PRELIMINARY EVALUATION OF NEW CONTROL LAWS ON THE EXPERIMENTAL FLY-BY-WIRE DAUPHIN HELICOPTER

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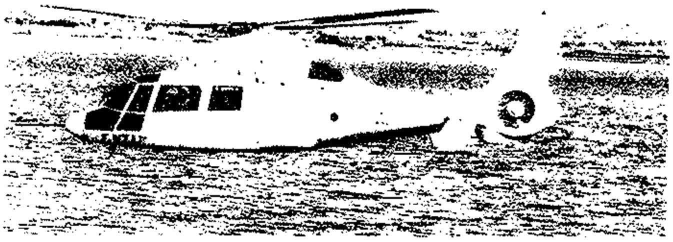


1) INTRODUCTION

The fly-by-wire concept is part of the context of generalized active control on helicopter, the main interest of which is the improvement in present aircraft handling qualities and the decreasing of the control work load during mission. These two topics constitute the main lines of research in the exploratory development of fly-by-wire systems for the DAUPHIN 6001 implementing, on the helicopter, new technologies that are already well-proven on aeroplanes.

The philosophy of the development of the fly-by-wire system on helicopters is rather different from that implemented for aeroplanes whose main aim was to increase the performances of their aircraft in terms of controllability and manoeuvrability. Improvement in these performances generally resulted in a decrease in the dynamic stability of the aeroplane and this was, then, artificially compensated by fly-by-wire systems. As the helicopter is unstable by nature and highly coupled between axes, the approach followed is radically different and consists, at a first stage, of restoring acceptable handling qualities for the helicopter and, at a second stage, in reducing the pilot's work load by proposing both a simpler flying mode on helicopter (by objectives) and an aid system in his tasks of monitoring flight envelope limits, especially for aggressive manoeuvres.

The purpose of present systems (automatic pilot) dedicated to the improvement of control has, so far, been limited to taking over from the pilot to maintain the helicopter on pre-determined pass. Their architecture was not initially designed to include the pilot in the loop apart from through an S.A.S. function ensuring a minimum apparent stability for pilot action. Nevertheless, the performances of these systems are limited, today, by safety requirements which impose operating ranges that are too limited to guarantee effective control during rapid manoeuvres.

As they provide a better safety level, fly-by-wire systems allow greater control ranges and, thus, allow considerably improved levels of flying qualities to be attained, a concrete example being the total uncoupling of control axes during manoeuvring. Furthermore, this type of flight control architecture facilitates the introduction of miniaturized controls, ideal, on the one hand, for the ergonomic optimization of future cockpits and, on the other hand, for passive monitoring of the flight envelope limits (preferably by sensitive action on the control sticks and no longer by means of a visual or audio signal in the cockpit).

To a great extent, these considerations justify the interest we should show in this type of flight controls, particularly for future combat helicopters.

2) AIMS OF FLY-BY-WIRE SYSTEMS EXPERIMENTS ON DAUPHIN 6001 HELICOPTER

The two main aims of fly-by-wire systems mainly concern the lightening of the pilot's work load during mission and the improvement of the helicopter handling qualities.

They can provide the following advantages:

1. to transform the helicopter into a stable aircraft throughout the flight envelope including attacking manoeuvres,
2. to guarantee uncoupling of the helicopter control axes at all times in order to simplify the flying of the aircraft in an operational envelope,
3. to increase the helicopter's controllability, if necessary, in order to cut down on the control actions now required on flexible rotor aircraft,
4. to make it simpler to learn to fly the helicopter by ensuring that the control objectives are perfectly suited to the operational constraints of each mission (control by objectives),
5. to provide automatic management of flight envelope limits that the pilot now has to monitor during mission by means of the visual and audio indications provided and the instructions given in his flight manual.

All these considerations form lines of research for the exploratory development of fly-by-wire systems for the DAUPHIN 6001. These studies have so far resulted in simulation tests to define the ideal control laws to reach the required levels of handling qualities and in the construction of the flying demonstrator (DAUPHIN 6001) to evaluate the performances of such a system in flight.

This document describes the methodology applied in preparing the control laws and details the architecture of the fly-by-wire system chosen for this demonstrator. The results of the first assessments are given at the end of this document, revealing the performances of control laws studied in the framework of these experiments.

3) DESCRIPTION OF THE SYSTEM ARCHITECTURE

The architecture of the system chosen for the DAUPHIN 6001 is a duplex electrical architecture with a mechanical back-up system in order to comply with the level of safety required on this type of flying demonstrator. This architecture is described in Figure No. 1 where all the components included in the fly-by-wire system are shown.

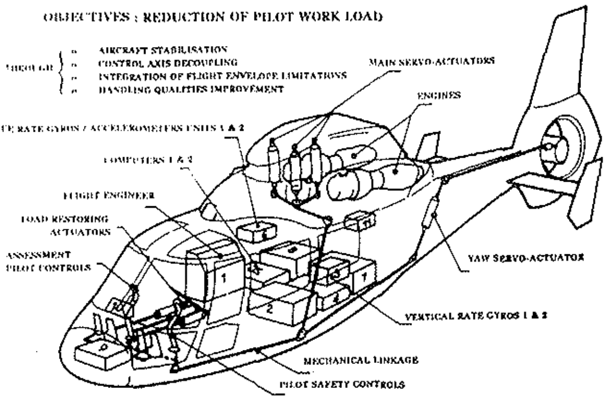


Figure 1 : Fly-by-wire aircraft demonstrator

The mechanical back-up system is provided in the left-hand position by the standard helicopter control linkage that has been retained on this flight demonstrator. This constraint, thus, required the installation of servo controls with two electrical and one mechanical input instead of the standard servo controls used up until now on series DAUPHIN aircraft. Owing to size problems, the tail servo control was retained and the fly-by-wire servo control operating the tail rotor is positioned in series with the latter. Switching to standby mode can be provided at a moment by copying of the equivalent mechanical positions to the copilot sticks, this being guaranteed by the mechanical link in the standby control linkage and the fly-by-wire servo control valves. Return to mechanical mode can be performed manually either by deliberate copilot action on his disengagement switches provided for that purpose (located on his cyclic and collective pitch sticks), by copilot load override on these controls or by the fly-by-wire system disconnecting lever located within reach of both pilots on the central console. Return to mechanical mode can also be ensured automatically on detection of a fly-by-wire system failure by means of the monitoring of operating parameters for the whole system input into the aircraft computers as well as the fly-by-wire servo controls.

Electrical control commands are generated by two aircraft computers that monitor one another. This monitoring is performed by exchange of data between the two computers to check the consistency of the data they receive and of the data they transmit to control equipment. This data concerns the received information from the various fly-by-wire system sensors (stick positions, helicopter movement state sensors and servo control position copying) and is processed internally according to the computer's control laws. These laws are used to generate the control commands to be transmitted to the servo control input stages in order to perform servo control movements that are compatible with the required control objectives. These commands are consolidated on output from the computers before being transmitted to the control equipment of each servo control.

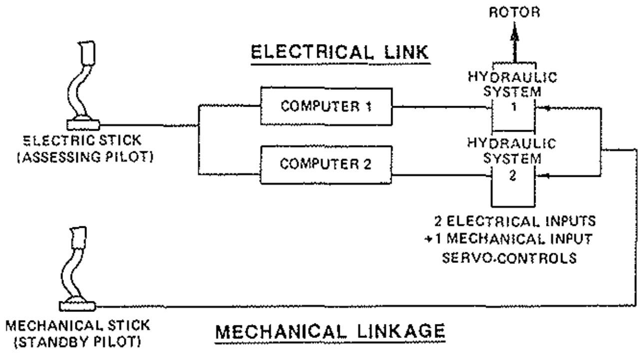


Figure 2 : Fly-by-wire general architecture

The commands transmitted by the computers are duplex and are delivered to both input stages of each servo control. These commands are monitored on entry into each servo control to check the consistency of the information from each computer. This monitoring is performed by an electronic system installed inside each servo control. The input stages have the task of slaving the commands from the two control valves which move the two servo control bodies.

The sensors used in the fly-by-wire system are, thus, duplicated, each set of sensors keeping its corresponding computer informed. The performances of the sensors used in this experiment are totally conventional and use data of gyrometric, gyroscopic, accelerometric and barometric types.

The electrical mode is engaged from a control box on which the different switches for the various fly-by-wire system operating modes are arranged. In particular, the "pre-flight test" functions, which allow the correct operation of the system and the "synchronizing mode" to be checked on the ground, are engaged directly from this control box. The latter mode must be engaged before any electrical mode engagement in order to avoid hard-overs on the servo controls. It consists of synchronizing the whole electrical flight control system (electrical sticks, computers) on the basis of the mechanical positions set before the engagement phase by the safety pilot via the standby mechanical control linkage. The synchronization of the electrical flight controls is checked by means of an indicator light installed directly on the control box thus allowing the switching to electrical mode. The electrical mode engagement lever is self-held, once it has been engaged, with self-holding being released after any system failure detection or any deliberate action by the flying crew and this disengagement resulting in mandatory return to mechanical mode. To facilitate the testing, this control box is equipped with a control law selector which allows several types of control law on the same manoeuvres or in the same flying conditions to be tested during a single flight.

