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DEVELOPMENT OF AN EXPERIMENTAL SYSTEM FOR ACTIVE CONTROL OF VIBRATIONS ON HELICOPTERS

DEVELOPMENT METHODOLOGY FOR AN AIRBORNE SYSTEM

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and Michel POLYCHRONIADIS Research Department

AEROSPATIALE HELICOPTER DIVISION

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SUMMARY

A Research program sponsored by the French Government Agencies has been conducted by the AEROSPATIALE HELICOPTER division with a view to developing an experimental system for active control of vibrations through higher harmonic controls applied to the main rotor blades.

All system development phases are presented within the framework of an airborne system design and development methodology.

The various stages prior to flight experiments are dealt with, from the theoretical modeling of the helicopter vibratory behavior, under effect of higher harmonic control, up to the integration of the system on a rotor test rig.

The flight test campaign conducted by Aérospatiale Marignane in 1985 on an SA 349 GAZELLE allowed validating the concept for reducing vibrations through a closed loop self-adaptive system within the whole SA 349 helicopter flight envelope.

In addition to the very important reductions of vibrations obtained from three different algorithms (80 % as an average in the cabin at 250 km/h), this test campaign showed the efficiency of a test methodology focused on the representativity of an off-line simulation.

INTRODUCTION

The design and development of a helicopter airborne system require several stages before the ultimate flight test phase.

Therefore, the experiments of a probatory system for active control of vibrations was conducted as per the methodology presented in Figure 1.
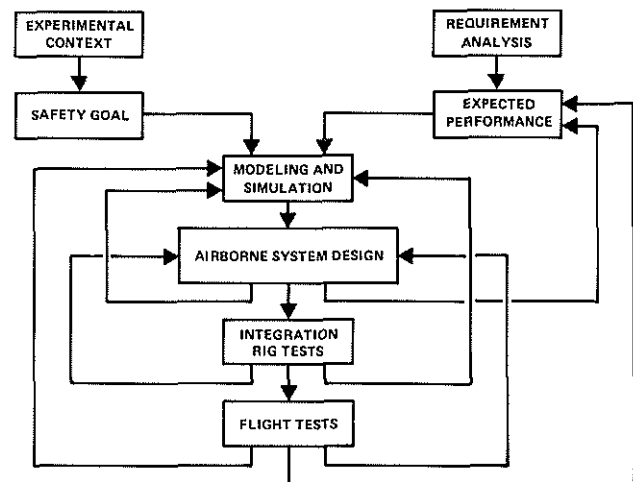

Fig. 1 : AIRBORNE SYSTEM DEVELOPMENT METHODOLOGY

Within the framework of this methodology, after a brief analysis of the origin and effects of vibrations on helicopters, the design and results of every stage will be presented.

THE VIBRATIONS ON HELICOPTERS : ANALYZING THE NEED

On helicopters, the problems raised by the vibrations generated by the dynamic components are significant and fraught with consequences (reduction of component service life, reliability constraints, reduction of comfort,...).

The means currently used to limit such phenomena are passive systems of the anti-vibrator or suspension type and provide acceptable results in numerous cases. However, the increasingly severe comfort requirements associated with faster and faster cruise speed goals make these systems limited in the future, which means that their weight may be redhibitory to maintain the required vibratory level.

Active vibrations control systems among which the higher harmonic control is a specific case, are envisaged (Ref (1) to (12)) concurrently with passive systems.

The higher harmonic control allows minimizing the vibrations generated in the structure at a characteristic frequency, by acting directly on blade pitch control.

In fact, on a three-blade helicopter, the prevailing vibration frequency in the airframe is 3/rev (1/rev : rotor rotation frequency). These vibrations originate from alternate loads at 3/rev along rotor centreline, transmitted directly to the airframe, and from loads at 2/rev and 4/rev frequencies in the rotor plane, transmitted to the airframe after change in reference area, as 3/rev frequency loads (Figure 2a).

Controls generated in series with respect to piloting commands at 3/rev frequency create 2/rev, 3/rev and 4/rev loads at rotor which may oppose those generating vibrations (Figure 2b).
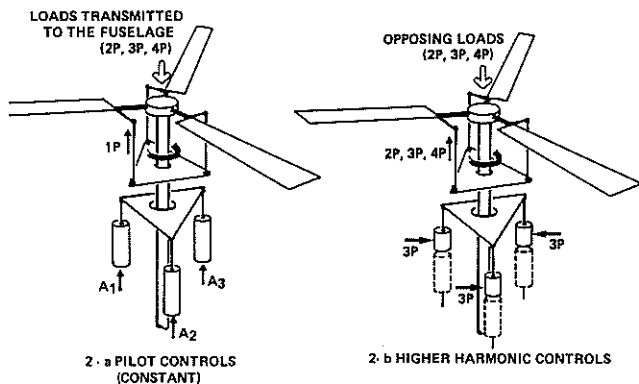
Fig. 2 : PRINCIPLE OF HIGHER HARMONIC CONTROL ON NON ROTATING SWASHPLATE (THREE-BLADE ROTOR)

So, the higher harmonic control system is intended to identify the higher harmonic control ──▶ vibrations transfer (variable according to flight case and aircraft configuration), so as to calculate the module and phase of every of the three optimum controls to be applied to the multicyclic actuators in order to reduce the vibrations in the airframe.

