotor and the 27 Hz from tail rotor processed at 30 Hz, a 7 and 3 Hz noise component were generated, which did not allow any trials for stabilizing the aircraft. Therefore, modifications were made in the control algorithms. The attitude and heading loop processing frequencies were moved from 30 Hz for both to 90 Hz and 180 Hz, respectively. Digital second order filters were introduced (a non-recursive filter implementation was selected) on the SAS, attitude, and heading loops. In this manner the rotor noise components were drastically reduced.

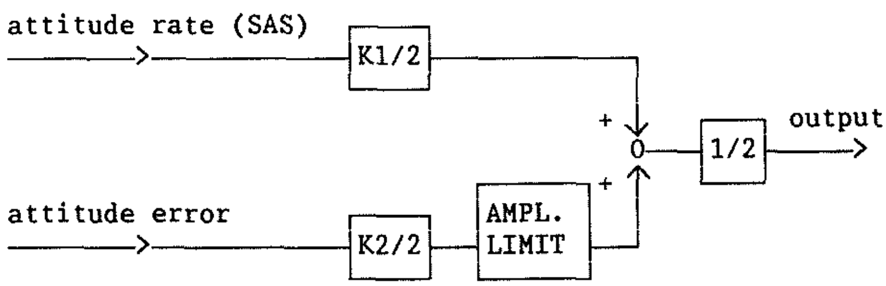
Signals provided directly in a digital format require a very accurate analysis. Oscillations were observed on signals coming from certain digital avionic systems. In a first analysis, the aircraft movement was assumed to be responsible for these oscillations, but an in-depth study demonstrated that the signal noise components were reflected in the helicopter controller bandwidth.

For asynchronous processing, a proper sampling frequency must be selected for the two involved digital systems, avoiding that a spurious component fall inside the control bandwidth. The time latency of signals has to be considered.

In a digital system, it is mandatory to consider the saturation limits for each signal along the path connecting the input sampling device to the output digital-to-analog converter. A saturation causes a loss of linearity, and in some cases could cause system instability. Consider, for example, the SAS and attitude hold control, and suppose one realizes the following digital scheme:

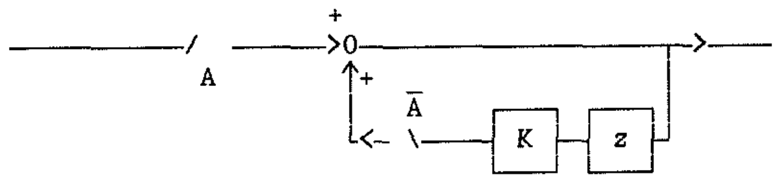


If the attitude error increases, the possibility exists that after multiplication by K2, the attitude error contribution could saturate. The SAS will no longer have complete control of the output, the result being a partially undamped system. In this situation, the A129 verified a divergent control. A possible solution might be:



By selecting the amplitude limit threshold to equal half of allowed digital range, the attitude error path will not lose any dynamic quality (with respect to the previous implementation), and thereby the SAS can have complete control of the output signal.

In a digital implementation of a controller, it is very common to introduce, along the different paths, some logical switches that can activate or deactivate output contributions according to the selected functions. This abrupt discontinuity could cause unacceptable transients in the output not taken into consideration during the system design. On helicopter autopilots, the activation of command micro-switches or force-trims to synchronize memory references is a common way to expose this problem. On the A129 AFCS, different solutions for avoiding transients have been introduced during flight test activities. A typically implemented algorithm is that of providing a low-pass filter that "washes-out" the residual contribution of a disconnected functional mode. The digital scheme is:

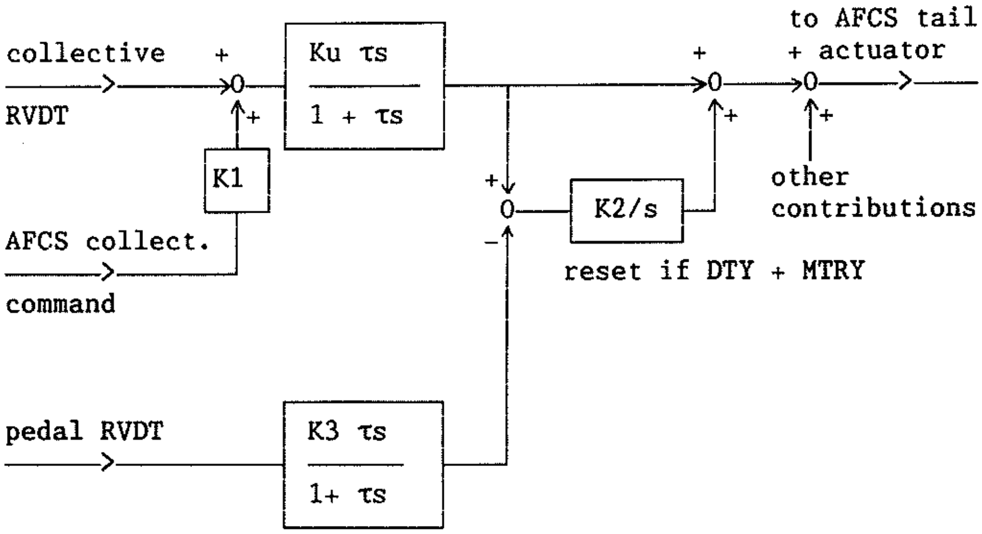


Switch A opens when the function is deactivated, forcing the input to zero (Ā closes). The gain K is less than 1 and determines, with frequency processing, the time constant for "wash-out".

8. COLLECTIVE TO YAW CROSS-COUPLING.

In this section, one of the functions optimized on the A129 is discussed. This function required a considerable effort, continuous software revision, and several flight tests in order to be optimized.

A collective movement, causing a torque modification, must be compensated by a tail rotor torque variation in order to avoid rotation about the helicopter vertical axis. Some aircraft provide a mechanical link between the collective and tail rotor. This generally works properly under certain flight conditions (hovering, cruise, etc.). On the A129, designed for primary FBW control of tail rotor, this mechanical link was not installed. For a particular collective command, different torque could be requested by tail rotor to guarantee the stabilization on yaw. The aircraft weight and speed can modify this request. For this reason, it is not possible to command the tail rotor angle of attack by looking only at the collective position. The following analog diagram represents the solution implemented on the A129. The Laplace transform notation, instead of the Z-transform, is shown for clarity.



The collective stick position (provided by RVDT sensors), plus the AFCS collective command, together determine the total amount of main rotor collective. The first block encountered, after the two signal addition, provides an output proportional to the collective variation which decays to zero with a time constant equal to τ. During this time, the integrator K2/s charges. By selecting the proper gains, the response will be proportional to the collective input:

if K3 = 0

$$H(s) = K_u \frac{\tau s}{1+\tau s}\left(1+\frac{K_2}{s}\right) = K_u \frac{\tau (K_2 + s)}{1 + \tau s}$$

if $K_2 = 1/\tau$ $\quad H(s) = K_u$

By having the possibility to reset the integrator (DTY = pedal microswitch activation, MTRY = pedal force trim activation), the tail rotor position could be adjusted at the flight start or during any situation by pilot pedal intervention. If the requested tail rotor torque modification is considerable, the pedal auto-trim could be activated by the AFCS. In this case, it is the pedal movement that compensates the main rotor torque variation. Its contribution has to be subtracted from the AFCS tail rotor actuator discharging the integrator. The signal coming from pedal position transducer (RVDT) accomplishes this function.

The gain Ku is a function of aircraft airspeed, and provides a tail rotor command dependent upon the helicopter airspeed. This allows the optimization of the cross-coupling function for the different flight conditions.

9. STRAPDOWN ATTITUDE AND HEADING REFERENCE SYSTEM INTEGRATION.

The A129 AFCS was designed to use gimbal attitude and heading reference systems. As mentioned before, several problems arose from the particular nature of the electrical signals provided by these systems.

A new requirement for a better navigation performance was the reason for integrating a strapdown attitude and heading reference system (AHRS). This 1553 interfaced system had to replace the vertical, directional and rate gyros for the AFCS functions. In addition, the system provides body referenced pitch and roll rates, not available in the previous configuration. The accumulated experience enabled Agusta to specify the proper system requirements and signal characterization. Pitch, roll, and yaw rates, generated by rate gyros, were required to be properly filtered with dedicated analog pre-sampling filters to avoid aliasing problems. The update rate for these signals was moved from 50 Hz to 200 Hz, reducing the time latency to a minimum. Attitude and heading signals computed by the system (integrating attitude rates) showed an improvement regarding noise rejection. Although pitch and roll SAS functions were optimized by deriving the attitude information (earth referenced), it was decided to directly use the pitch and roll rates (body referenced) provided by the AHRS system. Stability augmentation is a function that has to damp the aircraft movements around its body axes (longitudinal, lateral and vertical). The selection of body referenced rates is therefore more appropriate. With the implemented modifications, having selected the same control gains defined for gimbals configuration, the inner loop performance was considered satisfactory for the SAS, attitude and heading control beginning with the first flight test.