ACTIVE CONTROL OF AEROMECHANICAL STABILITY APPLIED BY EUROCOPTER.

by

Philippe ALMERAS
Dynamics Engineer
EUROCOPTER

SUMMARY

This paper presents the active control of aeromechanical stability as a powerful means of simplifying rotor design in future helicopters.

The mathematical simulation models are presented and the results are compared to flight test data.

The active control of ground and air resonance has been fully validated with flight tests in the Super Puma Mk2 helicopter which behaved in a highly efficient and robust manner.

The active control for drive train stability had already been tested in the Super Puma MK2 with good results.

The proposed controls are simple and easy to integrate in a conventional Flight Control System (FCS).

The actuators avalaible in the current FCS are sufficient as far as bandwidth required for the active control of aeromechanical stability is concerned.

With the generation of fly-by-wire AFCS helicopters, active control of aeromechanical stability shall be very easy to develop at a low cost. To give an example, it is envisaged on the NH90 helicopter to integrate active control for air resonance and drive train stability in order to simplify the interblade damper technology.

Notations:

b	number of blades
u	vector of control inputs
X	vector of coordinates
X_0	vector of equilibrium position
x	vector of state space
y	vector of output measurements
x,y,z	longitudinal, lateral and vertical translations of the fuselage mass center
$\alpha_x, \alpha_y, \alpha_z$	roll, pitch and yaw rotations about the helicopter body
β_i, δ_i	flap and lead-lag angle of blade i
θ_i	pitch angle about the blade i
$\theta_{MR}, \theta_{MGB}, \theta_{ENG1}, \theta_{ENG2}, \theta_{TR}$	drive train rotations
Ω	rotor speed
NG	engine gaz generator turbine speed
NTL	engine free turbine speed

1. INTRODUCTION

Designing and developing reliable main rotor head dampers has always been a particular concern for helicopter manufacturers because they represent a significant share of both the initial and direct operating costs.

Lead-lag dampers increase the maintenance, weight, volume and complexity of rotor systems. They are fitted to counter aeromechanical rotor/fuselage instabilities because it is difficult for the designer to avoid ground and flight resonances.

These dampers help to tailor adjust frequency and damping in the 1st lead-lag mode. We have three categories of dampers:

- Viscoelastic dampers (frequency adapters) combining high stiffness and low damping.
- Hydraulic dampers combining high damping and low stiffness.
- A mix between viscoelastic and hydraulic technologies in some applications.

The viscoelastic category offers more avantages regarding technology but may not be sufficient enough to avoid aeromechanical instabilities, especially in heavy helicopters.

The technology (viscoelastic /hydraulic) mix can thus be helpful but combines drawbacks inherent to hydraulic and viscoelastic components such as thermal and wear problems.

The interblade hub design has been developed in order to increase the space available with a higher damper lever arm as well as reduce the hub loads for rotors with a high number of blades. Regarding aeromechanics stability, this is a risky technology due to the absence of stiffness and damping in the first drive train mode.

This short review of hub and lead-lag damper technologies underlines the difficulties inherent to the design of simple and reliable dampers meeting the stringent requirements of modern rotors.

The purpose of active control is to improve the aeromechanical stability of modern rotors as well as simplify the design of lead-lag dampers that are expected to be cancelled in bearingless rotors.

2. AEROMECHANICAL ROTOR-FUSELAGE/DRIVE TRAIN STABILITY PROBLEMS.

The helicopter's aeromechanical instability also known as air or ground resonance is the result of coupling between the rotor's lead-lag regressive mode and the body's degrees of freedom.

Ground resonance:

In ground resonance, the body modes are generated by the structure on the landing gear. Ground resonance occurs when the frequency of the fuselage on the ground corresponds to the lead-lag frequency in the fixed system.

Obtaining satisfactory stability margins is one of the prime concerns in the current helicopter design.

The main difficulty with this design is the non linearity of the lead-lag damper and the landing gear characteristics.

A stable helicopter can thus become unstable when the pilot excites ground resonance by precessing the cyclic pitch in the rotor's sense of rotation, due to the modification of dynamic characteristics with non linearity phenomena.

Air resonance:

Air resonance is similar to ground resonance and involves coupling the 1st lead-lag, the 1st flap and the rigid body fuselage mode.

Air resonance is related to:

- articulated rotors in high manoeuvres (especially for heavy helicopters). The rigid roll body mode can then be coupled with the 1st lead-lag mode through Coriolis forces.

- rotors with a high hinge offset, both hingeless and bearingless ones. An interaction between the 1st regressive lag mode and the coupled flap and fuselage mode can occur.

Drive train stability:

The helicopter drive train system is composed of rotors, engines, shafts and gears.

This system can generate different dynamic problems such as torque oscillations and rotor speed variations that degrade the handling qualities.

The helicopter drive train dynamic analysis is mainly focused on two points:

- the suitable tuning of the torsional modes of the system, providing a proper separation from the $b\Omega$ as well as $2b\Omega$ excitation frequencies. The lead-lag stiffness of the blades is often adjusted to raise this mode over $b\Omega$ and obtain a sufficient safety margin with respect to this excitation.

- the adaptation of fuel control laws engine governor to the dynamic characteristics of the system in order not to decrease the natural damping of the first torsional modes.

High engine governor gains will ensure good accelerations but can lead to unstable coupling of the first drive train mode with the engine behaviour.

The compromise between accelerations and drive train stability is the major difficulty, regarding especially interblade technology due to absence of damping from the lead-lag dampers on the 1st drive train mode.

3. AEROMECHANICAL STABILITY MODELING.

The model that was used in this study has been developed over a number of years.

The helicopter elements that were taken into consideration are shown fig. 1.

The helicopter's body is represented as a rigid fuselage with 6 degrees of freedom:
- longitudinal, lateral and vertical translations of the center of mass identified x, y and z respectively
- roll, pitch and yaw rotations about the center of mass identified α_x, α_y and α_z respectively.

The landing gear is assimilated to perfect springs and dampers in the three directions for each one (fig. 1-a).

The hinged rotor has four identical blades, assumed to be rigid. The three degrees of freedom are presented: pitch (θ), lead-lag movement (δ) and flap movement (β) (fig 1-b).

The lead-lag damper is modelized with stiffness and damping; interblade configuration is possible.

The rotor/fuselage/drive train coupling is the result of the torsion characteristics of the drive train components. This drive train is modelized with sub-assemblies (Main Rotor θ_{MR}, Main Gear Box θ_{MGB}, Engine 1 θ_{ENG1}, Engine 2 θ_{ENG2} and Tail Rotor θ_{TR}) for which equivalent mass characteristics are determined individually and set to the rotor mast rotation. The links between these components are represented with torsion springs (fig. 1-c).

The engines behaviour (gaz generator turbine and free turbine) is represented with parametric tables given by the motorist. Engine governors are modelized too (fig. 1-d).

The aerodynamic forces applied on the blades are based on classical, two-dimensional quasi-steady theory and uniform inflow.