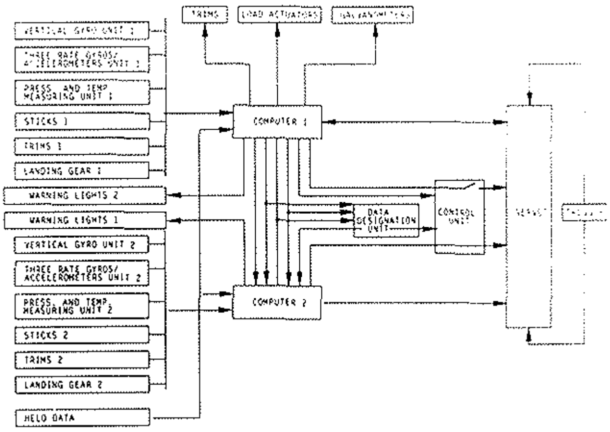


Figure 3 : Synoptics of FBW architecture

The flight engineer is provided with a data selection station which allows him, on the one hand, to input pre-programmed calibrated stimuli into the system and, on the other hand, to modify the control law gains, if necessary, and to check the status of the electrical system at all times. This box can, thus, be used to trace the origin of a failure and take remedial action, if possible, when a failure occurs.

The performances of the servo controls have been increased with respect to those now installed on series-produced DAUPHIN aircraft. Their bandwidth is at 12 Hz and their maximum speed of displacement reaches 120 mm/s allowing full travel in 0.5 s.

The aircraft computers are programmed in various languages (PASCAL and LTR) thus reducing the sources of error in the programming of onboard software. An ARINC frame allows the exchange of the required information between the two computers.

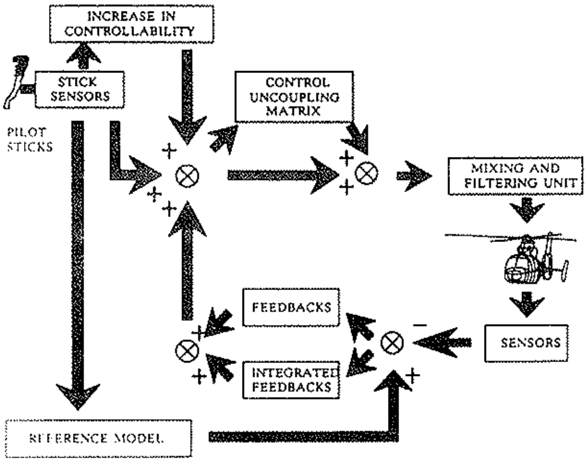
All this equipment makes up the architecture of the fly-by-wire system selected in the context of the exploratory development of the DAUPHIN 6001. The participants in this program were SFENA (for the A/C computers, the control box and the data selection station), SAMM for the servo controls and the artificial feel actuators which enable handling the loads in the pilot's sticks), and the flight test centre (for their collaboration in the in-flight assessment).

4) ARCHITECTURE OF CONTROL LAWS

The architecture of control laws assessed to date in the context of this exploratory development is based on a technique of implicit type reference model follow-up. This architecture, which is well suited to provided control by objectives, also guarantees a good degree of robustness of the control laws thus generated.

The principle consists of dynamically slaving the helicopter to a reference model representing the ideal dynamics desired on stick action. This slaving principle affords a certain flexibility in the selection of the control objectives desired, which are variable according to the requested mission, without calling into question the global architecture of the control laws. Precision between the behaviour of the helicopter and that of the reference model is guaranteed by integral feedbacks built into the control laws, which also allow the management of long term helicopter modes.

The architecture of these laws, thus, includes several functional blocks which have the role of ensuring that the helicopter has good performances in terms of axes uncoupling, stability and controllability. This can be represented in the following form.



Two feedback blocks (direct and integrated) are shown on this architecture. Their role is to ensure good dynamic stability for the helicopter throughout the flight envelope and to provide satisfactory coupling between axes. The integrated feedbacks also allow slaving of the helicopter in the medium/long term to the reference model in order to achieve the control objectives required by the pilot via his stick movements. The "control uncoupling" block is only there to facilitate the task of control laws in the uncoupling of helicopter axes on pilot-controlled actions.

The "increase in controllability" block allows the temporary modification of the instantaneous control set value in order to increase the helicopter's apparent controllability, if required.

The "mixing unit and filtering" block represents control mixing at output from the computers in order to actuate the input stages of the four DAUPHIN 6001 servo controls. The filtering shown in this architecture corresponds to the elimination of vibration natural frequencies that are found directly on the received information required to prepare the control laws. The re-introduction of these vibration frequencies on the servo controls is completely pointless and, even, dangerous in case of resonance. The equivalent dephasing induced by the introduction of this filtering can result in a pure delay equivalent to 50 ms at 2 Hz, i.e. in the control frequencies dealt with by the control laws.

5) QUALITATIVE ASSESSMENT RESULTS

5-1) Choice of control objectives

The control objectives retained at a first stage for in-flight assessment were standard and are close to the natural instantaneous behaviour of an helicopter. This deliberate choice was the result of tests performed on simulator where several control laws have been assessed to date and for which pilot advice seems to be justified by the need to be able to switch from a conventional helicopter to a new type of aircraft without too much discontinuity in the control philosophy. This industrial approach justifies the initial choice of control objectives at the beginning of the experiment, this pilot encompassing all the missions that a helicopter fulfils today without claiming to display the optimum handling qualities for each mission.

The control proposed and provided by the reference model thus consists of:

- controlling the angular rate of pitch on the longitudinal stick,
- directly controlling the collective pitch on the collective stick,
- controlling the angular rate of roll on the lateral stick guaranteed coordinated turns at cruising speed,
- controlling the angular rate of yaw at low speeds and the lateral load factor on the rudder pedals at cruising speed.

This control is effectively closer to the natural behaviour of a helicopter in the short term and, at the same time, offers much improved stability and axis uncoupling.

In order to be able to compare the performances of this control law with respect to conventional control, a direct law representing a unit transfer between pilot sticks and servo controls was implemented in the aircraft computers. This law also allowed the whole fly-by-wire system to be validated on the functional level before any experimentation on new control laws.

5-2) Pilot advice

To date, 5 pilots have assessed the control laws proposed in this exploratory development. The general opinion of pilots concerns behaviour of the law in terms of axis uncoupling and the level of stability achieved, these being visible in turbulent areas, in particular. The definition of the control law required only a few flying hours, thus showing the level of robustness of a law architecture of this type. Learning of this law proved to be instantaneous and required very few flying hours for pilots to become accustomed to it, thus justifying the choice of the control objectives retained for this first experiment. The handling qualities provided by the law comply with the simulation results and correspond to the requirements initially set in our experiment on the levels of stability and uncoupling to be achieved.

Manoeuvrability in roll seemed, in principle, too great at high speeds. This excessive manoeuvrability, which leads to pilot-induced oscillations encountered in the holding of a given attitude in turbulent conditions, is actually due to the "roll" command being input on the relevant axis after too great a delay. The excessive threshold encountered on the considered axis control stick command. This threshold is related to a poor knowledge of the roll stick neutral position (due to the measurement noise on this axis and the mechanical play in the stick). As could be thought initially, this delay is not linked to the delay in inputting the roll command (that was later assessed in the analysis of handling qualities carried out in the scope of these DAUPHIN 6001 experiments - see adjoining paragraph). This problem in the cyclic control linkage will be solved by the introduction of a ministick-type control on this axis. This control feature is awaited by the pilots who participated in this assessment campaign, since it is best switch to this type of experimental control law.

On the whole, the quality of axis uncoupling and the level of stability of the aircraft particularity in heavy turbulences, seemed totally satisfactory. Transition between cruising speeds and low speeds did not raise any specific problems in either directions.

This control law remains to be assessed for a group of set figures (typical manoeuvres representing certain mission task elements accomplished by helicopters to date). This, more pragmatic, approach should allow us to quantify the performances of this type of control, in the COOPER-HARPER scale, for the accomplishment of a given mission (in terms of helicopter flight characteristics noted by the pilot).

6) QUANTITATIVE ANALYSIS OF HANDLING QUALITIES

6-1) Frequential analysis of handling qualities

The purpose of this study is to determine the equivalent transfer functions between pilot stick and angular speeds generated by stick action. The analysis of the latter provides information on the performances of the control laws in terms of delay time and equivalent bandwidths in order to assess the position with respect to proposed new handling quality standards, now proposed in ADS.33C.

For this determination, stick inputs of the sinusoidal type with variable frequencies, applied manually by the pilot, allow a coherent frequential analysis of the helicopter's generated temporal responses to be carried out and the characteristics of the desired transfer functions to be deduced. These transfer functions are shown in appendix (Fig. 4-9) and enable deducing the performances of the control law, in terms of equivalent bandwidth and of delay in inputting the stick actions on the three axes (roll, pitch, yaw).The analysis of the collective axis is not performed as this axis remains conventional with respect to a mechanical control.

The spectral analysis of the signals recorded on the three axes allow us to determine the coefficient of the various desired transfer functions in the following canonic form:

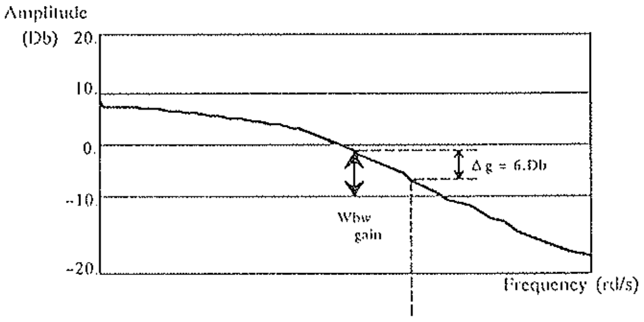
$$\frac{\text{attitude}}{\text{Stick}} = \frac{K.\exp(-\tau .s).w_n^2}{s.(w_n^2 + 2\rho \ . \ w_n \ .s + s^2)}$$

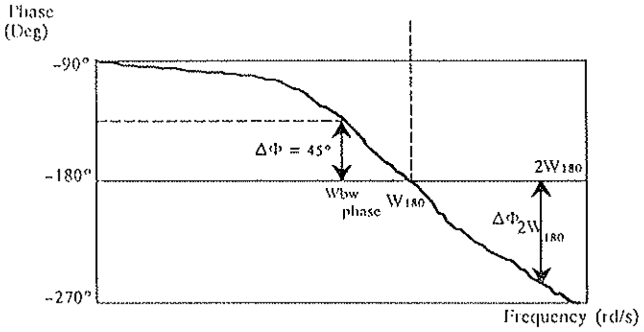
On the basis of these transfer functions and their representation in Bode form, it is possible to identify the τ equivalent pure delay as well as the Wbw equivalent bandwidth of the helicopter on each axis.

