GENERALIZED HIGHER HARMONIC CONTROL TEN YEARS OF AEROSPATIALE EXPERIENCE

by Michel Polychroniadis

AEROSPATIALE Helicopter Division
Marignane, France

ABSTRACT

The paper presents an overview of Aerospatiale's investigations in the field of Rotor Active Control Technology by Higher Harmonic Blade Pitch Control. The main topics analyzed are vibration reduction, rotor noise reduction and performance improvement by stall alleviation.

As far as vibration reduction is concerned, the paper recalls the successful development of a closed-loop system tested on the SA349 experimental Gazelle in 1985 and presents the work performed since: flight tests with blades equipped with pressure transducers and design studies on a production system for the future NH90 helicopter.

The reduction of blade vortex interaction noise has been demonstrated in flight on the SA349 helicopter with an open-loop HHC system.

HHC ability to improve the rotor performance has been studied theoretically and has shown significant gains with HHC at high speed and lift. These studies were followed by preliminary wind tunnel tests at S2 Chalais on a 3-bladed HHC equipped rotor. In parallel HHC systems were designed with actuators on the rotating part and algorithms have been studied for future closed-loop systems.

In conclusion, the paper introduces the Optimum Rotor Control concept where an integrated system equipped with different sensors will determine in real time the blade pitch control ideally adapted to the flight configuration.

1 Introduction

Higher harmonic blade pitch control on a helicopter main rotor (i.e. controls whose frequencies are multiples of the rotor rotational frequency) features numerous degrees of freedom for improving rotor behavior.

Like some helicopter manufacturers, Aerospatiale focused its initial efforts on active vibration control. After flight testing exprimental systems, studies are in progress so as to integrate active vibration control on new helicopters under development. In the meantime new functions have been studied and are currently being tested; the most promising appear to be noise reduction and performance improvement.

We will present an overview of the company's activities in the last ten years in the field of HHC. The following topics will be covered: vibration reduction, noise reduction and performance improvement.

For each of the above functions, we will present the studies and tests conducted by Aerospatiale. Particular emphasis will be placed on the expected improvements and on the technological constraints related to each application.

Finally we will analyze the possibilities of integrating all these techniques in a generalized active rotor control system.

2 Active Vibration Control

2.1 Flight Tests of an Experimental System on the SA349 Gazelle

Aerospatiale launched a research program in 1980 whose aim was to flight-test an experimental active vibration control system based on HHC. The system was installed on the experimental SA349, derived from the SA342 Gazelle (fig. 1).

Figure 1 - SA349 Experimental Helicopter

Since both the system and all the 1985 flight data have already been detailed in References [1] and [2], only the main system results and characteristics are summarized below:

- swashplate control system (3/Rev. in the non-rotating system) generating controls at 2/Rev., 3/Rev. and 4/Rev. in the rotating system,
- maximum control travel ± 1°,
- closed-loop system (fig. 2).

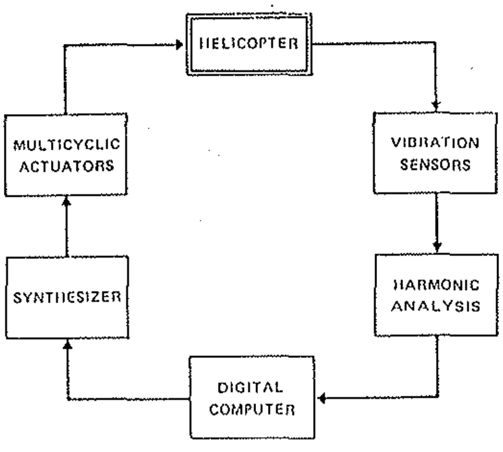

Figure 2 - Higher Harmonic Control Self-Adaptive System on SA349

The system was tested in closed-loop throughout the flight envelope of a conventional helicopter. In cruise flight at 250 km/hr, mean reductions of 80% were obtained in the cabin with local reductions of 95% at certain points, a performance substantially better than a conventional suspension (fig. 3). Three control algorithms were developed and flight-tested, demonstrating a fast adaptive control capability to changing flight conditions.