This leads to the functional diagram presented in Figure 3. The harmonic analysis allows deriving the Fourier coefficients corresponding to the preponderent frequency, i.e. 3/rev, from the vibratory measurements. From this data and knowledge of previous higher harmonic controls, the digital computer computes the modules and phases of the three higher harmonic controls. The latter are converted into three 3/rev sinusoidal signals by the synthesizer ; the signals are transmitted to the multicyclic actuators.
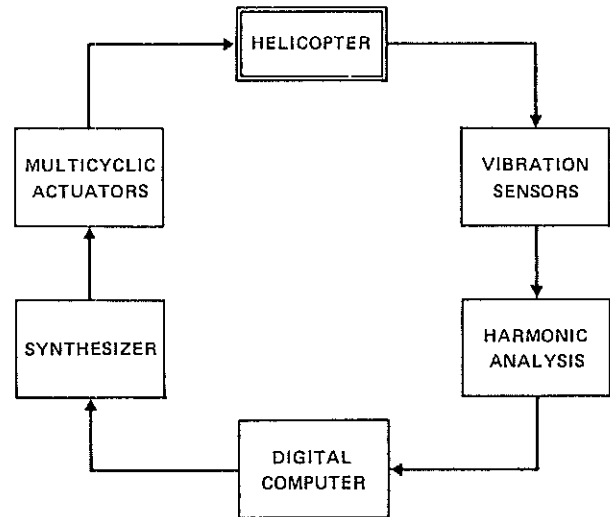
Fig. 3 : HIGHER HARMONIC CONTROL SELF-ADAPTIVE SYSTEM

The theoretical value of the concept and a first quantification of potential gains were obtained by a digital rotor simulation and airframe structure tests. They were confirmed by simplified tests on rotor rig performed at Aérospatiale's in 1977.

EXPERIMENTAL CONTEXT : SAFETY OBJECTIVE

A research program partly sponsored by the French Government Agencies was launched by Aérospatiale's Helicopter Division in 1980. This program was intended to develop an experimental system for control of vibrations through higher harmonic controls, with tests performed on SA 349 three-blade research aircraft derived from the SA 342 GAZELLE (Figure 4).

Fig. 4 : SA 349 EXPERIMENTAL HELICOPTER

Since the probatory tests are intended to demonstrate the validity of the concept without prejudicing the optimum performance that can be obtained with such a system, the authority of the higher harmonic control has been limited to a low amplitude (+/- 1.7 degrees pitch) so as not to compromise the aircraft safety in case of failure of the system.

The amplitude limitation value of the higher harmonic control has been obtained by failure simulation using an SA 349 GAZELLE flight mechanics model : any failure of the system leads to changes in the flight parameters (angular rates, attitudes,.....) not questioning the aircraft safety. This is easier within the framework of such an experimentation where the aircraft control is always performed «hands on».

EXPERIMENTAL SYSTEM DESIGN AND REALIZATION

Considering the performance and safety requirements, a self-monitored system has been obtained.
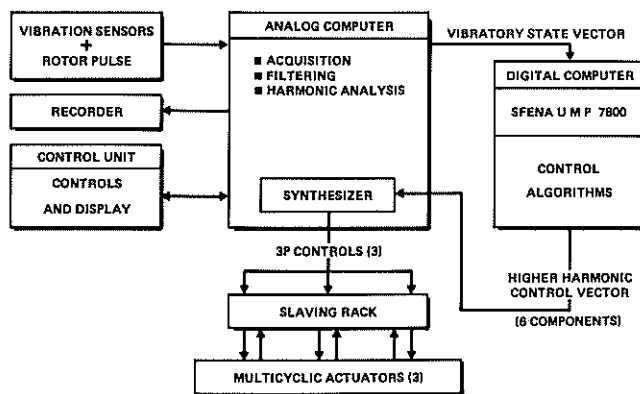
EQUIPMENT :

Fig. 5 : EXPERIMENTAL SYSTEM ARCHITECTURE

The experimental system (Figure 5) mainly incorporates :

- vibration sensors (accelerometers mounted at different cabin locations) and a rotor rpm magnetic sensor (for accurate knowledge of 1/rev and synchronization) ;

- an analog computer for harmonic analysis (extraction of 3/rev vibration component), 3/rev command generation (synthesizer function) to the multicyclic actuator slaving rack, and safeties management ;

- a digital computer where computation algorithms process the optimum «control vector» from the «vibratory vector» issued from the analog computer ;

- a multicyclic actuator slaving rack ;

- three electro-hydraulic actuators (so-called multicyclic actuators) series-mounted to the conventional mechanical input servo-controls, with a 10 mm limited travel, corresponding to a blade pitch of +/-1.7 degrees. These actuators have been developed for this application in order to obtain good performance at high control frequencies (3/rev i.e. 19 Hz for the SA 349 helicopter) and under high dynamic loads ;

- a control unit mounted in the cabin and serving as an interface between the system and the test crew.