The system's equations are expressed by the Lagrange method. The linearized periodic coefficient perturbation equations are converted into a constant coefficient system with Coleman's transformation wich proceeds as follows (four bladed rotor):

$$\beta = \beta_0 + \beta_1 .\cos(\Omega t+(i-1).\frac{\pi}{2})+ \beta_1 .\sin(\Omega t+(i-1).\frac{\pi}{2})$$
$$\delta_i = \delta_0 + \delta_{1C}.\cos(\Omega t+(i-1).\frac{\pi}{2})+\delta_{1S}.\sin(\Omega t+(i-1).\frac{\pi}{2})$$
$$\theta_i = \theta_0 + \theta_{1C}.\cos(\Omega t+(i-1).\frac{\pi}{2})+\theta_{1S}.\sin(\Omega t+(i-1).\frac{\pi}{2})$$

The system is also expressed with:

$$M.(X_0).\ddot{X}+ C(X_0).\dot{X}+ K(X_0).X = F(X_0).\theta$$

where X is the coordinates vector, X_0 is the equilibrium position vector and θ are the control inputs.

X^T=[x y z α_x, α_y α_z β_0 β_{1C} β_{1S} δ_0 δ_{1C} δ_{1S} θ_{MR} θ_{MGB} θ_{ENG1} θ_{ENG2} θ_{TR}]

θ^T=[θ_0 θ_{1C} θ_{1S}].

The Automatic Flight Control System (AFCS) can be modelized with all actuators transfer functions (serial actuators, servoactuators...).

Then, the equations are transformed into a first order form:

$\dot{x}$=A.x+B.u
y=C.x
where x is the state space variable vector, y is the output measurements vector and u is the input excitations vector.
This form is also used to compute time history responses as well as frequency response with the MATLAB tool.

4. ACTIVE CONTROL OF AEROMECHANICAL STABILITY

The very interesting point for the active control of the aeromechanical stability concept is that the actuators (hydraulic or electrical units) used in classical FCS are compatible with the control frequencies due to their very low values (less than 1/REV).

It can be pointed out that the conventional Stability Augmentation System (SAS) installed in many helicopters uses body pitch and roll rate feedback to the longitudinal and lateral cyclic controls to stabilize the helicopter's pitch and roll motions.

It is well known that improper design of a high bandwidth FCS can destabilize a helicopter air or ground resonance modes (the problem is generally solved with the introduction of a low-pass or notch filter in the FCS feedback loop to prevent reinjection of air/ground resonance oscillations into the cyclic control actuators).

This means that air/ground resonance can also be achieved provided the proper compensation is introduced in the body state feedback loop.

The first step is to select parameters that are easily available in the helicopter (accelerations, angular velocities in the fixed system) and as far as the observation variables of the phenomenon are concerned.

Then, the helicopter is identified for the phenomenon observed and the model can be preset. Control laws were developed with simulations at this stage

Ground resonance active control:

The theoretical model that helped elaborate the control strategy and the control loop is shown in Fig. 2.
Helicopter tests were performed with a Super Puma Mk2 with a specific and experimental viscoelastic damper designed to reduce the ground resonance stability of this helicopter (fig. 3).

Active control is based on the injection of a cyclic control into the rotor calculated from a parameter measured in the fixed datum.

Acceleration was selected, treated and the signal was fed as a voltage in the AFCS. The swashplate was thus processed in the rotor's sense of rotation to have the excitation at drag frequency in the rotary datum.

During the tests with a high weight helicopter, divergent oscillations were noted after excitation (fig. 4). The pilot had to take off as a result of high vibrations and loads. This unstable behaviour in ground resonance corroborated the theoretical calculations.

The closed loop was tested with controller gains and phases derived from theoretical calculations. It was shown that the system is unstable in open loop (considered unacceptable by the pilot) and perfectly stable in closed loop (time half the amplitude below 2 seconds during the certification tests).

This active control of ground resonance can easily be integrated in a classical FCS.

Air resonance active control:

A similar control strategy was decided for air resonance and for the same helicopter: Super Puma Mk2.

A specific and experimental viscoelastic damper was developed as for ground resonance to ensure stability problems on this helicopter.

The theoretical model allowed elaborating the control strategy and the control loop is similar to the ground resonance one.

The observation parameters were the angular roll and pitch velocities.

A comparison of calculations and measurements is presented (fig. 5) and it can be noted that measurements compare very favourably with theoretical predictions.

During tests the helicopter was in turn and the pilot excited the air resonance mode with a longitudinal cyclic stick maneuver: the time history responses in open and closed loop show the high efficiency of the active control (fig. 6).

The frequency responses comparison shows the suitable control in phase and gain to suppress the mode response (fig. 7).

An active air resonance stability control is envisaged on the NH90 helicopter in order to simplify the current interblade damper technology. The first flight tests were very satisfactory.

Active control for drive train stability:

Theoretical studies were also conducted for active stabilization of 1st drive train mode for interblade rotors in particular.
The objective is the reduction of high resonance in the frequency areas where engine governor laws are still active and with sufficient gains to keep good accelerations.

The theoretical model allowed elaborating the control strategy and the control loop is shown in Fig. 8.

The 1st drive mode was identified in flight prior to the active control feedback development. This identification was conducted with the main rotor collective pitch as exciter and on the Super Puma Mk2 helicopter. The parameters measured on the drive train were the main rotor's mast torque and the engine shaft's torque.

A highly significant damping increase in closed compared to open loop is shown fig. 9.

A similar control strategy was tested on the NH90 helicopter:

A comparison is presented as an example, between the temporal responses of the parameters measured and those derived by simulation (Fig. 10). The great similarity between model and tests confirm the validity of the model.

First tests were very satisfactory:
Highly significant damping increase in closed compare to open loop is shown (Fig. 11): There are 50% damping increase and 30% response attenuation.

5. CONCLUSION

Active control of aeromechanical stability is surveyed and the following conclusions are drawn:

1. Considering that weight gain and hub compactness must be improved for new generation of helicopters, there is a possibility

with active control of aeromechanical stability to simplify the design of main rotor lead-lag dampers.

2. The developed mathematical model described here to simulate the aeromechanical behaviour of the helicopter has proved its usefulness in the development of active control laws all over the domains concerned.

3. The active control of ground and air resonance was fully validated with flight tests in the *Super Puma Mk2 helicopter* with modified, low damping, lead-lag dampers.

4. *Every controller that was proposed* can easily be integrated in a classical FCS. The current FCS actuators are sufficient as far as the bandwidth required for active control is concerned.

5. With the generation of fly-by-wire AFCS helicopters, active control of aeromechanical stability will be very easy to develop at low cost.

As an example, it is envisaged on the NH90 helicopter to integrate active control for air resonance and drive train stability in order to simplify the interblade damper technology.

6. REFERENCES

1. T. KRYSINSKI
"Active Control of Aeromechanical stability"
Agard symposium "advances in Rotorcraft Technology", 27-30 may 1996 Ottawa.

2. WALKER W.R.
"A review of helicopter aerolastic stability research", La Recherche Aérospatiale, 1995, n°1, 15-27

3. STRAUB F.K. and WARMBRODT W.
"The use of Active Controls to Augment Rotor /Fuselage Stability", Journal of the American Helicopter Society,
Vol. 30, n°3, July, pp. 13-22.

4. NAHAS
"Helicopter Ground Resonance" A Spacial Model Analysis, Aeronautical Journal,
1984, pp. *299-307*.

5. JOHNSON W.
Helicopter Theory
1980, Princeton University Press

6. COLEMAN R.P. and FEINGOLD A.M.
"Theory of self-excited Mechanical Oscillations of rotores with Hinged Blades",
NACA report 1351, 1958.