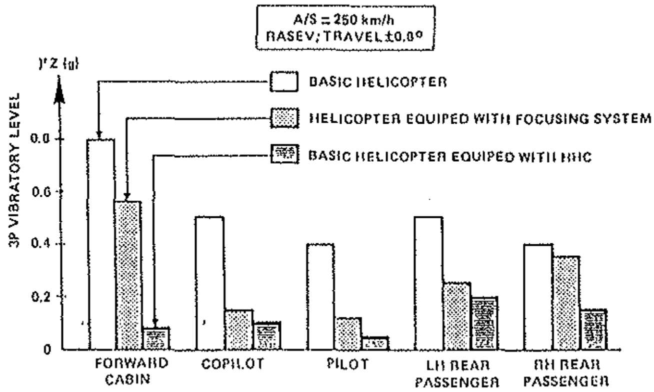

Figure 3 - Effectiveness of SA349 System (Comparison with a Passive System)

The very promising 1985 results encouraged Aerospatiale to continue the active vibration control program by flight-testing blades equipped with pressure transducers and by conducting application studies on new production helicopters.

2.2 Further SA349 Tests on Blades Equipped with Pressure Transducers

The local aerodynamic behavior of a rotor in flight was analyzed on a set of blades fitted with pressure transducers. Developed and flown on the SA349, this blade set generated a large databank containing flight results with conventional monocyclic control (fig. 4).

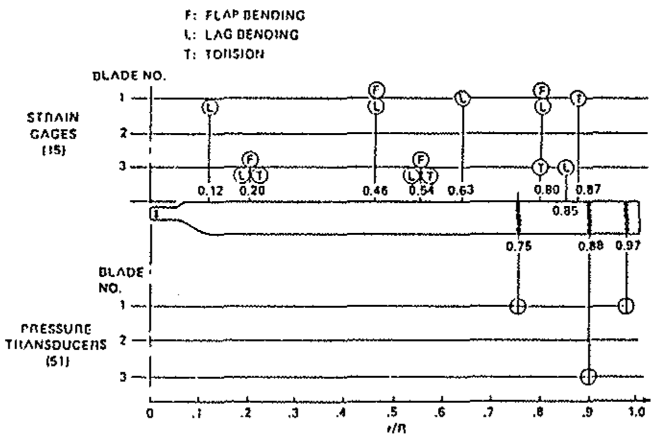

Figure 4 - 349GV Blades with Pressure Transducers

Subsequent to these flight tests, the decision was taken to gain a better understanding of the vibration reduction phenomena by using the 349GV blades with an HHC system. These 1988 tests measured the effect of HHC on local blade lift by integrating the recorded pressures over each equipped blade station. A typical result is shown in Figure 5 which compares the lift variation at station 0.88R with and without optimum HHC. The decreased vibration level results from the reduced higher harmonics of the local lift. This correlates closely with the lower dynamic exciting forces and moments measured at the rotor center.

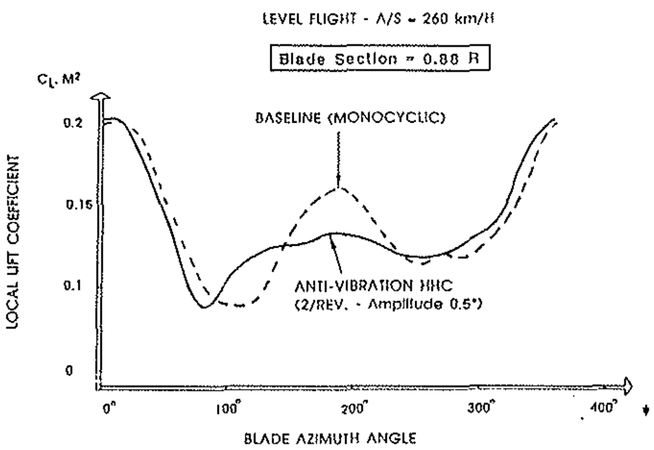

Figure 5 - Anti-Vibration HHC Effect on Local Lift
(Flight Tests on the SA349 with Blade Pressure Transducers)

2.3 Study of a System for NH90

In view of the SA349 results, it was considered appropriate to study the integration of an HHC system on the future European NH90 helicopter.

The first computational step was to convert the results on the 3-bladed SA349 into the 4-bladed NH90. These computations demonstrated that the required travels and control force variations were virtually the same on the NH90 and the SA349. This result was also substantiated by analysis of the published HHC test data on a 4-bladed rotor.

Using these assumptions, an HHC system integrated in the NH90 FBW system was defined (fig. 6) and compared with a conventional suspension. HHC was found to provide the best solution to meet the extremely stringent vibration requirements of the NH90 (cabin acceleration level < 0.1g at 140 kts) in terms of weight, cost and adaptability to the different helicopter conditions. Thus, for the same performance, a 50% weight saving has been obtained with the HHC system (including fuel consumption required for actuator control) compared to a passive suspension.