The various components of the higher harmonic control system have been developed, as per Aérospatiale's specifications, by the French companies Giravions Dorand (slaving rack), Air Equipement (actuators), SFENA (digital computer) and Aérospatiale's Helicopter Division for the other items.

SOFTWARE :

As regards the airborne software, its design, validation and programming have been achieved by a team from the Direction des Etudes de l'Aérospatiale jointly with ONERA (CERT/DERA) for the study of stochastic algorithms.

Three algorithms for computation of the optimum control have been developed, all three were based on a linear representation of the higher harmonic control effect on airframe vibrations resulting from simplified rotor modeling and experimental aircraft structure tests :

$$Z_k = S \cdot \theta_{k-1} + Z_0$$

where :

- Z_0 vector of 2n Fourier 3/rev coefficients corresponding to n accelerometric measurements, without higher harmonic controls,

- Z_k measurement vector at computation step k, after higher harmonic controls,

- θ_{k-1} vector of the 6 Fourier 3/rev coefficients corresponding to the controls to the 3 actuators at computation step k-1,

- S matrix representative of the vibratory vector sensitivity to the higher harmonic control vector (dimension :2n rows, 6 columns).

The control vector θ_k is calculated at every computation step by minimizing a quadratic criterion J :

$$J = Z^T_{k+1} \cdot Z_{k+1} + \Delta\theta^T_k \cdot W \cdot \Delta\theta_k$$

with $\quad \Delta\theta_k = \theta_k - \theta_{k-1}$

incorporating both the vibratory energy to be decreased $(Z^T_{k+1} \cdot Z_{k+1})$, and a balancing term on control variation $(\Delta\theta^T_k \cdot W \cdot \Delta\theta_k$ with W definite positive matrix) allowing a progressive, hence «prudent», action on the system.

The algorithm is then intended to :

- identify S at every time since it depends on flight conditions and aircraft configuration. Identification of Z_0 is not required in so far as the optimum control is calculated in an iterative way using a variation model :

$$\Delta Z_k = S \cdot \Delta\theta_{k-1}$$

- calculate the optimum control variation $\Delta\theta_k^*$.

Three algorithms of two different types have been studied :

- the Deterministic Adaptive Algorithm (AAD)

- the Stochastic Adaptive Regulator (RAS)

- the Stochastic Adaptive Regulator with Vibrations Estimate (RASEV)

The AAD algorithm is of the deterministic type. It performs identification of the S matrix by transmitting «calibrated» controls or extra-signals. After the first identification on initialization, comparing the measured vibratory level and an estimated vibratory level (by calculation) allows determining whether it is necessary to identify S once again.

This algorithm thus implies :

- a significant excitation of the system during identification phases,

- selecting a criterion to identify S only when a modification of the flight conditions is probable, since every identification phase requires sending 6 calibrated controls, a priori not optimum in the vibration reduction direction.

Except for the identification phases, the optimum control calculation is achieved at every computation step, considering that S has actually been identified and by minimizing criterion J :

$$\partial J / \partial (\Delta \theta_k) = 0 \text{ hence :}$$

$$\Delta \theta^*_k = -(W + S^T . S)^{-1} . S^T . Z_{k-1}$$

The RAS algorithm, of the stochastic type, uses the a-priori statistics of measurement and system «noises» to identify S at every computation step. It consists of 2n Kalman filters, each one identifying a row of matrix S. For the filter condition equation, the assumption retained is the low S matrix variation between two successive computation steps. The measurement equation results from variations modeling : $\Delta Z_k = S . \Delta \theta_{k-1}$

The algorithm initialization is achieved by sending low amplitude random controls.

Since the identification of matrix S is achieved at every computation step by using the previous control variation, the latter can be calculated so as to be optimum, with the same expression as for algorithm AAD.

Thus, the RAS algorithm :

- allows permanent identification of matrix S, the optimum higher harmonic control being sent at every computation step,

- takes into account statistical characteristics of measurement noise.

The RASEV algorithm, is of the same type as the previous one. It only differs by the taking into account of the global model :

$$Z_k = S . \theta_{k-1} + Z_o$$

It then identifies S and Z_o at every computation step using Kalman filters whose status vectors consist of a row of matrix S associated with the corresponding component of vector Z_o.

The optimum control calculation is identical to that achieved by the other two algorithms.

The RASEV algorithm thus features :

- a permanent identification with entry of optimum controls at every computation step,

- a better introduction of modeling.