Delay τ is obtained directly by the following formula:

$$\tau = \frac{\Delta\Phi_{2W_{180}}}{57.3\ (2W_{180})}$$

The pulse W_{180} corresponds to the cutout pulse relative to 180° dephasing on the Bode diagram and ΔΦ2W180 corresponds to the dephasing deviation between that obtained at the dual pulse of W_{180} and at 180°.





In our case of control by objectives (angular speeds), the bandwidth Wbw for each axis is given by the minimum of Wbw phase and Wbw gain obtained for each transfer function.

The results obtained for the different axes and on the law by objectives are shown in appendix (Fig. 4-9). These correspond to the transfer functions for the various axes identified for two level flight points (relative to IAS < 40 kts, IAS = 80 kts). The numerical values obtained for the equivalent pure delay for each axis and the corresponding bandwidth are shown herebelow.

Transfer function for IAS < 40 kts

Roll axis

The equivalent delay for this axis is equal to : τ = 0.16 sec
The Wbw bandwidth obtained on this axis is equal to : WbW = 2.6 rd/s

Pitch axis

The equivalent delay for this axis is equal to : τ = 0.17 sec

The Wbw bandwidth obtained on this axis is equal to : WbW = 1.9 rd/s

Yaw axis

The equivalent delay for this axis is equal to : τ = 0.15 sec

The Wbw bandwidth obtained on this axis is equal to : WbW = 1.9 rd/s

Transfer function for IAS = 80 kts

Roll axis

The equivalent delay for this axis is equal to : τ = 0.15 sec

The Wbw bandwidth obtained on this axis is equal to : WbW = 1.9 rd/s

Pitch axis

The equivalent delay for this axis is equal to : τ = 0.19 sec
The Wbw bandwidth obtained on this axis is equal to : WbW = 2.6 rd/s

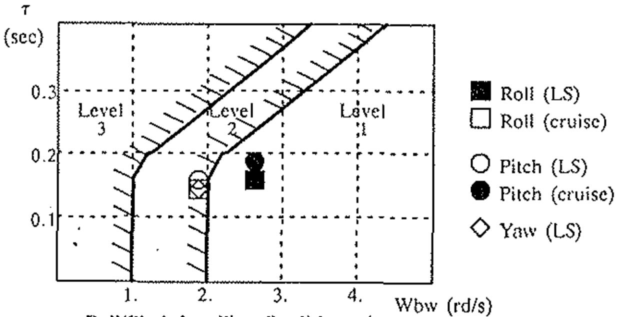
Yaw axis

The equivalent delay for this axis is equal to : τ = 0.14 sec

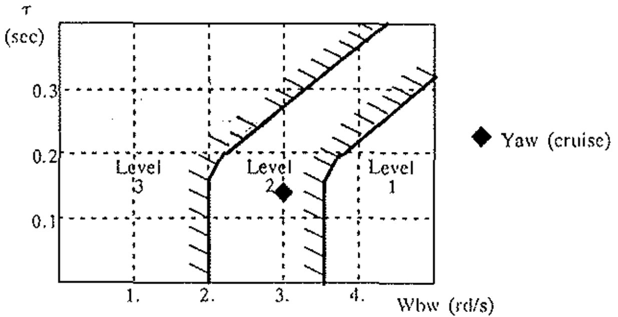
The Wbw bandwidth obtained on this axis is equal to : WbW = 2.9 rd/s

Taking these result into account and referring to the handling quality criteria suggested in the proposed new ADS.33.C standard, we know that the DAUPHIN 6001 equipped with this developed control law is positioned at the boundary of the level 1 unit on the three axes. Since the initial objective was not the optimization of this manoeuvrability, the results are deemed globally satisfactory. The bandwidth will remain to be further improved on the three axes, so as to obtain higher degree of freedom in the adjustment of this controllability.

These results are synthesized by the diagrams shown herebelow, representing the criteria retained for our study.



Roll/Pitch handling Qualities criteria
Yaw handling Qualities criteria retained at low speeds (LS)



Yaw handling qualities criteria retained at cruising speed

Analysis of the helicopter stability in closed loop configuration allows us to represent the modes obtained in closed loop with the control law by objectives (Fig. 12-13). The degree of robustness of the control law related to the concentration of modes in the damping cone relative to $\rho = 0.6$ will be noted for the whole flight envelope. (The EVANS locations shown in appendix are relative to sweeping operations on DAUPHIN 6001 speeds from hover to V.N.E.). For comparison, the helicopter's specific modes obtained by direct law are also shown (Fig. 10-11). (The divergence of the phugoid modes visible in open loop configuration and their convergence obtained in closed loop configuration will be noted).

6-2) Temporal analysis of handling qualities

Analysis of axes uncoupling

This analysis consists of checking the quality of uncoupling between axes after inputs applied to each one. The results obtained in flight are shown in appendix (Fig. 14-17), revealing the various steps applied on the various axes and the resulting manoeuvres of the helicopter for several flight configurations.

The satisfactory behaviour of uncoupling between axes for the whole flight envelope will be noted, particularly for the medium/long term, the short term not being totally mastered due to the lack of provision of sufficient information on the control laws.

To improve the latter case, the provision of values derived from the angular speeds would be a sufficient method of countering the instantaneous manoeuvres that are not yet mastered, this information consists, in fact, in managing the rotor flapping angles.

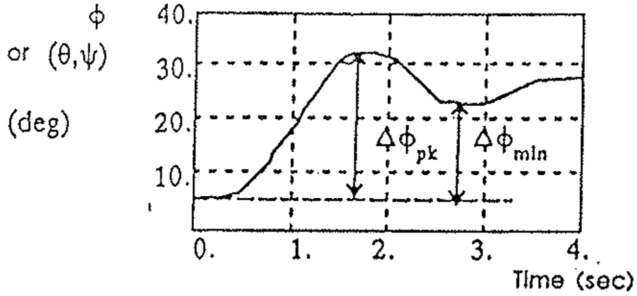
Controllability study

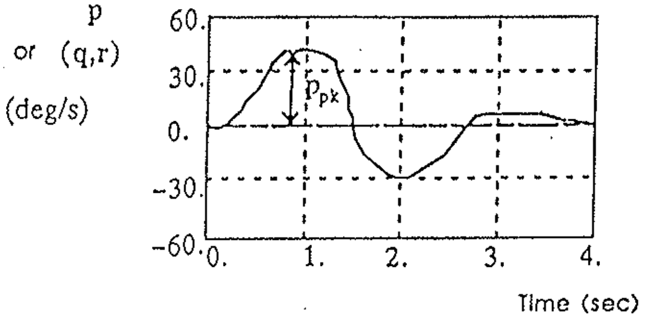
The second aspect of the temporal analysis consisted in studying the angular speed peaks obtained with moderate-amplitude attitude changes. This analysis was performed on all three axes: roll, pitch and yaw. The results obtained on these three axes are shown in the following diagrams, in compliance with the proposal of standard ADS.33.C.

The stick actions inputted on each axis were reasonable in this first experiment, with no attempt to reach too fast attitude variations as felt by the pilot. These first results show that level 2 of standard ADS.33C is reached.

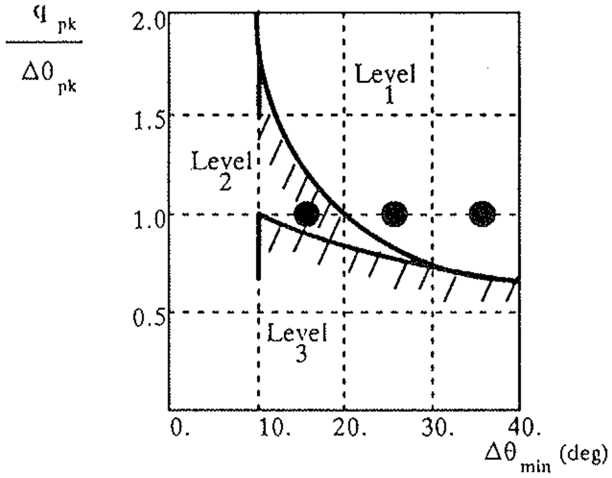
We still have to improve this controllability by faster stick actions, with wider amplitude (the results shown in the controllability diagram below correspond to 10-30 % stick actions over 1 sec.).