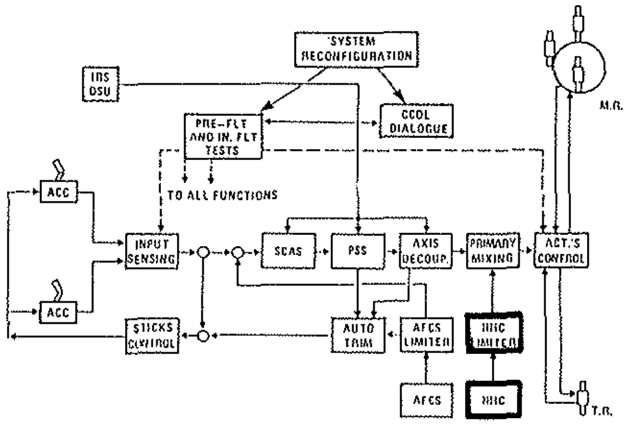

Figure 6 - HHC integrated in the NH90 FBW System

3 Rotor Noise Reduction

Acoustic measurements on the SA349 Gazelle indicated that HHC could significantly influence the noise induced by the main rotor.

Two types of tests were conducted:

- measurements with the vibration reduction HHC generated by the closed-loop system,

- measurements with different open-loop HHCs, with systematic amplitude and phase variations. The aim of the tests was to manually determine the optimum noise controls.

Noise levels were measured in each test by microphones installed on the helicopter skids and on the ground (fig. 7).

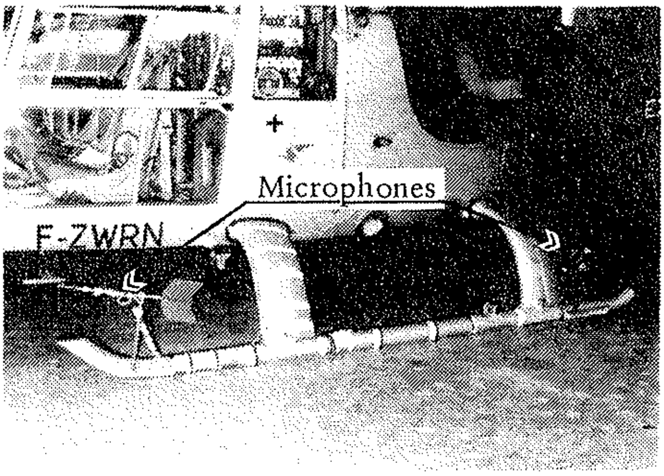

Figure 7 - Acoustic Measurements on the SA349 (Microphones on LH Side)

With the anti-vibration HHC based on the RASEV algorithm, noise reductions were recorded in certain flight approach conditions: a 3 TPNdB (Tone Perceived Noise) reduction in the maximum noise emitted on a 6° slope approach corresponding to a reduction of 1.5 EPNdB (Effective Perceived Noise) in the acoustic nuisance. This indicates that a certain noise/vibration compatibility exists but it does not apply throughout the flight envelope.

In the second phase it was decided to systematically investigate open-loop noise reduction controls by amplitude and phase variations.

The most spectacular results occurred during approach, which corresponds to the acoustic certification procedures. Figure 8 shows one result indicating how a 1° amplitude control affects the aircraft noise. It is clear that the optimum HHC removes the acoustic pressure peaks (induced by the blade/vortex interaction noise). This leads to a very large reduction of 6 TPNdB of the maximum noise level (-3.5 EPNdB), which was quite noticeable to the crew during flight.