OFF-LINE SIMULATIONS :

A linear simulation of the helicopter vibratory behaviour under effect of higher harmonic controls allowed developing the previously described algorithms. This simulation is featured by five matrices S and vectors Z_o corresponding to various cases of longitudinal speed. Figure 6 shows the evolution of a column of matrix S for a longitudinal speed from 200 km/h to 280 km/h, with «connection» between two successive speeds being achieved with polynomial functions.
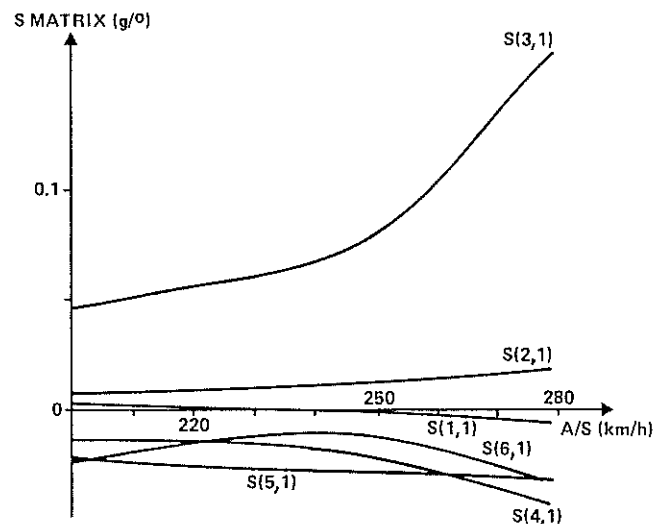

Fig. 6 :   EVOLUTION OF A COLUMN OF MATRIX S, USED IN OFF-LINE SIMULATION

An example of results obtained by simulation of closed loop algorithms is presented in Figure 7 showing the effect of higher harmonic control on the mean vibratory level in cabin, in the case of an acceleration phase (speeding up from 200 km/h to 280 km/h). The evolution of the vibratory level is presented on every diagram, with and without higher harmonic control, for the helicopter fitted with its passive suspension system.
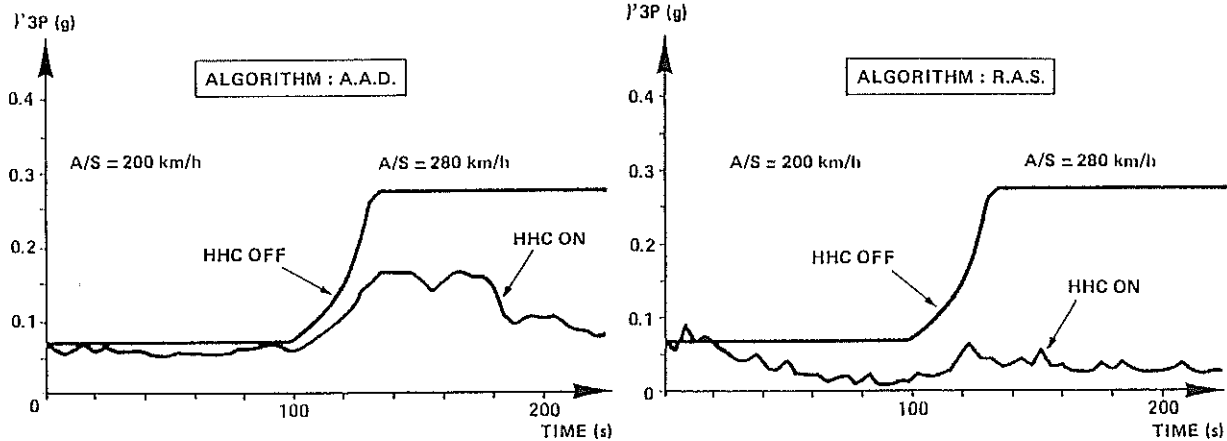
Fig. 7 : ANALYTICAL SIMULATION (LEVEL FLIGHT ACCELERATION)

Within the limits of retained modeling, these simulations allowed demonstrating the good self-adaptivity performance of algorithms during the evolution phases (especially for the stochastic algorithms), estimating the potential vibration gains and evaluating the effect of the various algorithm adjustment parameters on their efficiency (convergence rapidity, gains, self-adaptivity.....).

ROTOR RIG TESTS : EXPERIMENTAL SYSTEM INTEGRATION

After realization of the previously described system, programming the algorithms on the digital computer and validating them in real-time simulation, tests of the higher harmonic control system on rotor rig were carried out in late 1983 before final installation on aircraft.

The dynamic components comply with those of the SA 349 helicopter (turbine, mechanical transmission, hub, rotor). The higher harmonic control system tested is that which was installed on aircraft.

The rotor rig tests essentially allowed testing the complete integration of the system, from the data acquisition channel to the higher harmonic control realization and partly validating the safety analysis through failure simulation.

TEST PERFORMANCE METHODOLOGY : IMPORTANCE OF SIMULATION
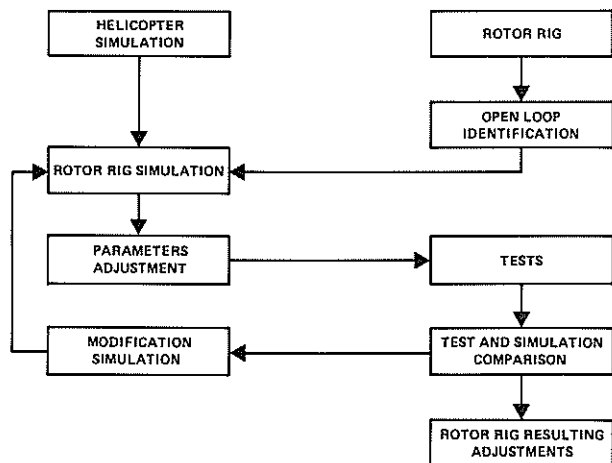

Fig. 8 : ALGORITHMS TEST METHODOLOGY

Establishing a test methodology (Figure 8) constituted an essential asset before the flight experiments.