7. ACHACHE M., POLYCHRONIADIS M.
"Development of an Experimental System for Active Control of Vibration on Helicopters - Development Methodology for an Airbone System" - 12th ERF - Garmisch Partenkirchen, sept. 86

8. POLYCHRONIADIS M.
"Generalized Higher Harmonic Control Ten Years of Aerospatiale Experience"
16th ERF, Glasgow, sept. 90

9. Ph. ROESCH, M. ALLONGUE,
M. ACHACHE
"Towards generalized active control of helicopters"
19th European Rotorcraft Forum Italy,
Sept. 1993

10. M. ALLONGUE, T. KRYSINSKI
"Validation of New General Aerospatiale Aeroelastic Rotor Model through the wind tunnel and flight test data"
46th AHS Annual Forum
Washington USA, 1989

11. B. GUIMBAL
"Design, evaluation and proof-of-concept flights of a main rotor interblade viscoelastic damping system"
14th European Rotorcraft Forum Italy,
Sept. 1988

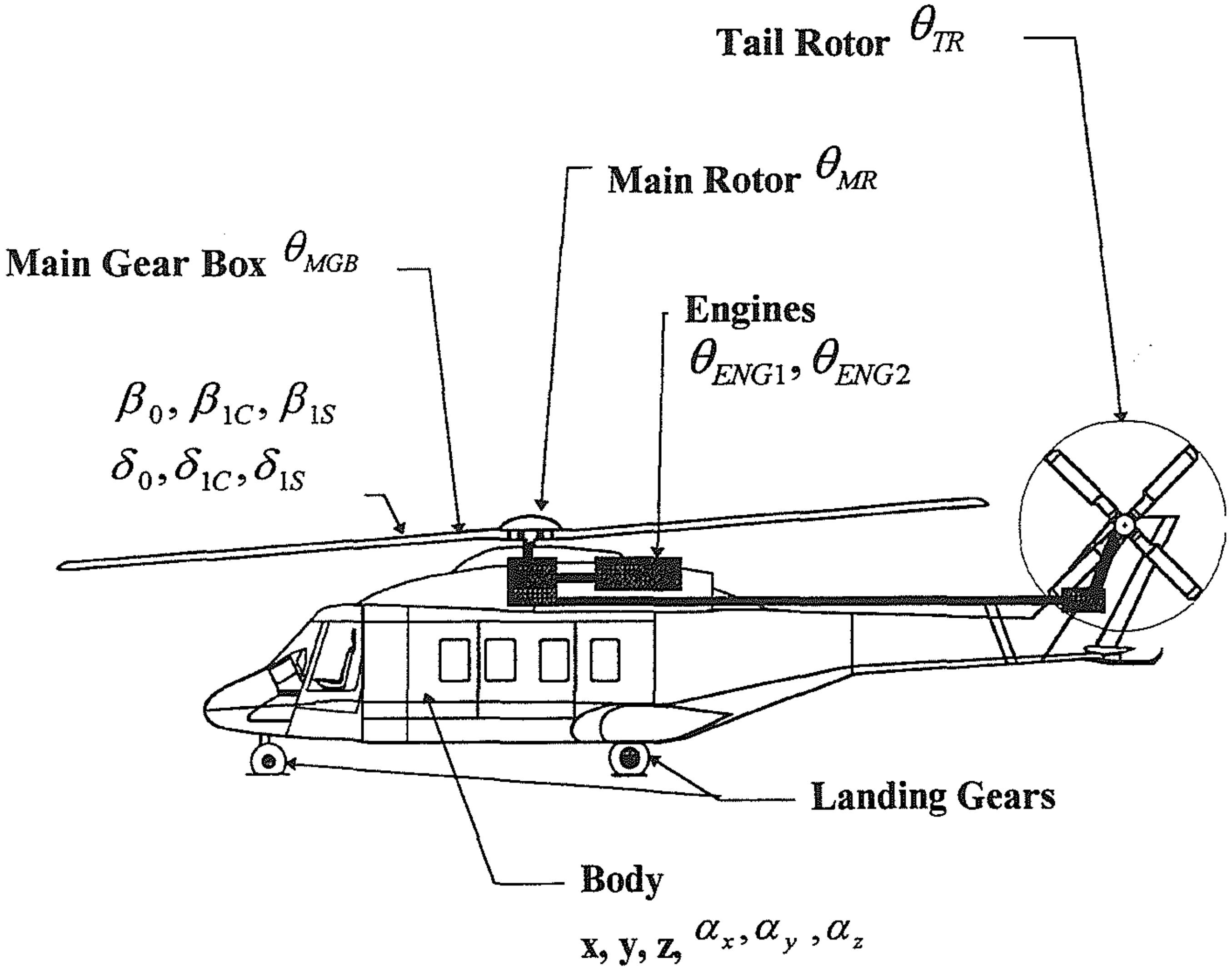


Fig. 1: AEROMECHANICAL STABILITY MODELING

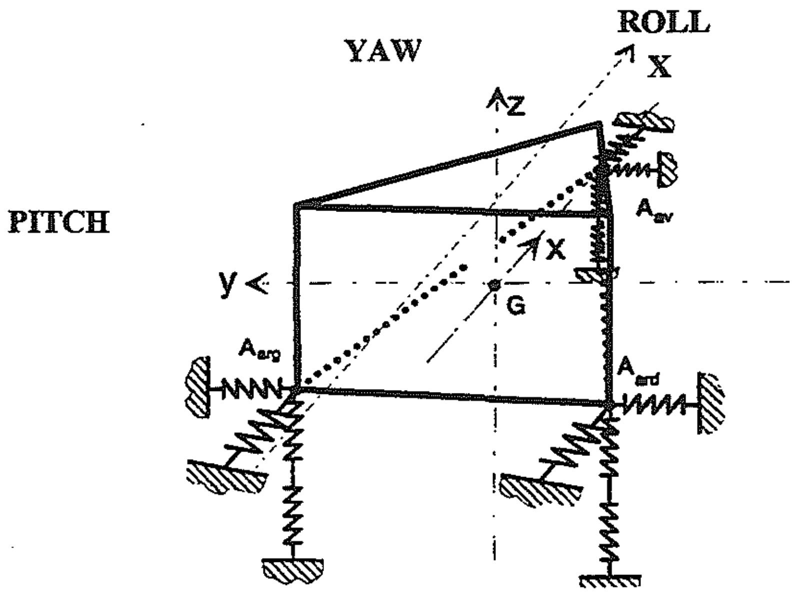


Fig. 1-a: Landing gear modelisation

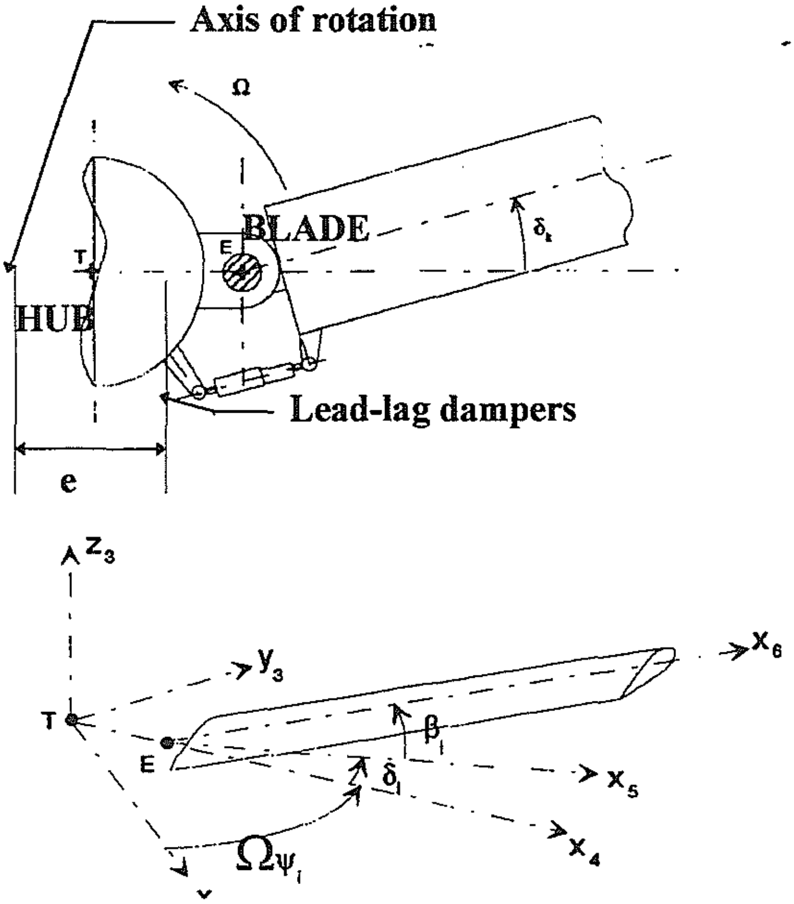