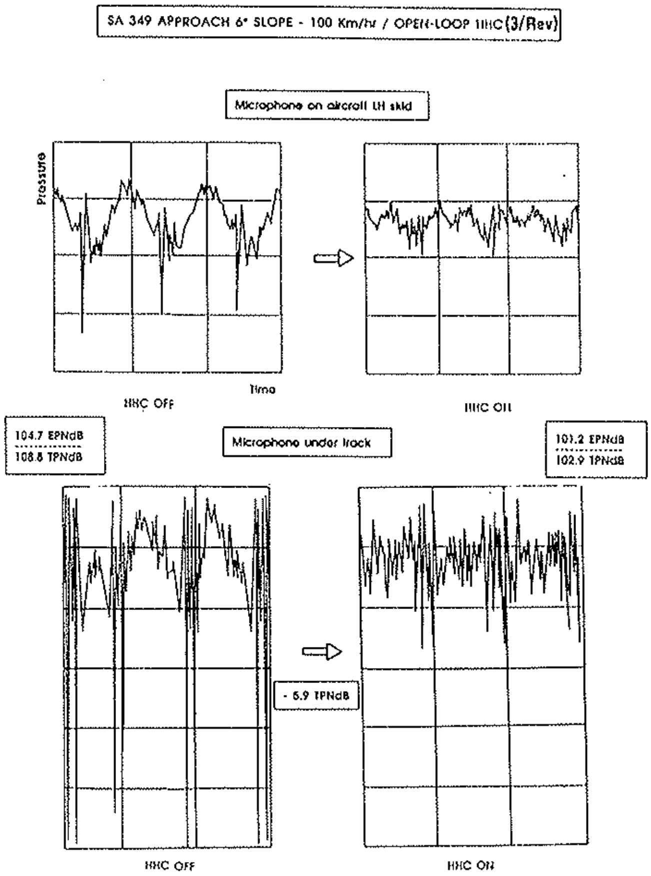

Figure 8 - BVI Noise Reduction with HHC Flight Tests on the SA349

These results can be compared with DLR [4] or NASA-LANGLEY [5] wind tunnel data showing similar gains on 4-bladed rotors operating with swashplate control HHC systems and with equivalent control travels.

This illustrates the potential of such a technique, available in the near term with swashplate control systems identical to those developed for active vibration control.

The next step in this research will be the development of closed-loop systems based on joint MBB/DLR/NASA-LANGLEY wind tunnel tests scheduled at DNW in the near future.

4 Performance Improvement

4.1 Theoretical Studies

Starting in 1985, Aerospatiale began theoretical HHC studies aimed at improving performance.

The large number of degrees of freedom made it necessary to combine an optimization method with the rotor performance computer model (lifting line method) as shown below in Figure 9.

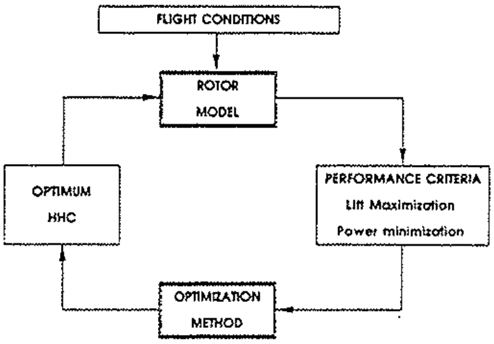

Figure 9 - Optimization method used to determine optimum performance controls

The controls considered were of the 2/Rev., 3/Rev., 4/Rev. and 5/Rev. types or combinations of them. The following parameters were varied: flight conditions, control amplitude and phase, optimization criteria (power minimization or lift maximization).

Figure 10 summarizes the results obtained with a 4-bladed rotor of the SA365N Dauphin type. Power/Lift curves are plotted at different advance ratios for the baseline monocyclic control and for the optimum HHCs (combination of 2/Rev. , 3/Rev. and 4/Rev.). HHC can produce significant gains at high speed by maximizing lift (+22% at λ = 0.5) or by minimizing power. In contrast the potential performance gains for existing helicopters in cruise conditions (λ < 0.4) appear quite small.

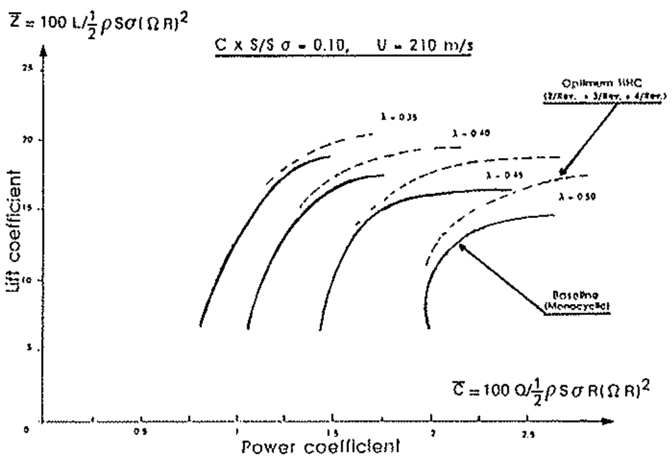

Figure 10 - Performance Improvements with HHC (Calculations)

During this investigation, the 2/Rev. control proved to be the most effective both for minimizing power and for increasing lift. The amplitudes of the optimum controls were frequently higher than 4°, i.e. well over the amplitudes required to reduce vibration.

Typical results are plotted in Figure 11 as maximum lift gains versus HHC amplitudes for a 2/Rev. control and a combined 2/Rev. and 3/Rev. control.