It is based on the significance of an off-line simulation, representative of the rotor rig behaviour under the effect of higher harmonic controls.

So, the first tests on rotor rig were intended to identify the higher harmonic controls ⟶ non-rotating swashplate loads transfer, since the rig rigidity does not allow measuring the effects on accelerometers. Figure 9 gives an example of evolution of stress measurement with respect to the variation of every component of the control vector.
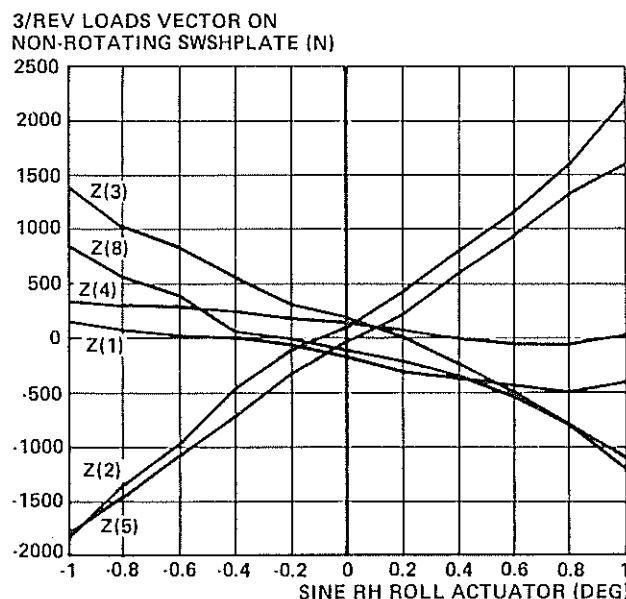
3/REV LOADS VECTOR ON
NON-ROTATING SWSHPLATE (N)

Fig. 9 : OPEN LOOP ROTOR RIG IDENTIFICATION

From the identification results, an off-line simulation was established so as to make a first adjustment of algorithms before testing the system in closed loop on rig. In the algorithms, the vibratory vector was replaced with the non-rotating swashplate loads vector, the rotor rig being free from vibrations, even in the presence of higher harmonic controls.

These simulations showed, in a first time, that considering the low level of stresses at 3/rev frequency, without higher harmonic controls, it was necessary for the algorithm tests to increase this level artificially with exciting controls at 3/rev frequency (directly introduced at input of multi-cyclic actuators (Figure 10)), and to verify that the system was able to counteract the effect of these inputs.
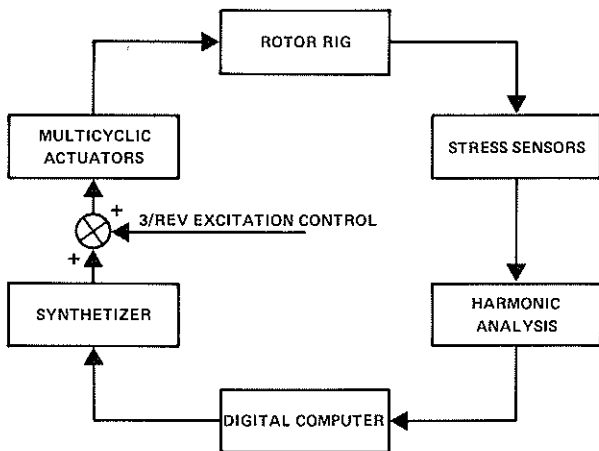

Fig. 10 : FUNCTIONAL DIAGRAM OF THE H H C SYSTEM DURING ROTOR RIG TESTS

TESTS OF HIGHER HARMONIC CONTROLS ALGORITHMS ON RIG

A partial validation of algorithm logic has thus been achieved. An example of results is presented in Figure 11 showing the behaviour of two algorithms (the effect measured herein is the mean of the dynamic loads transmitted by the non-rotating swashplate). It is noted that from an initial excited state, a few seconds after the system start signal, the algorithms finally reach the optimum control corresponding to the minimum stress level (level close to natural level in the case of rotor rig).
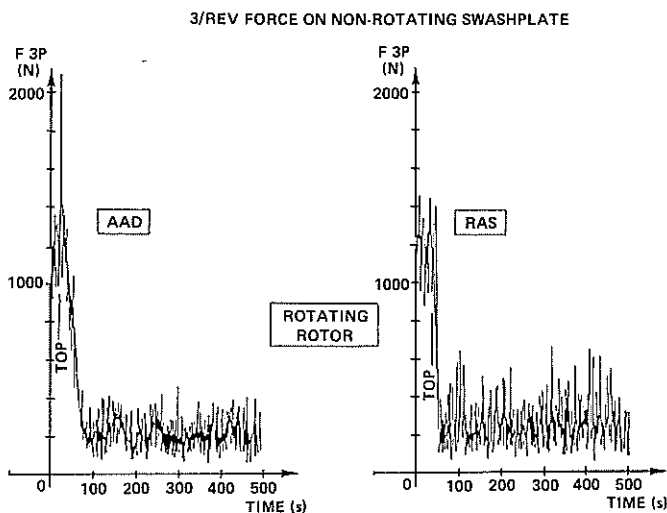