Fig. 1-b: Blade modeling

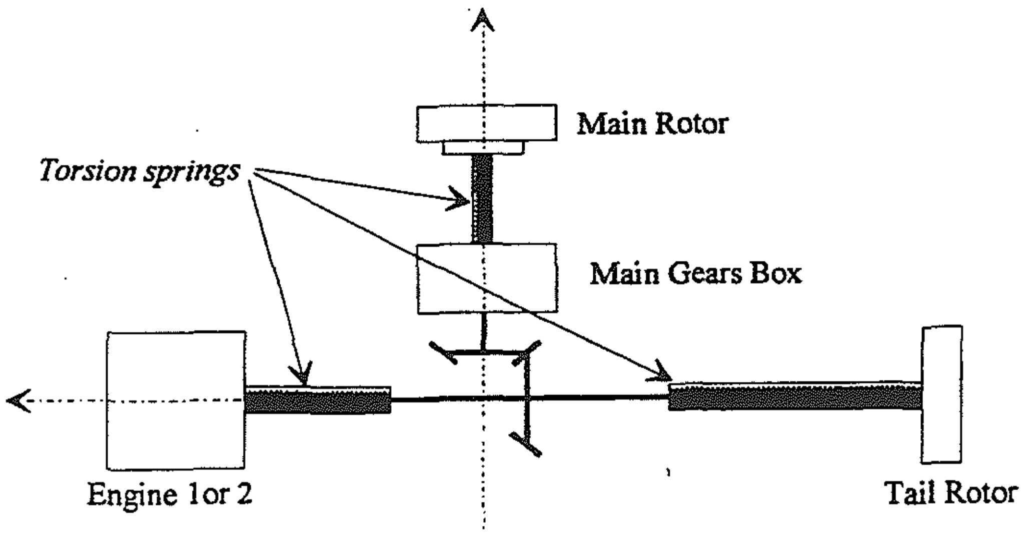


Fig. 1-c: Drive train torsional modelisation

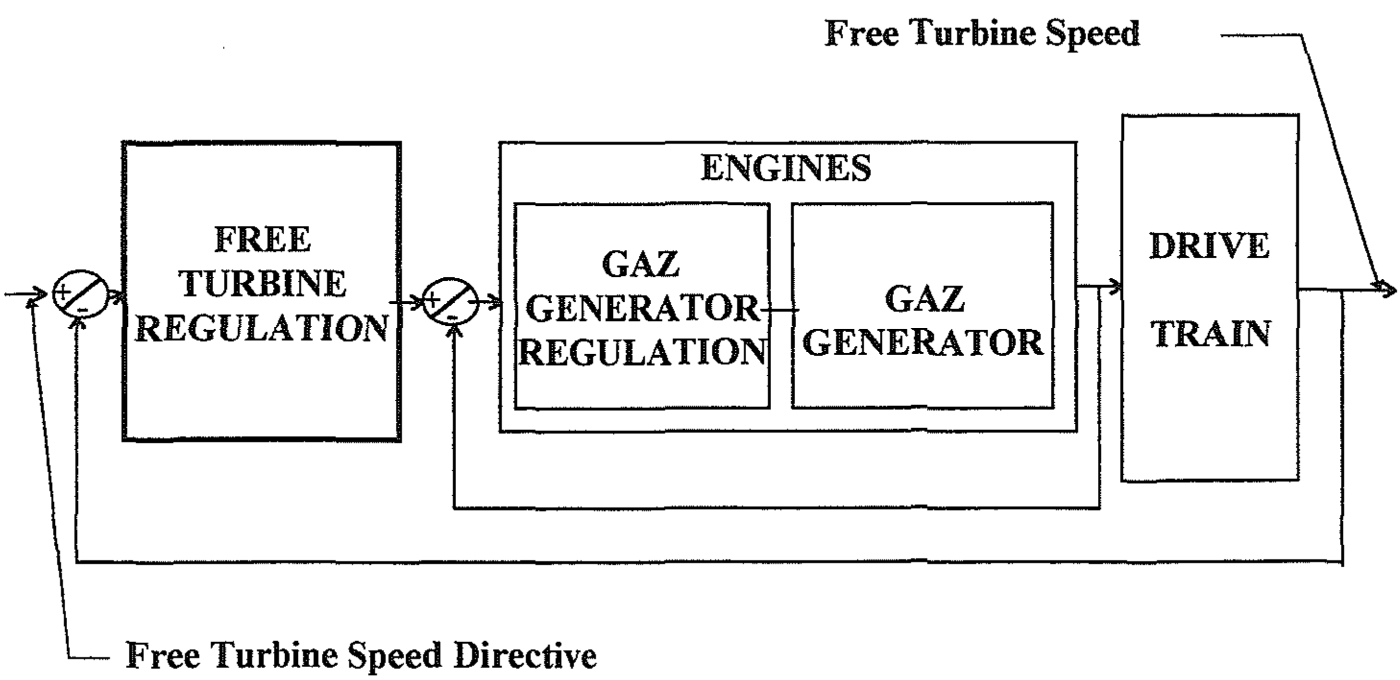


Fig 1-d: Engine behaviour modelisation

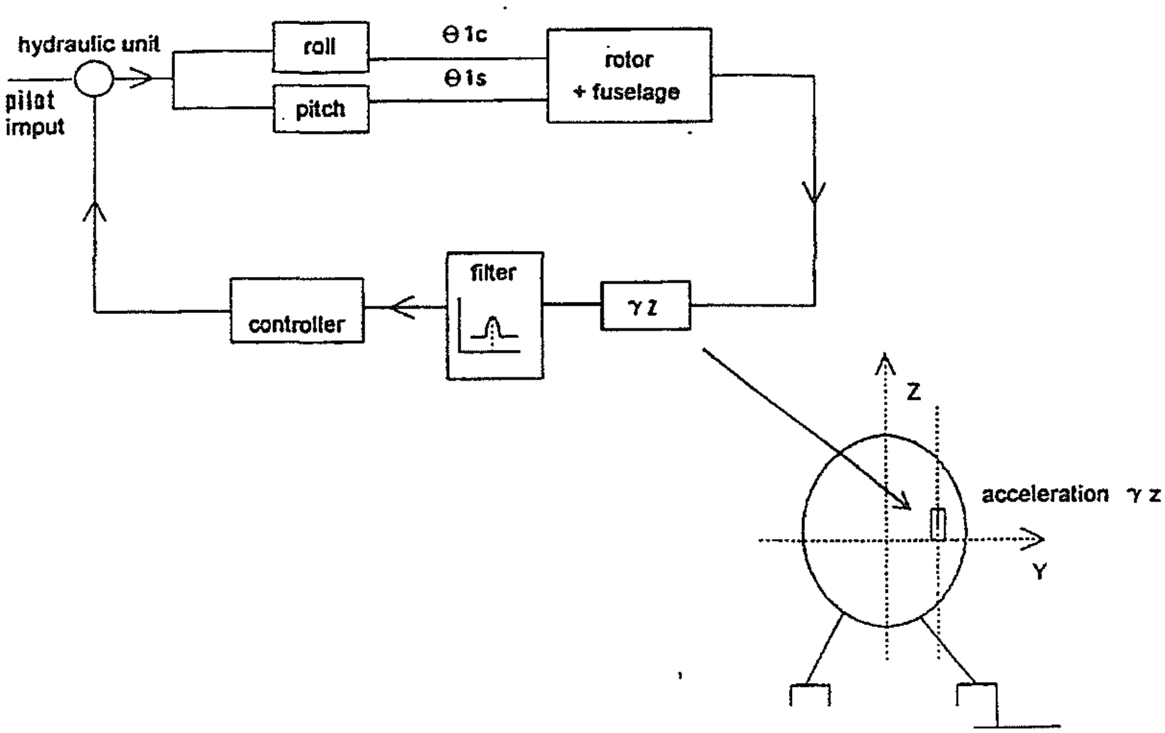


Fig. 2: ACTIVE GROUND RESONANCE CONTROL LOOP

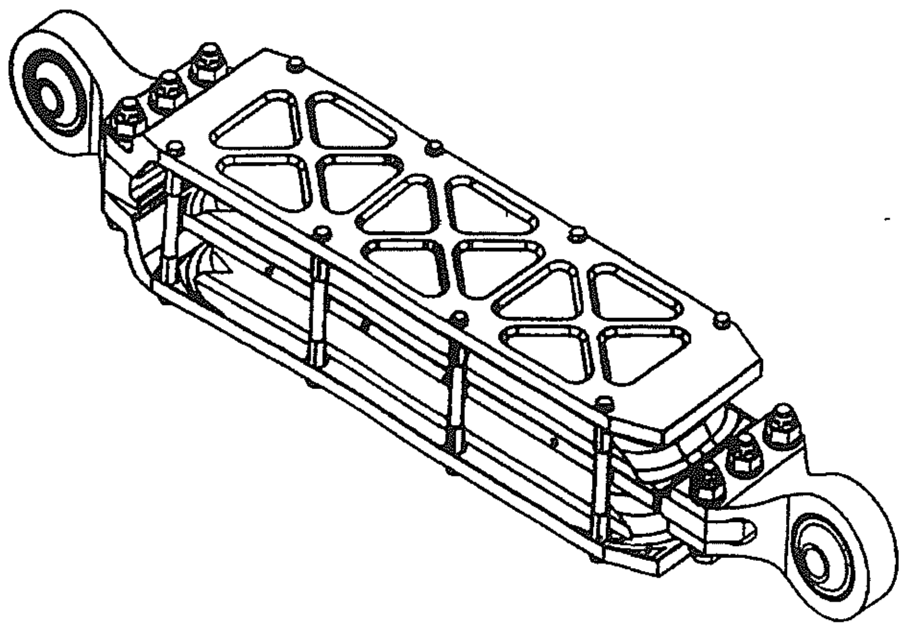


Fig. 3: EXAMPLE OF VISCOELASTIC TECHNOLOGY DAMPER TO TESTING GROUND AND AIR RESONANCE ACTIVE CONTROL

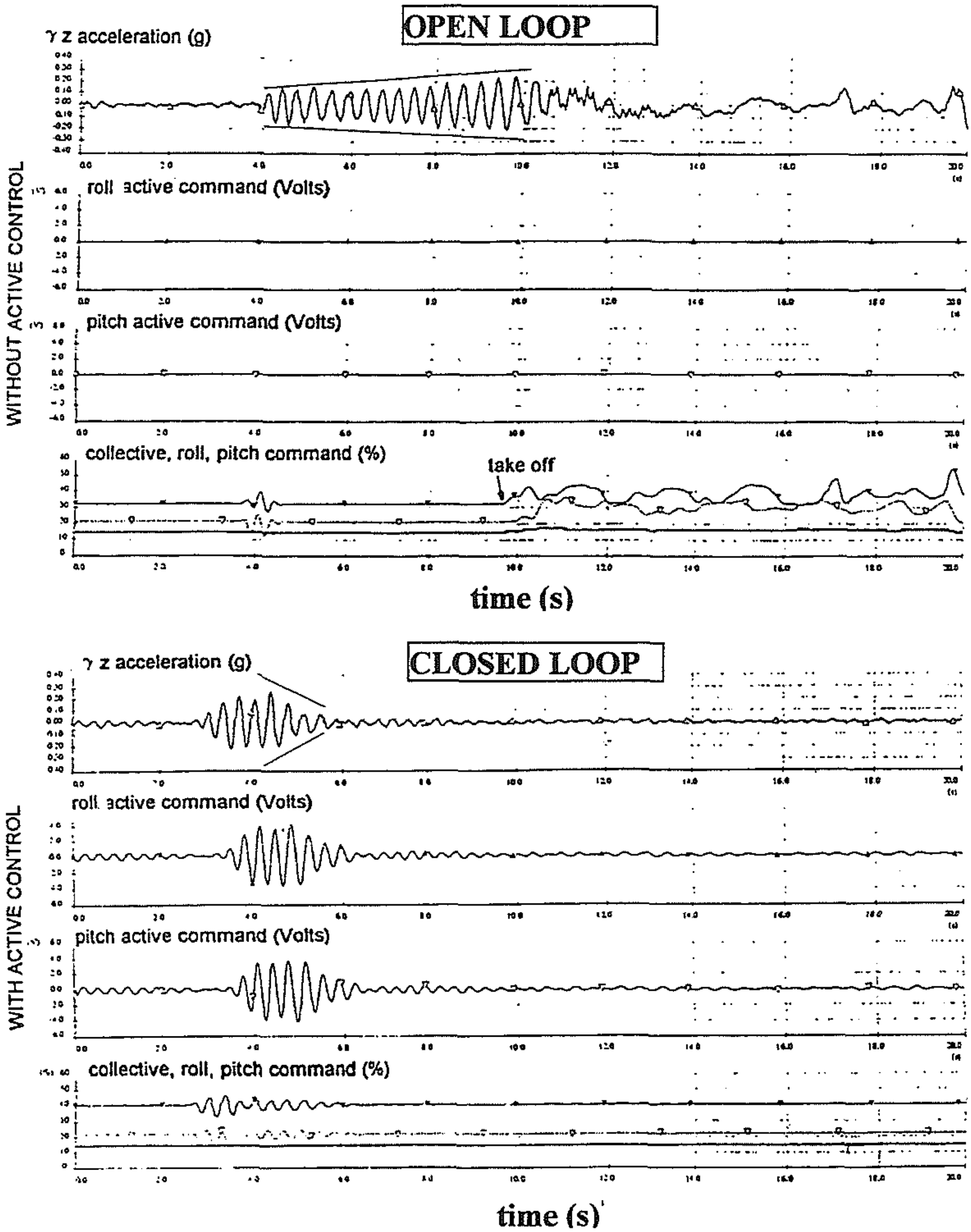