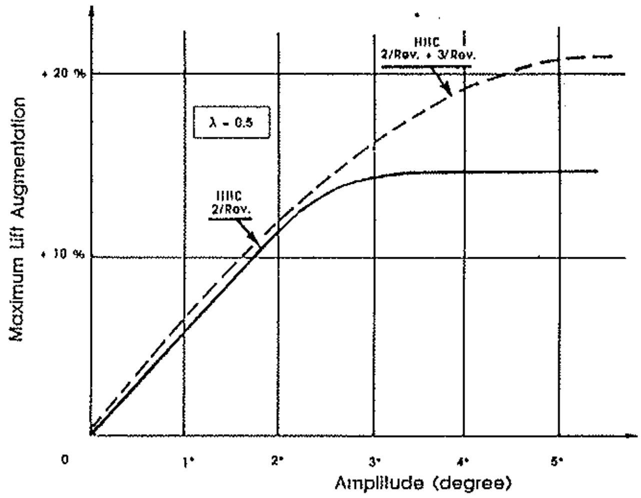

Figure 11 - Variation of Lift Improvements with HHC Amplitude

When the effect of HHC optimized for performance is examined locally, its main action is to decrease the stall area which means the rotor lift limits can be extended (fig. 12).

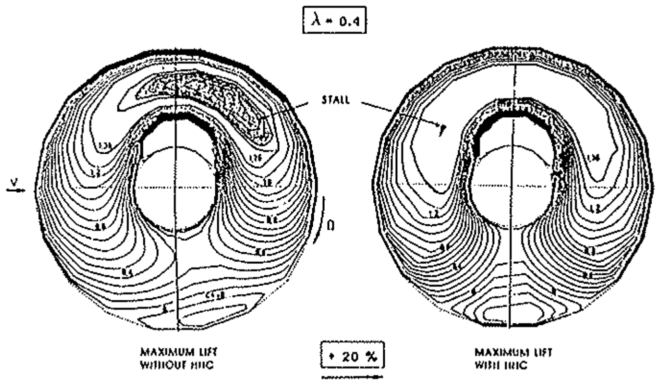

Figure 12 - Effect of HHC on rotor stall

It can thus be concluded from these studies that significant improvements are possible with HHC at lift maximization (stall margin on maneuverable helicopters), or at power reduction on high speed helicopters (V > 350 km/hr).

In contrast to noise or vibration control, the 2/Rev. control is here very significant which requires an Individual Blade Control (IBC) system for rotors with more than 3 blades (With swashplate control actuators on 4-bladed rotors, only 3/Rev., 4/Rev. and 5/Rev. controls are possible in the rotating system).

Computations indicate that performance improvements are still possible with a swash-plate control system on a 4-bladed rotor, but the gains are lower - down by roughly half - compared to those with a rotating system.

Lastly it should be noted that the drop in maximum lift due to HHC can result either in an extended flight envelope for a given rotor or in new rotor design at the same load factor requirement (rotor solidity ratio can be decreased).

4.2 Wind Tunnel Tests

The theoretical studies were followed in 1988 by preliminary tests in the ONERA S2 Chalais wind tunnel on a 3-bladed rotor equipped with non-rotating system HHC (fig. 13).

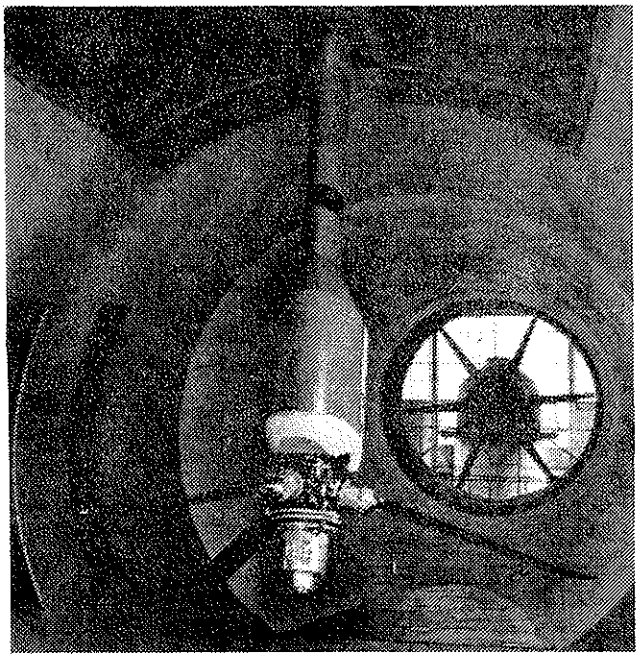

Figure 13 - S2 Chalais Wind Tunnel

In these tests on each flight configuration, the monocyclic control was fixed and the amplitude and phase of HHC (2/Rev., 3/Rev. and 2/Rev. + 3/Rev.) were varied.