The definition taken is ΔΘpk, ΔΦpk, ΔΨpk and **q**pk, **p**pk, **p**pk, **r**pk:

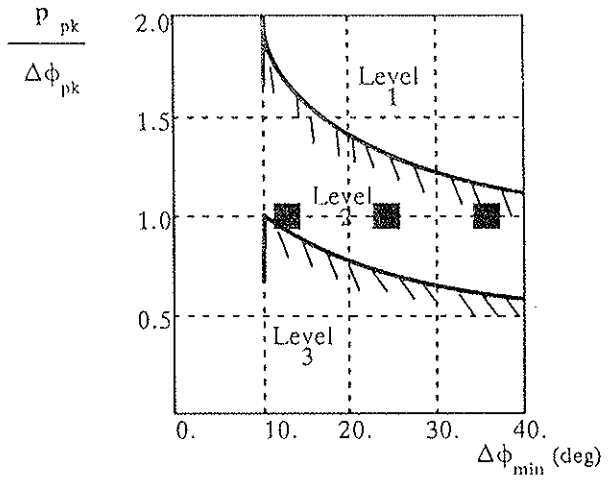




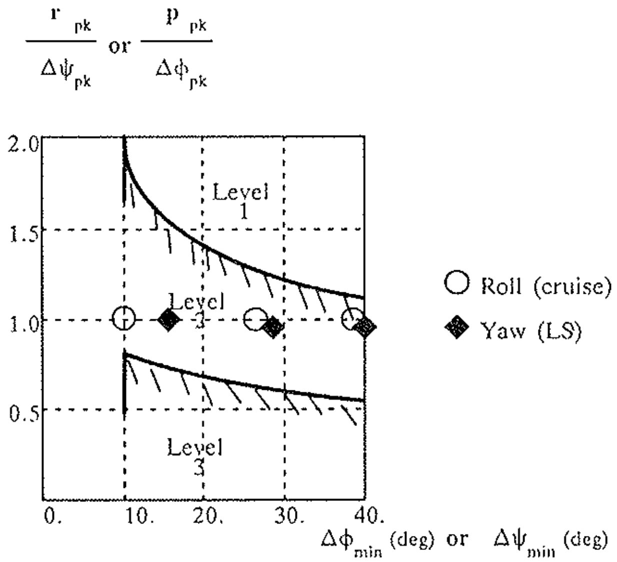
The results obtained on the various axes were as follows:



Controllability criteria in pitch (low speeds)



Controllability criteria in roll (low speeds)



Controllability criteria in yaw (low speeds) and roll (high speeds)

7) CONCLUSION

The fly-by-wire system, which is promising in the degrees of freedom that it offers, opens an interesting road in the provision of optimum handling qualities for our future helicopters. The exploratory development carried out in the context of the DAUPHIN 6001 was dedicated to the search for new control concepts with a view to alleviating the pilot's workload in mastering his aircraft. This approach, which was predominantly of an industrial nature at a first stage, produced fairly satisfying results with respect to the robustness of the control laws generated in this manner (rapid definition). The duplex architecture of the fly-by-wire system retained for this experiment is far from being representative of the architecture of NH90 helicopter. Nevertheless, this experiment provides a wealth of information on the problems that may be encountered in the creation of this new type of flight controls.

These first experiments, rather promising, enable assessing a new type of flight control, with better ergonomic features and better suited to the helicopter cockpit available room requirements. This new type of stick will be experimented on DAUPHIN 6001 helicopter in the next few days, so as to assess the control performances obtained with these controls, all integrated.

Certain concepts remain to be studied in depth, such as the management of the limits of flight envelopes which, today, represents a relatively major work load for the pilot and may sometimes limit the aggressiveness of his manoeuvres. The evaluation of more traditional control concepts will also be performed in the scope of this exploratory development in order to comply with the logic of the development of NH90 laws. This logic involves considering only control concepts that are standard and familiar to pilot at a first stage before going on, at a second stage, to more futuristic concepts such as those assessed up to now in the scope of this exploratory development.