Fig. 11 : CLOSED LOOP ALGORITHM TESTS (ROTOR RIG)

Figure 12 gives an example of comparison between the results from rig tests and the results obtained in simulation for the RAS algorithm, with identical adjustments.
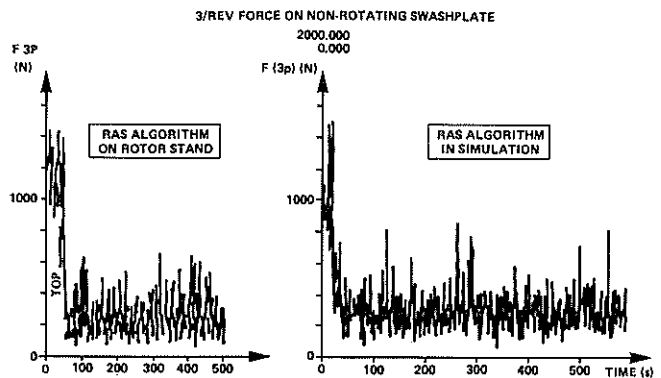

Fig. 12 : COMPARISON OF ROTOR STAND AND SIMULATION TEST RESULTS

This test performance methodology allowed reducing the duration of tests on rotor rig to three months approximately.

EXPERIMENTAL SYSTEM FLIGHT TESTS

The higher harmonic control system has been assessed in flight for two configurations of the basic aircraft : «free» focusing system (corresponding to the SA 349 GAZELLE fitted with its passive suspension system) and «blocked» focusing system (corresponding to an aircraft without passive vibration filtering).

For each of these configurations, the three multicyclic algorithms have been tested in closed loop throughout the flight envelope. The higher harmonic control travel has been limited to +/−1 degree during these experiments, considering the important dynamic loads on the flight control channel, encountered during the identification tests. The+/−0.8 degrees travel has been retained for the complete tradeoff analysis of the three algorithms, a travel increase up to 1 degree has been achieved for RASEV algorithm only.

The position of system acquisition sensors has been subjected to an optimization during these tests, which led to retaining four accelerometers : on vertical and longitudinal axes in forward section of cabin, and on vertical axis at pilot and copilot stations. Three of the sensors are on vertical axis, most of the objectionable vibration level being on that axis.

This paper deals with the results obtained with the active system acting on the helicopter without passive vibration filtering system (focusing system blocked), this case very likely corresponds to the use predicted for future helicopters.

TEST PERFORMANCE METHODOLOGY

The experimental system flight tests have been conducted as per the methodology implemented during rotor rig tests as based essentially on the significance of off-line simulation including a model representative of the helicopter vibratory behaviour under the effect of higher harmonic controls.

The airborne software is thus made up of various modules that can be selected in flight via the control unit and allowing complete identification of the SA 349 helicopter and tests of the three algorithms :

- Measurements without higher harmonic controls
- Calibrated control step sequences (5 levels possible)

- AAD algorithm
- RAS algorithm — Two sets of parameters possible
- RASEV algorithm

The test installation consists of a measurement bay intended not only to record the flight parameters, vibrations and stresses, but also to record all digital computer variables, transmitted by ARINC 429 link. Processing of these variables is achieved on IBM computer, which allows both using graphic tools and comparison with simulation, located on IBM.

OPEN LOOP IDENTIFICATION

The identification phase which is a prevailing step in this methodology has been conducted during specific flights thanks to the first two modules of the airborne software : measurements without higher harmonic controls and calibrated control step sequences.

It allowed constructing an important data base concerning the effect of higher harmonic controls, useful for the algorithm simulation development. Figure 13 is an example of curves obtained in flight stabilized at 160 km/h, representing the components of vibratory vector Z with respect to the amplitude of one of the control vector components.
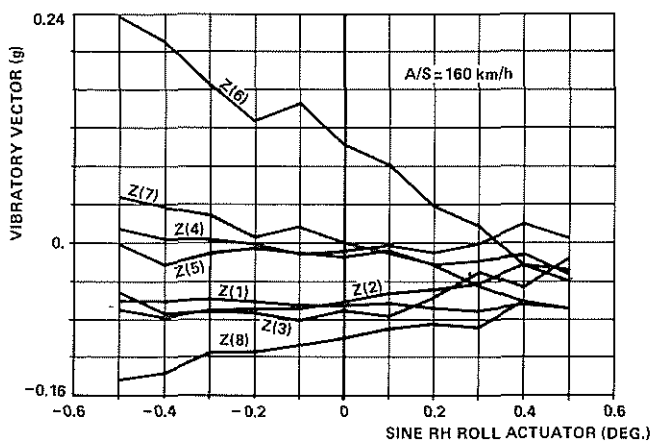

Fig. 13 : OPEN LOOP IDENTIFICATION FLIGHT
TESTS

SIMULATION PARAMETER ADJUSTMENT

The multicyclic algorithms adjustment parameters were obtained after off-line simulations on ground based on the identified open loop test results, the similarity between the helicopter and its simulation representation (with respect to the vibratory behaviour) thus permitting to retain the same adjustments during the flight tests.