In this case it should be noted that the rotor static loads are not the same as for the basic case (consequently flight condition is modified).

Typical results are shown in Figure 14 where the static forces, power and flapping angle are plotted versus the phase angle of a 2/Rev. control. HHC is seen to have a significant effect on rotor performance. Most of the computed results agree with the measured trends, except for the influence on propulsion and consequently on computed power.

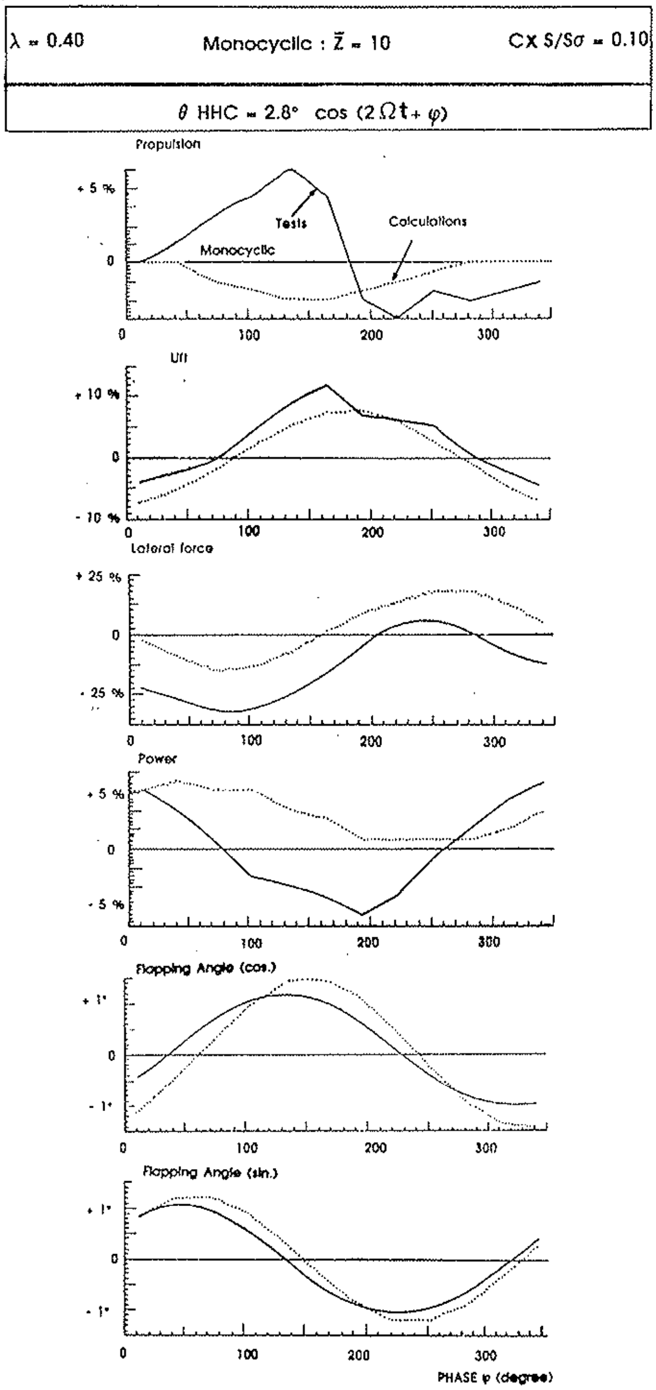

Figure 14 - Effect of HHC on Performance (Comparison of Computations with S2 Chalais Test Data)

In conclusion, although these preliminary tests have not directly confirmed the computed improvements of the theoretical study (restricted test envelope and limited number of test points), they have indirectly validated the theoretical approach by proving the capability of the computation codes to predict the effect on lift, which is the most important for improvement of performance.

4.3 Future Tests in S1 Modane Wind Tunnel

Research on optimum performance controls will be continuing with tests scheduled on a 4-bladed rotor with HHC blade control in a rotating system (Individual Blade Control) in the S1 Tunnel at Modane.

In these tests, performance, noise and vibration will be measured to determine the compatibility of the various criteria. In addition the rotor will be fitted with pressure transducers to investigate the local aero-dynamic effects of HHC.

Two activities are currently underway to prepare for these tests:

- development of an IBC actuators system for wind tunnel tests (fig. 15),
- joint development with ONERA (CERT/DERA) of closed-loop algorithms (fig. 16).