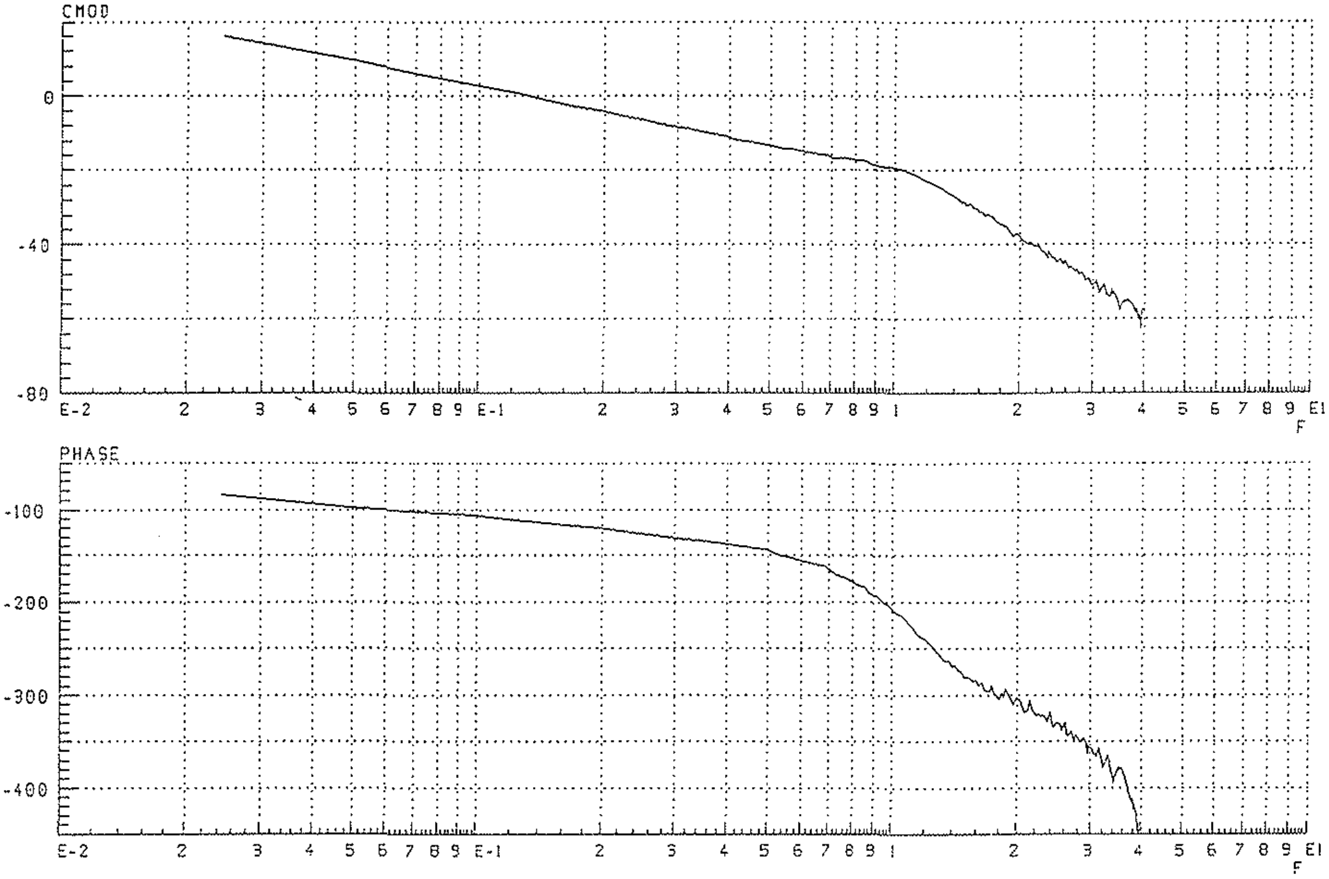


Figure 4 : Pitch Transfer θ/θ_{2m} *(vi = 80 kts)*

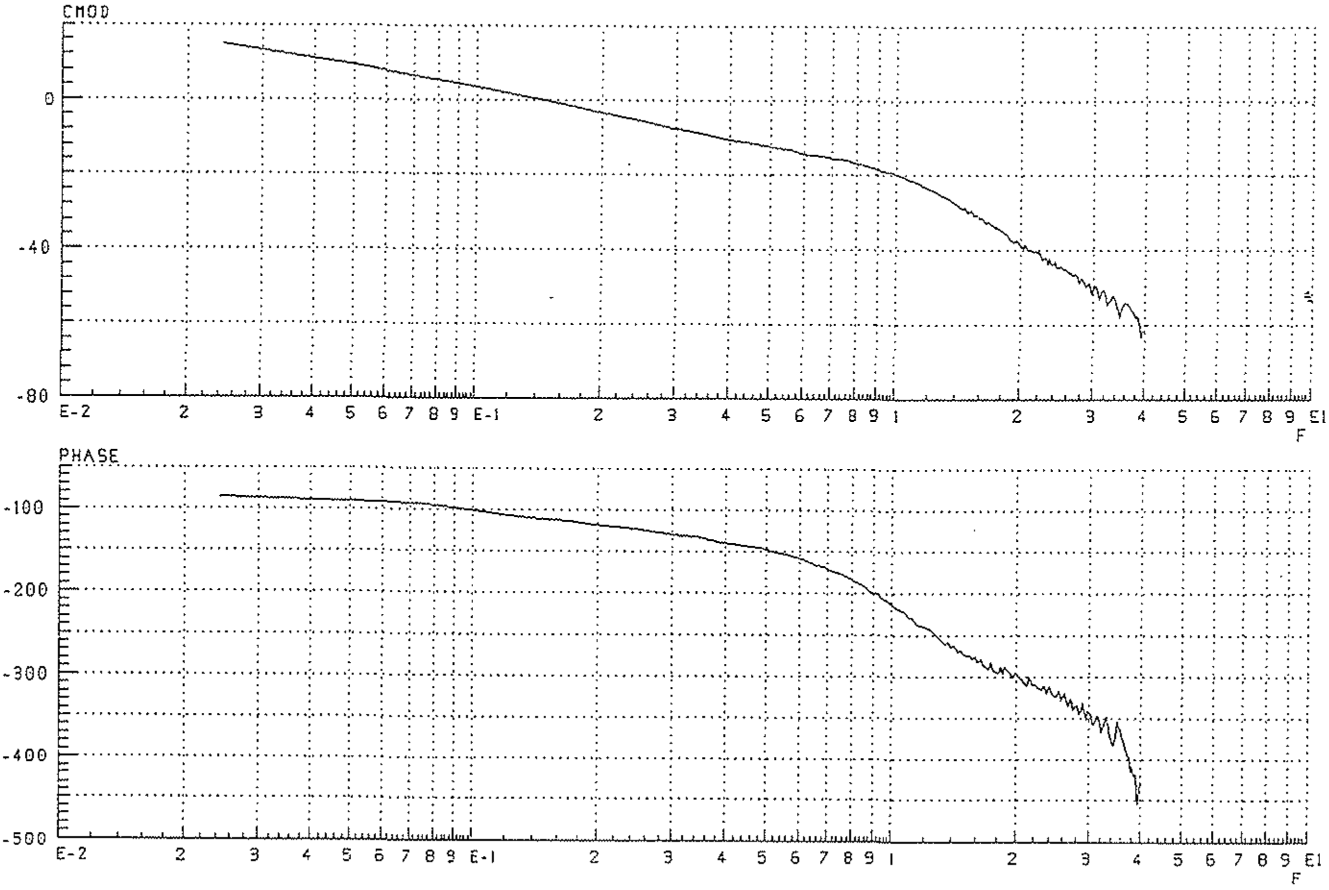


Figure 5 : Pitch Transfer θ/θ_{2m} *(Hover)*

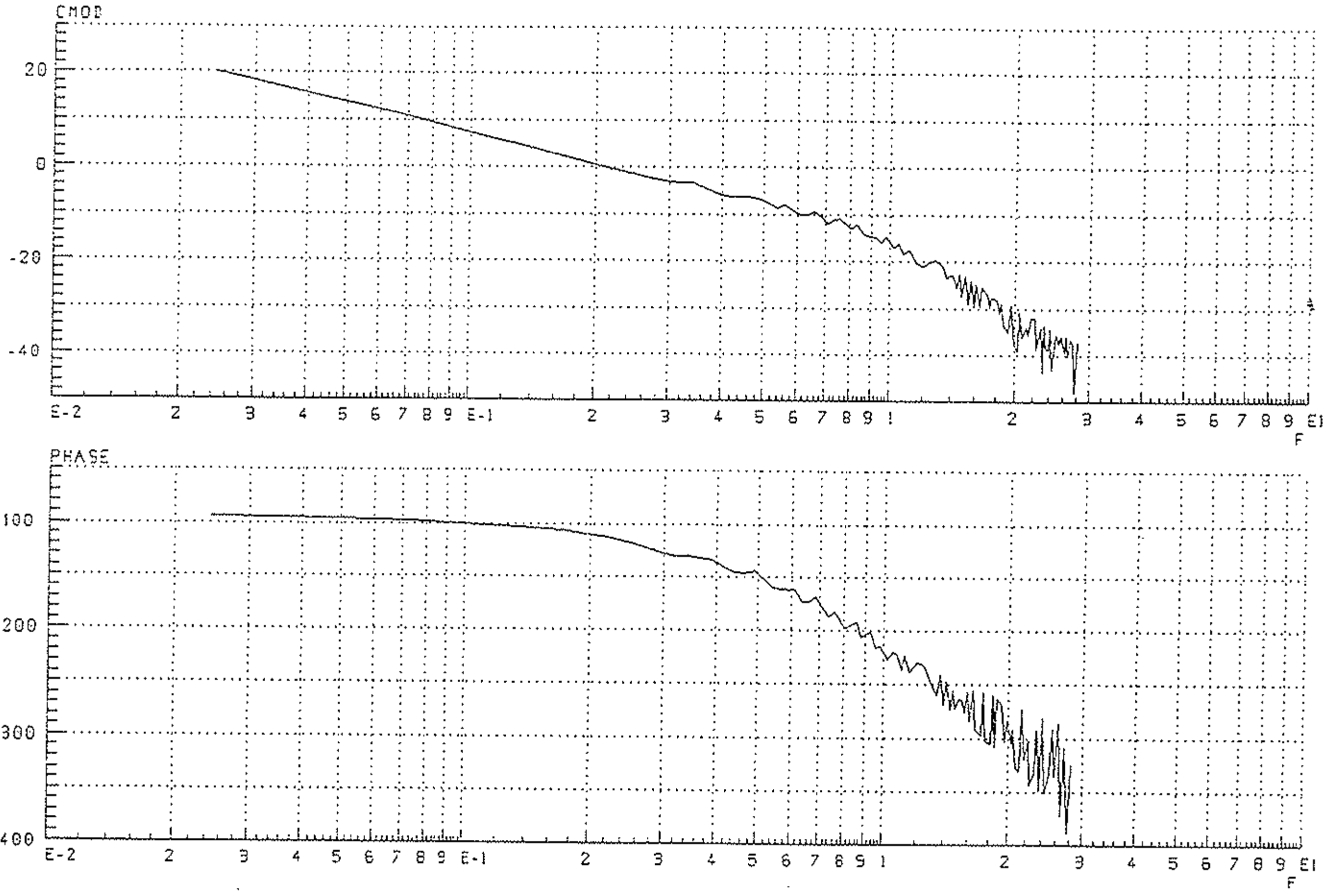


Figure 6 : Roll Transfer φ/θ_{1m} (vi = 80 kts)

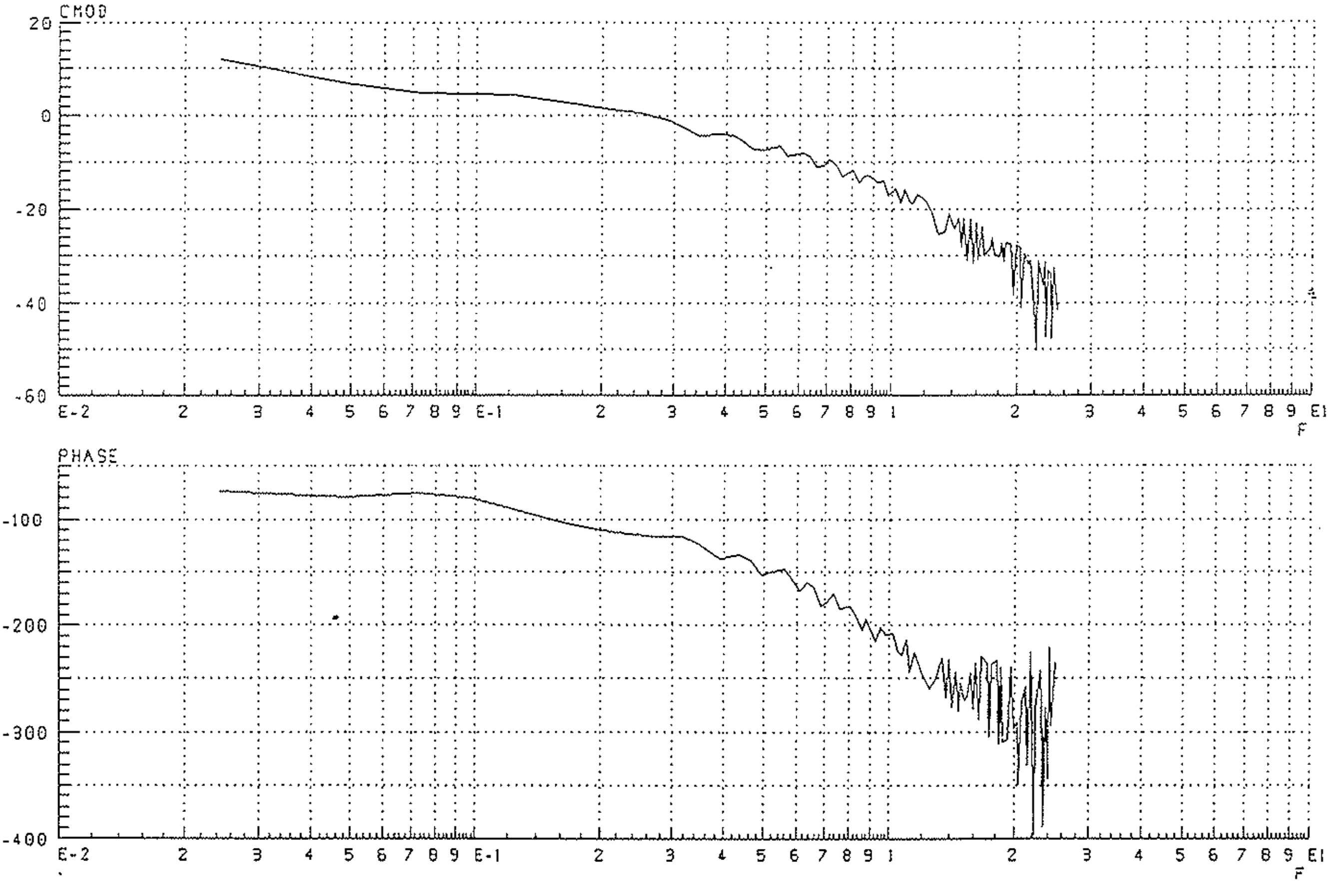


Figure 7 : Roll Transfer φ/θ_{1m} (Hover)