Figure 14 corresponds to a comparison between the simulation (bold lines) and the flight (dotted lines) for a measurement vector component, during a test consisting of successive level flights at various speeds.
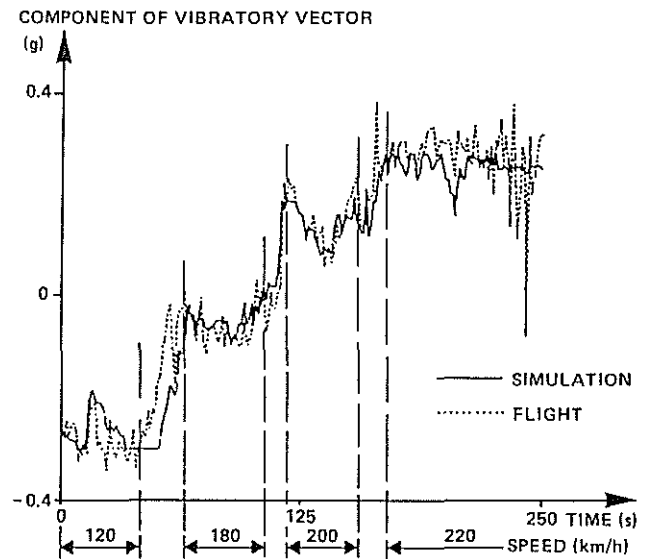

Fig. 14 : FLIGHT/SIMULATION COMPARISON AT
ISO CONDITIONS
(LEVEL FLIGHT AT VARIOUS SPEEDS)

This methodology thus permits :

- to proceed rapidly with the flight tests of the closed loop system ; thus, three weeks only were necessary, after the identification flight test, to initiate the closed loop tests.
- to minimize these tests thanks to the preliminary adjustments obtained in off-line simulation.

MULTICYCLIC ALGORITHMS FLIGHT TEST (CLOSED LOOP)

The test procedure adopted for the development and comparison of the three algorithms consisted of successive level flights stabilized at various speeds, with the system remaining active during the acceleration phases. This procedure has thus permitted to test the algorithm performance both for reducing the vibrations and for the self-adaptivity criterion (rapid consideration of flight case).

After development, the algorithms were assessed throughout the SA 349 GAZELLE flight envelope.

The comparison of the three algorithms is presented in Figure 15, it was obtained during a closed loop flight, with the previously described test procedure (the Global Vibratory Level corresponds to the measurements RMS at 3/rev frequency, taken on the sensors used by the system).
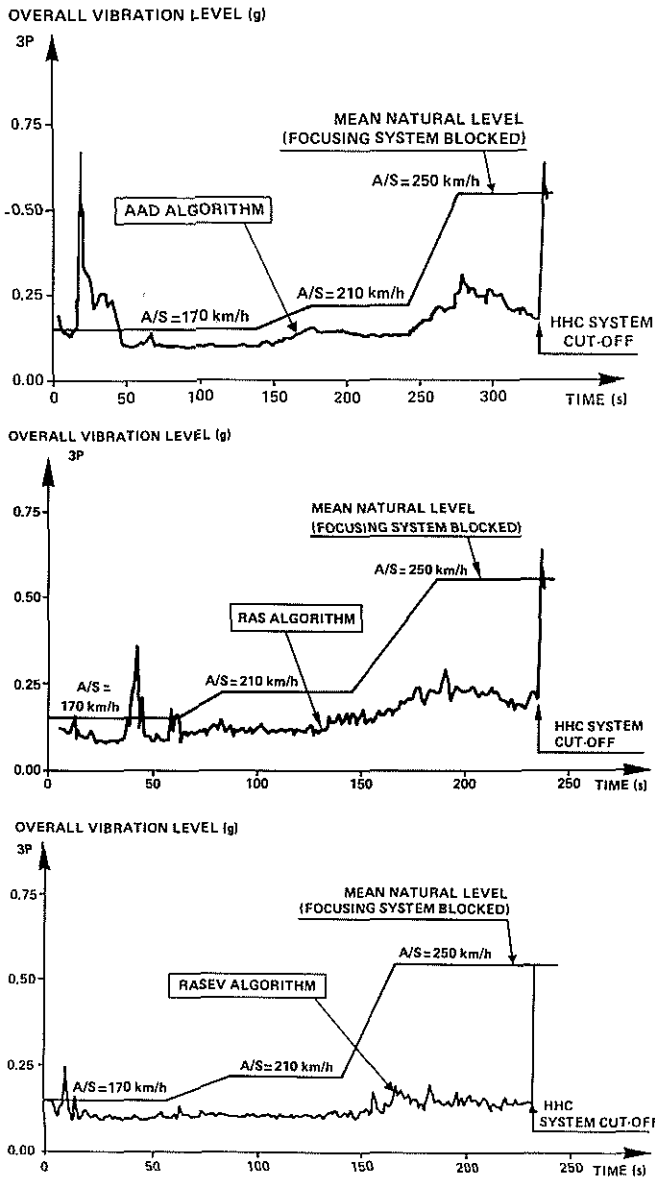
Fig. 15 : H H C ALGORITHMS RESULTS
(TRAVEL ± 0.8°) IN LEVEL FLIGHT
ACCELERATION PHASE