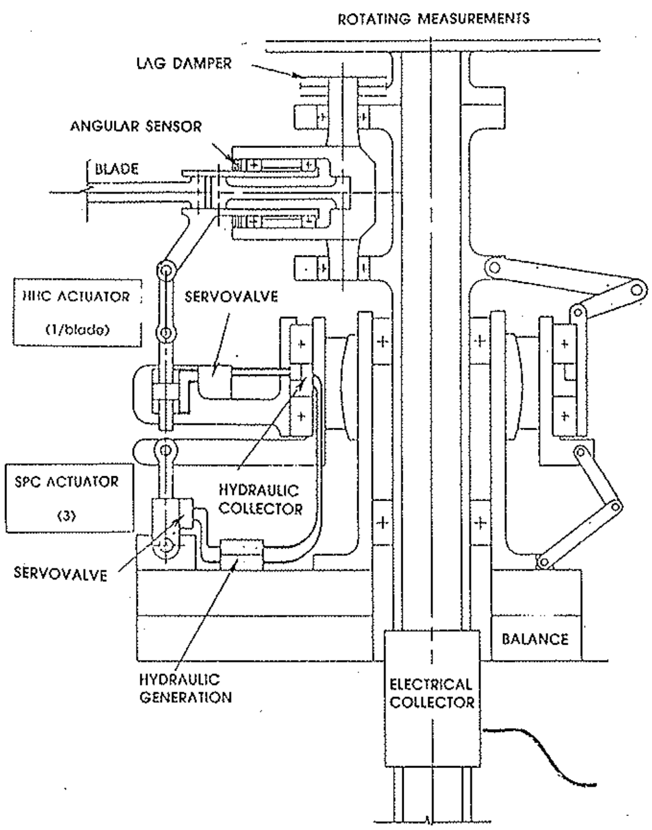

Figure 15 - IBC System for S1 Modane Wind Tunnel Tests

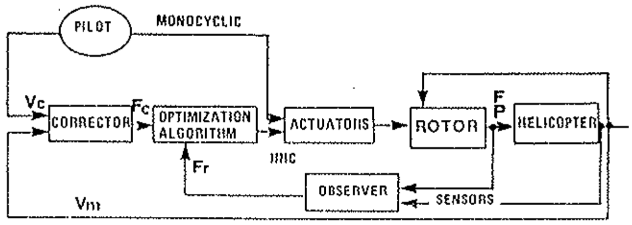

Figure 16 - HHC Closed-loop Algorithm for Performance Improvement [6]

5 Generalized Higher Harmonic Control

The results given above demonstrate the very broad range of HHC applications.

The table in Figure 17 summarizes these results by giving the potential improvements, the technological constraints and the flight conditions most suitable for each function.

FUNCTION	GAINS	TECHNOLOGY SPC/IBC	CONTROL TRAVEL	FLIGHT CONDITIONS
VIBRATION REDUCTION	-80%	NON-ROTATING SPC	1°	CRUISE
NOISE (BVI) REDUCTION	-3.5 EPNdB	NON-ROTATING SPC	1°	APPROACH (CASE OF BVI)
PERFORMANCE IMPROVEMENT	LIFT +22% at $\lambda \sim 0.5$	ROTATING SYSTEM IBC (GAINS LOWER IN SPC)	>3°	MANEUVERS + HIGH SPEED FLIGHT

Figure 17 - Summary of HHC Applications

It is seen that each function is particularly effective in its own specific flight conditions. Nonetheless the compatibility between certain of these criteria must be studied if only to ensure that prioritizing one criterion causes little or no degradation to the others. This is one of the objectives of the scheduled S1 Modane tests. In the long run, it is safe to predict that all these trade-offs will be managed by a generalized active control system combining all these techniques.

These future systems will employ computational algorithms combining several criteria (vibration, noise, performance). These algorithms will process the inputs from sensors mounted on the helicopter to generate in real time the "optimum control" best adapted to the flight condition (fig. 18).

Active rotor control will also open the way to other functions not covered in this paper, such as active stability control of ground or flight resonance, whose theoretical feasibility has already been demonstrated by Aerospatiale.