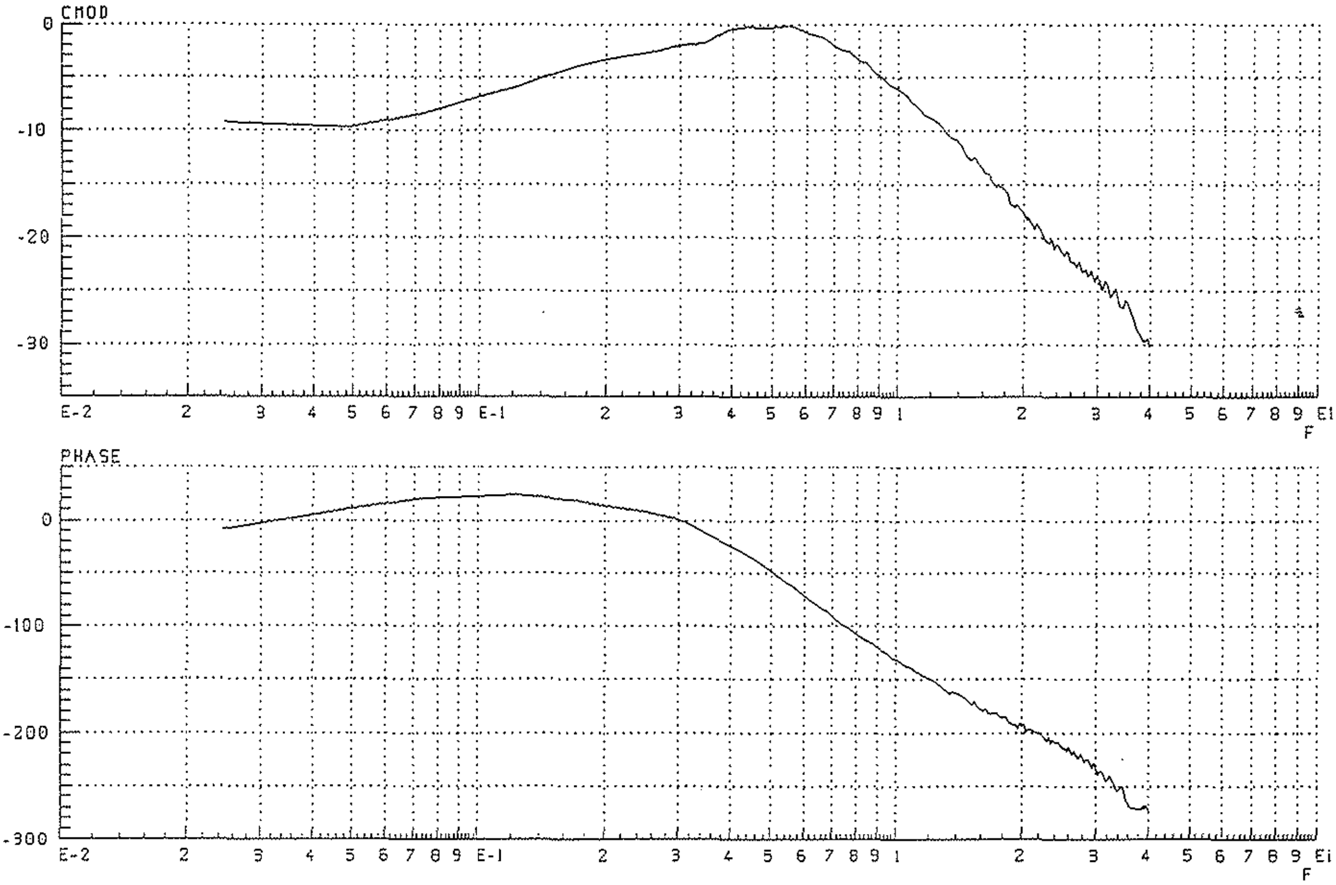


Figure 8 : Yaw Transfer $^{r}/\theta_{rm}$ *(vi = 80 kts)*

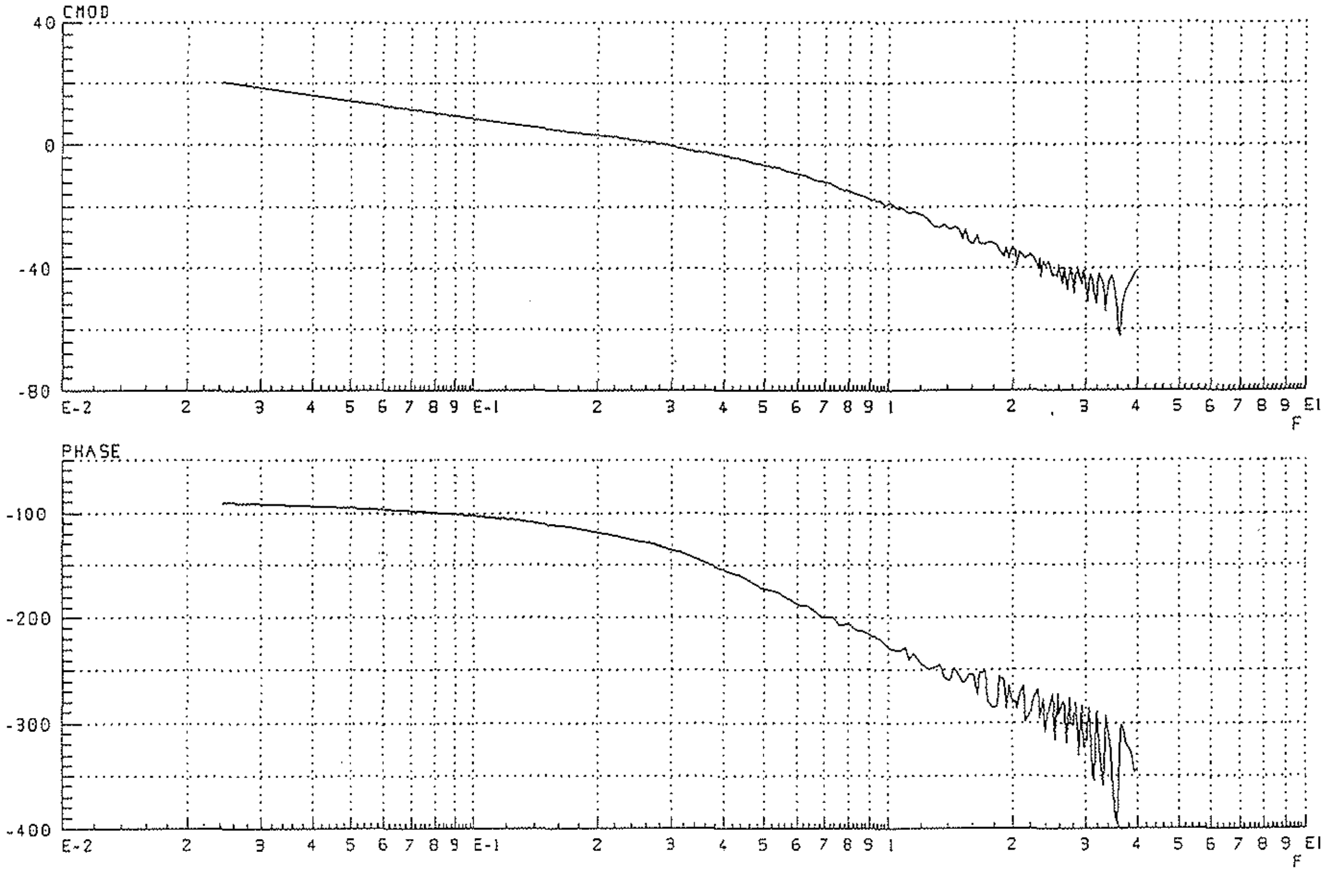


Figure 9 : Yaw Transfer ψ/θ_{rm} *(Hover)*

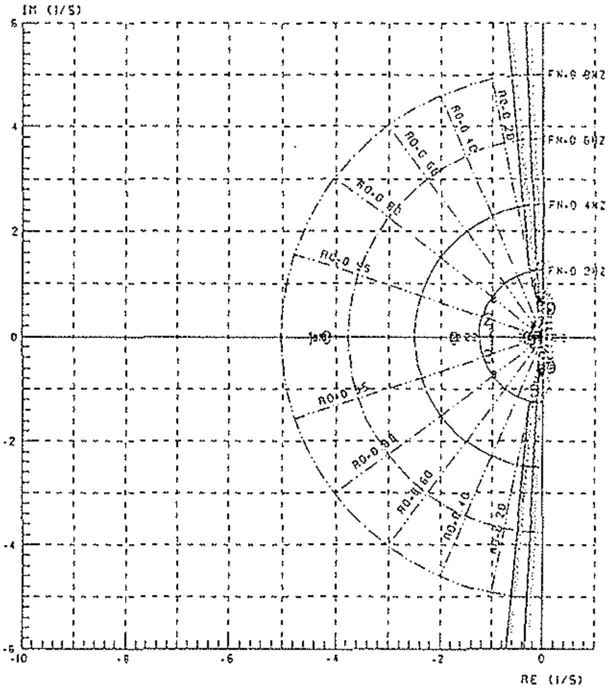


Figure 10 : Open Loop Stability (0 kts < vi < 40 kts)