Fig. 4: SUPER PUMA MK2 WITH SPECIFIC VISCOELASTIC DAMPERS

COMPARAISON OF CLOSED AND OPEN LOOP ACTIVE CONTROL OF GROUND RESONANCE

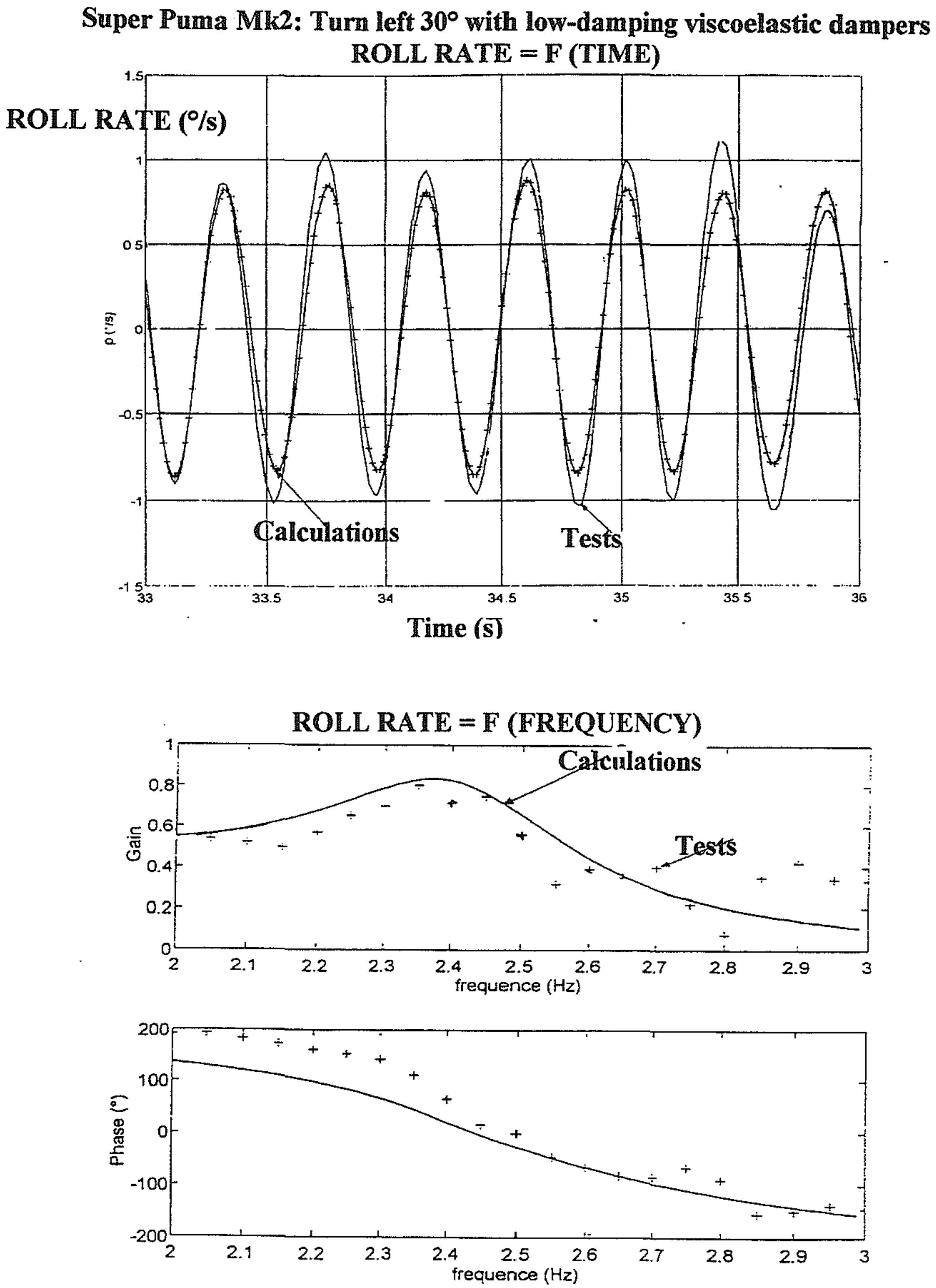


Fig. 5: AIR RESONANCE MODE IDENTIFICATION, CALCULATIONS/MEASUREMENTS COMPARISON

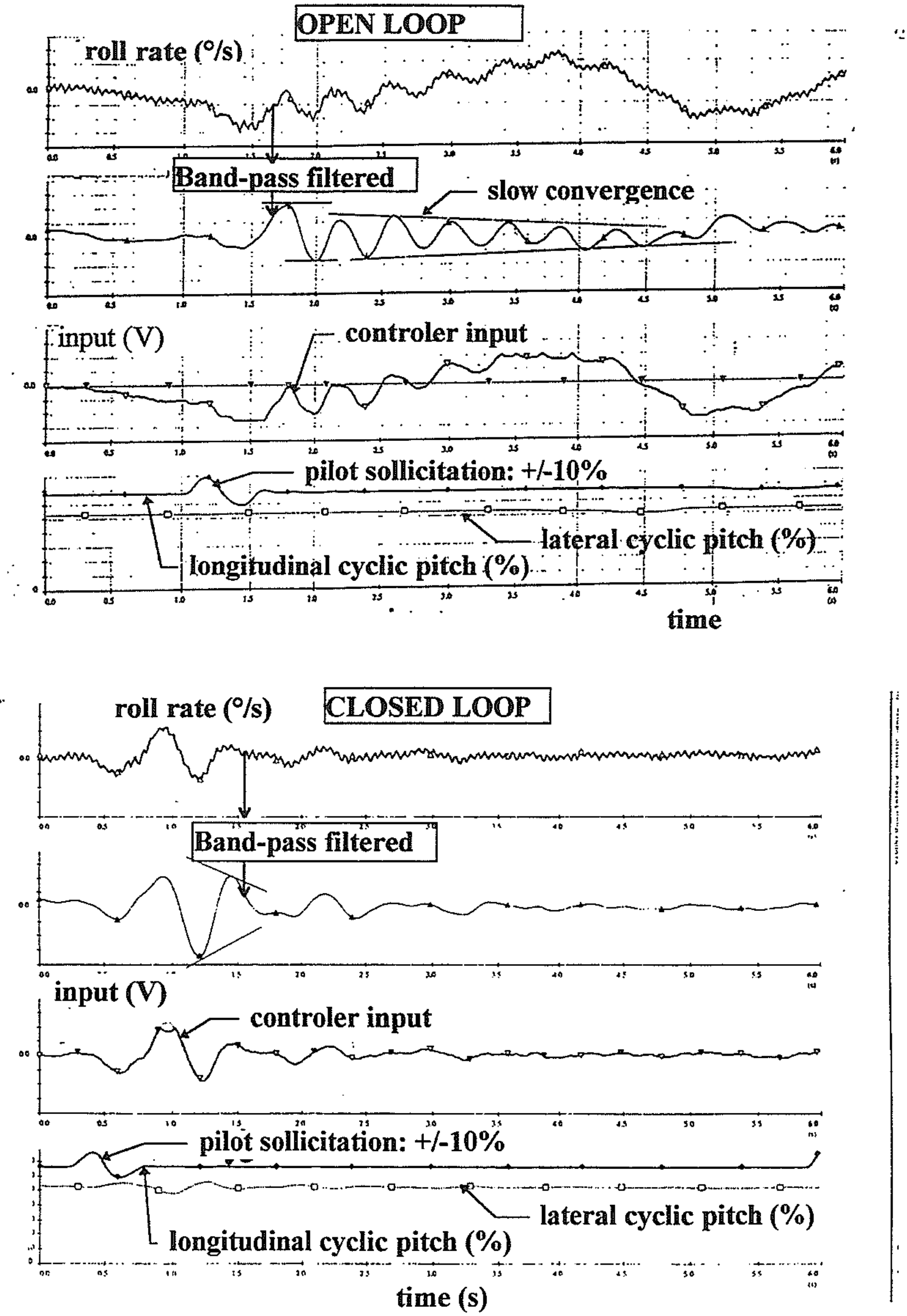


Fig. 6: ACTIVE CONTROL FOR AIR RESONANCE - TIME DOMAIN
Super Puma Mk2: Turn left 30° with low-damping viscoelastic dampers

Super Puma Mk2: Turn left 30° with low-damping viscoelastic dampers
TRANSFER FUNCTION: ROLL RATE / LATERAL CYCLIC PITCH