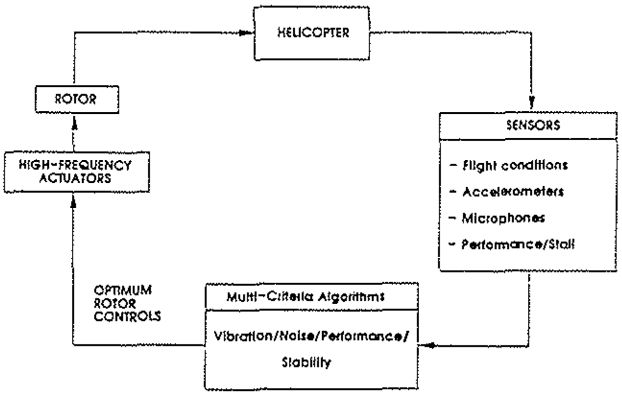

Figure 18 - Generalized Active Rotor Control System

6 Conclusions

The investigations conducted by Aerospatiale during the last ten years have shown numerous potential applications of HHC (fig. 19):

- active vibration control (AVC) is already an effective, flight-proven technique. The studies forming part of the NH90 definition have shown that, when integrated in an FBW system, AVC provides an excellent solution for meeting future vibration requirements.

- rotor noise reduction, particularly noise induced by blade/vortex interaction, has already undergone preliminary flight testing on the SA349 with very promising results. If these results are confirmed in future tests, this technique should easily become feasible by combining it with an active vibration control system (with swashplate control actuators travel-limited to 1°).

- active performance control, notably stall alleviation, is currently being studied theoretically and in the wind tunnel. Significant improvements appear feasible throughout extensive parts of the flight envelope (high maneuverability or high speeds). This function can only be fully exploited by the development of HHC actuator systems in a rotating system (IBC); this therefore implies production application of this technique in a more distant timeframe.

Eventually compatibility studies between the different functions and development of "multi-criteria" algorithms will prepare the development of "generalized active rotor control" systems. These systems will integrate all these techniques and will generate real-time optimum HHC giving the best trade-off between noise, performance and vibrations for every flight condition.

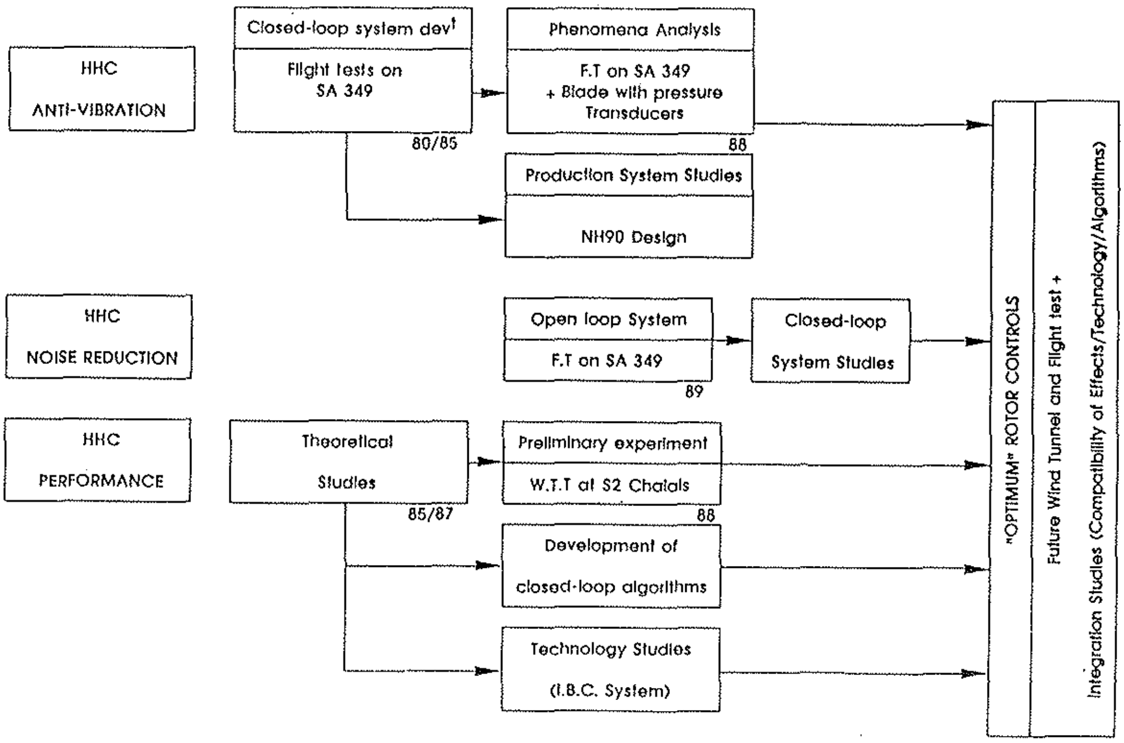

Figure 19 : Overview of Aerospatiale Investigation

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