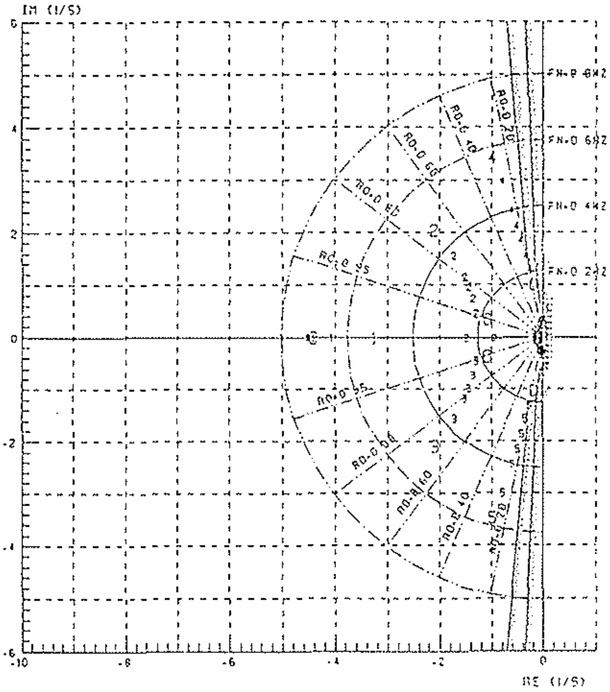


Figure 11 : Open Loop Stability (40 kts < vi < 175 kts)

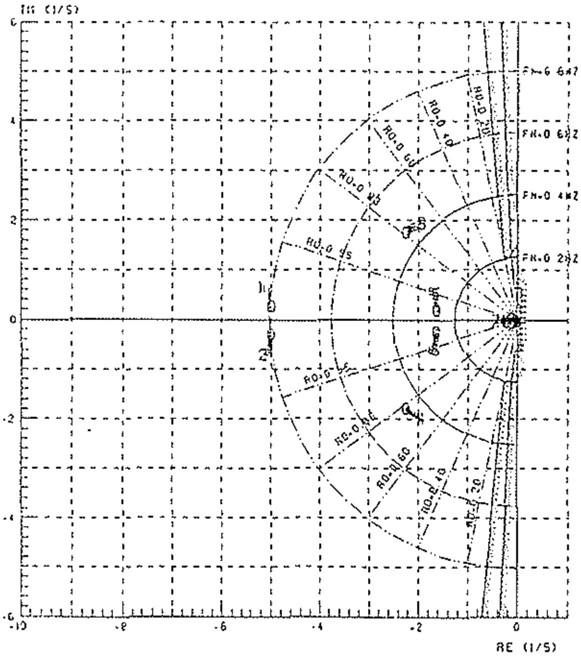


Figure 12 : Closed Loop Stability (0 kts < vi < 40 kts)

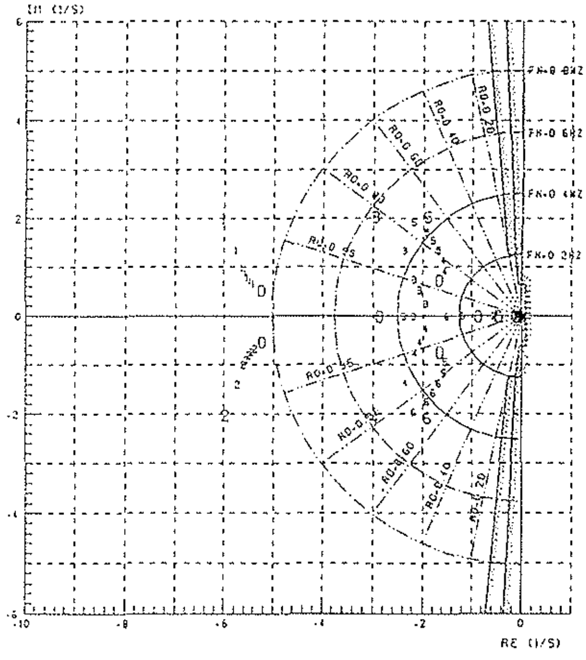


Figure 13 : Closed Loop Stability (40 kts < vi < 175 kts)

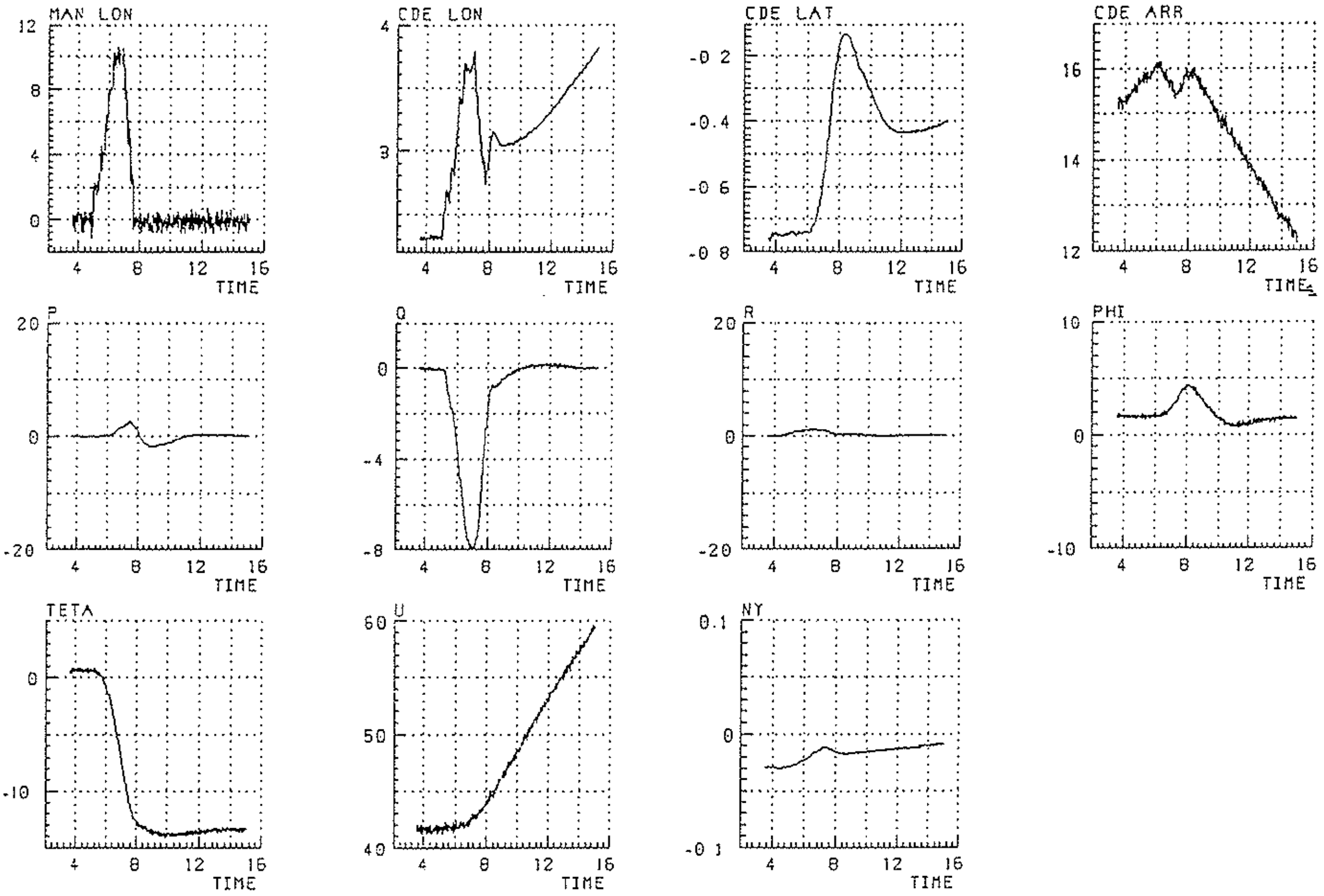


Figure 14 : Step On Pitch Axis (vi = 80 kts)