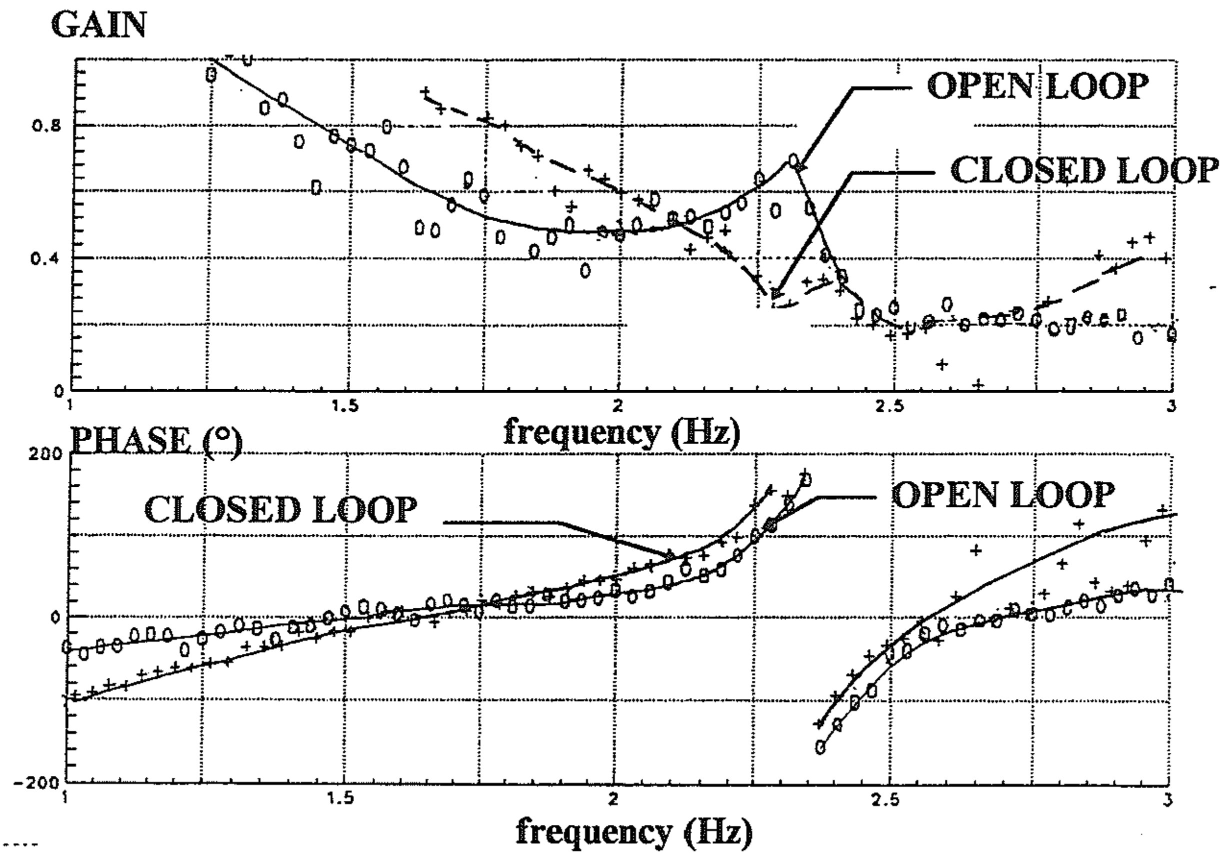


Fig. 7: ACTIVE CONTROL FOR AIR RESONANCE FREQUENCY DOMAIN

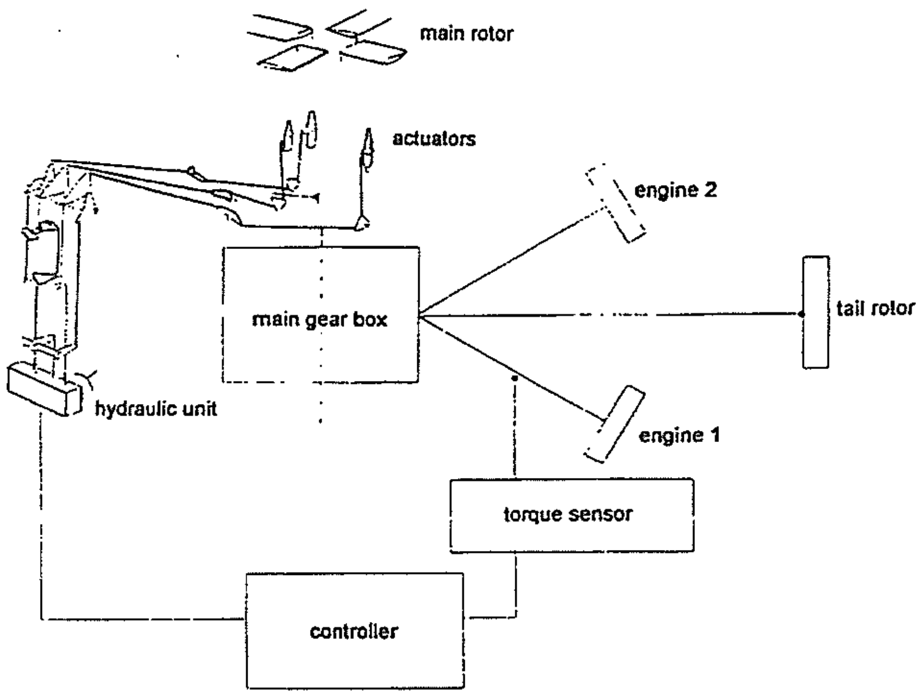


Fig. 8: DRIVE TRAIN ACTIVE CONTROL LOOP

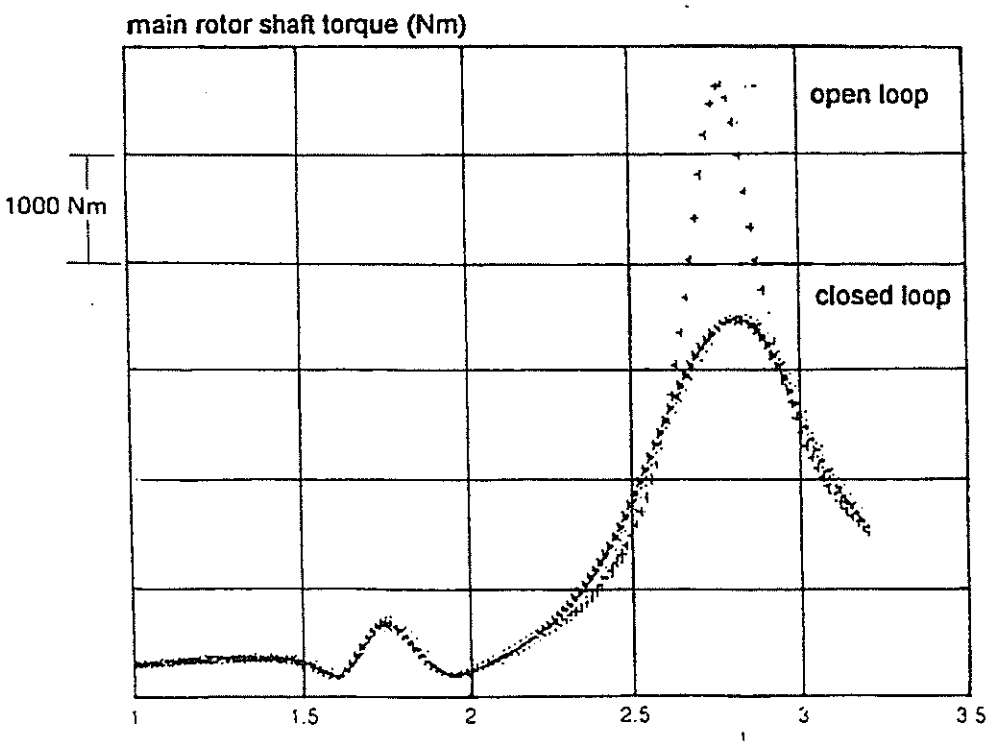


Fig. 9: SUPER PUMA MK2 - ACTIVE CONTROL OF DRIVE TRAIN

NH90: MAIN ROTOR MAST TORQUE RESPONSE FOR A COLLECTIVE PITCH SOLLICITATION