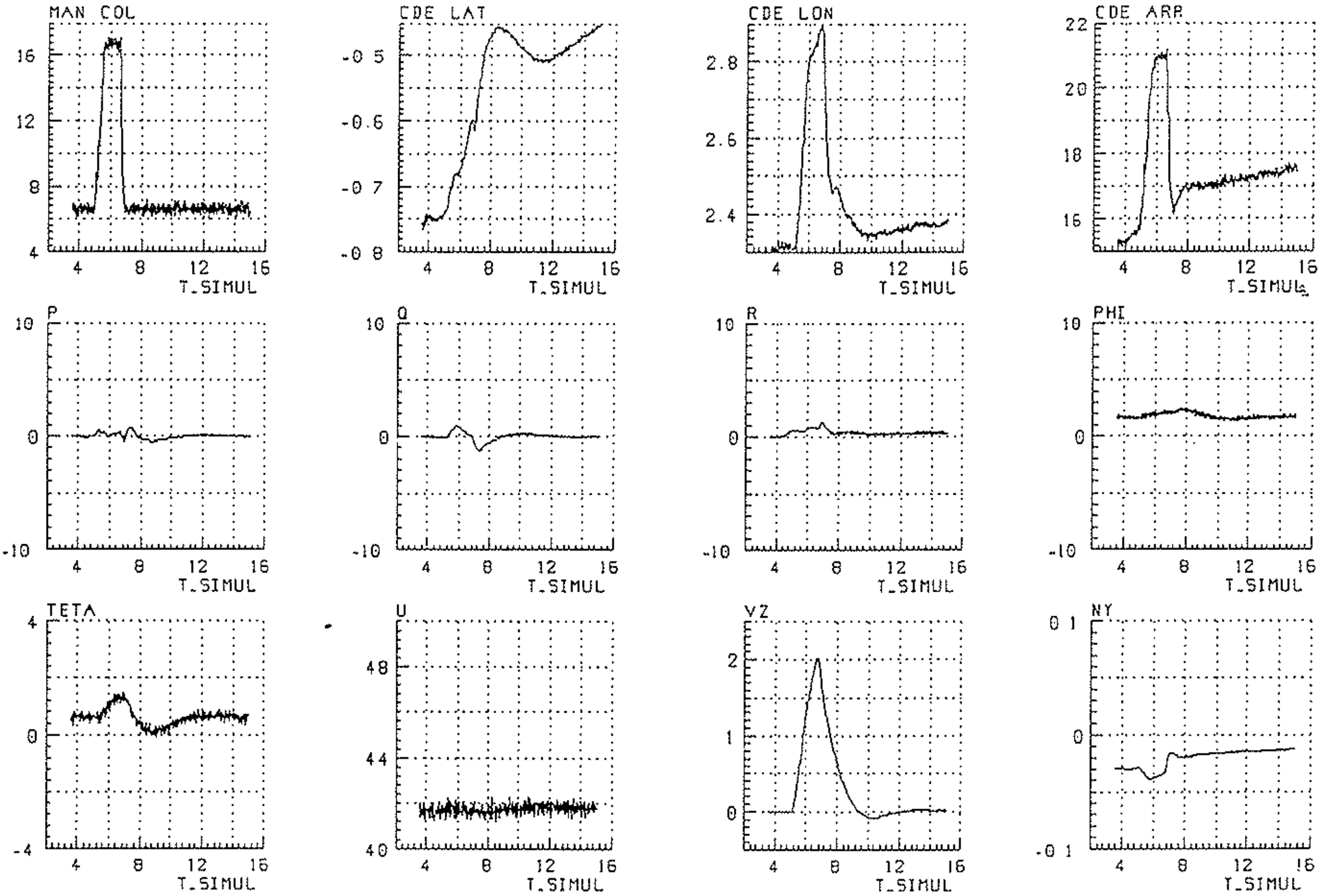


Figure 15 : Step On Collective Axis (vi = 80 kts)

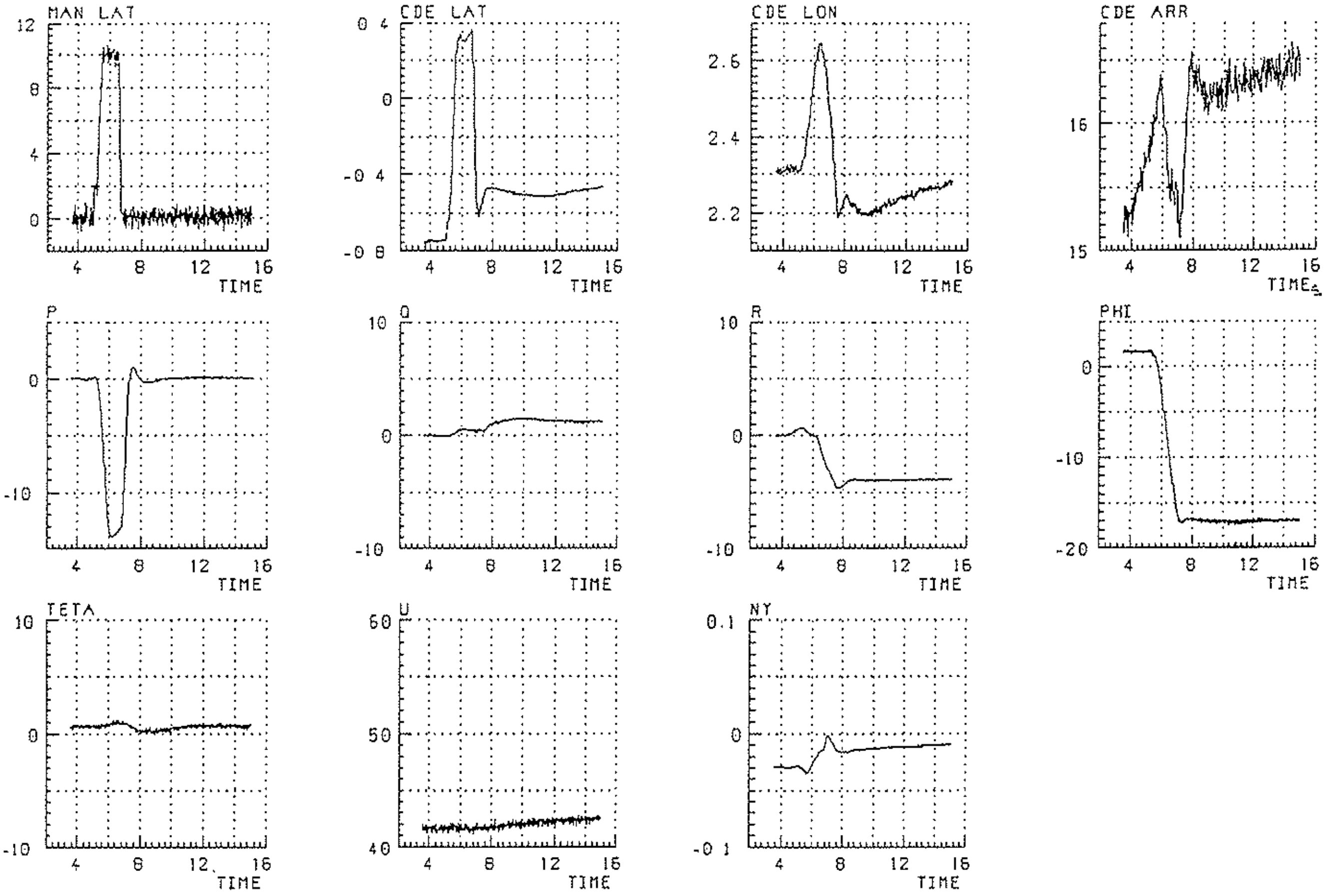


Figure 16 : Step On Roll Axis (vi = 80 kts)

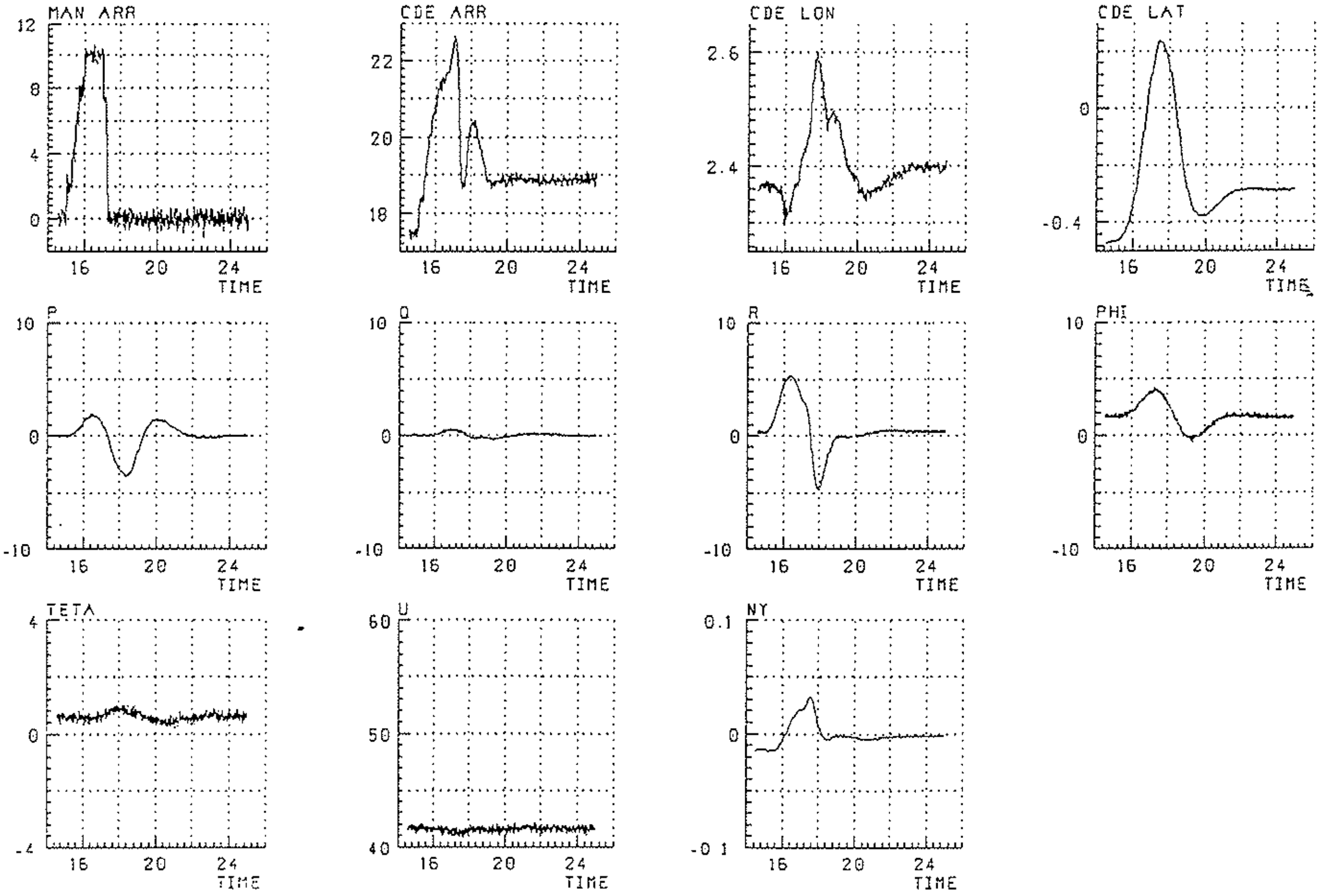


Figure 17 : Step on Yaw Axis (vi = 80 kts)