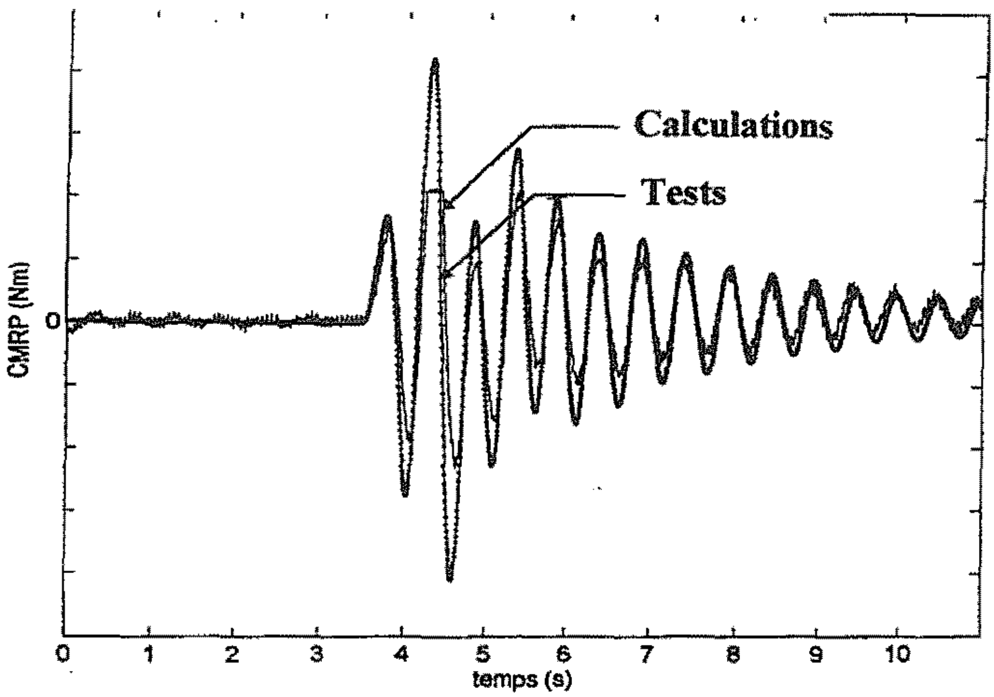
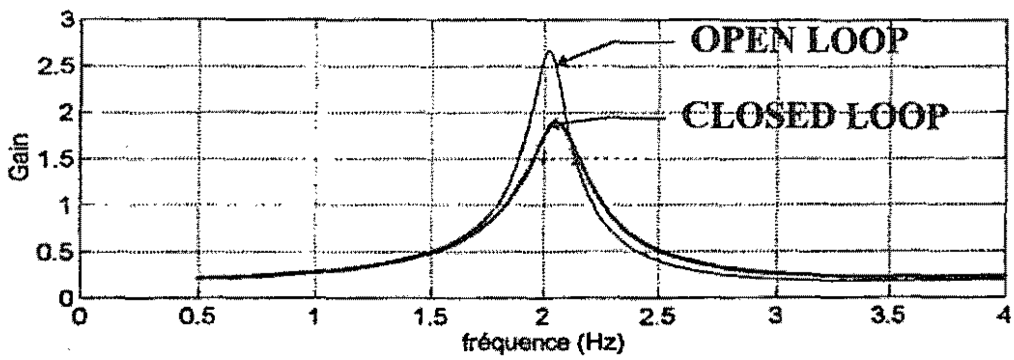


Fig. 10: DRIVE TRAIN MODE IDENTIFICATION, CALCULATIONS/MEASUREMENTS COMPARISON



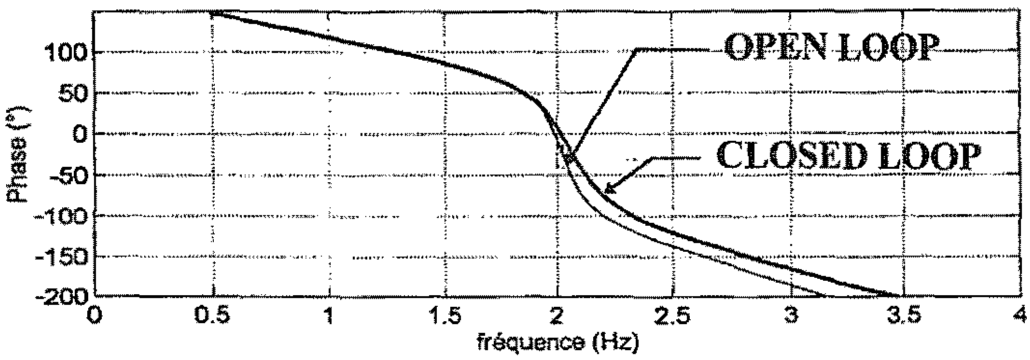


Fig. 11: NH90 - ACTIVE CONTROL OF DRIVE TRAIN
Transfer function: Main rotor shaft torque information / collective pitch