Thus, it can be noted that vibration gains obtained with the three algorithms are fairly close (approximately 80 % at 250 km/h), the RASEV algorithm being the more efficient. Figure 16 details the vibratory levels obtained at 250 km/h with the three algorithms tested and without any vibration filtering system (basic helicopter), measured along the vertical axis at three points of airframe.
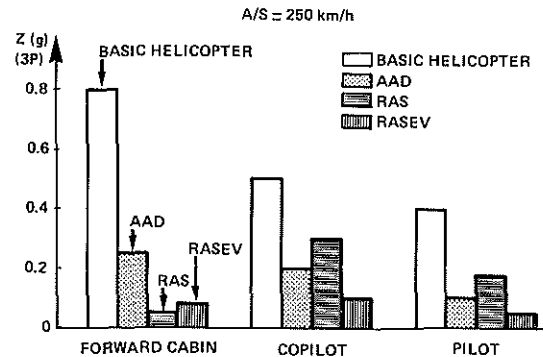

Fig. 16 : ALGORITHM COMPARISON
(MAX. CONTROL TRAVEL: ± 0.8°)

A part of the differences noted between stochastic algorithms (RAS and RASEV) and deterministic algorithm (AAD) is explained by the differences in the «useful» travel (travel used for the optimum control). Thus, for the same maximum travel, the AAD algorithm has a reduced (0.2 degree approximately) effective travel in order to retain some margin for the identification steps.

In fact, during these tests, it has been demonstrated that the vibration gains were directly connected to the travel allowed for optimum control.

The effect of control travel on 3/rev vibrations in the cabin is presented in Figure 17, for the three algorithms and three level speeds. The maximum control travel implemented in the algorithms during flight tests, was+/–1 degree. By extrapolation of the curves, it can be deduced that larger vibration gains could be obtained with the higher harmonic control system with greater controls travels.
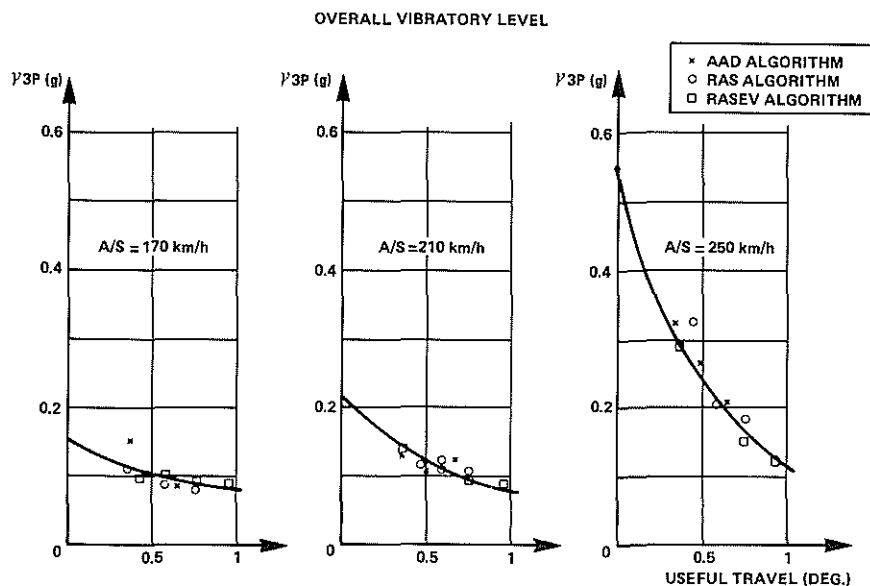
OVERALL VIBRATORY LEVEL

Fig. 17 : EFFECT OF CONTROL TRAVEL (MAX. CONTROL TRAVEL ±1°)

But, it should be reminded that the reduction of vibrations is not the only criterion for selection of algorithms.

The self-adaptivity performance is also important for the final selection of an algorithm since it directly affects the passengers comfort ; in fact the passengers are particularly sensitive to sudden variations in the vibration level.

As regards this criterion, the AAD deterministic algorithm shows some drawbacks : the identification generates high vibration «peaks» when initiating the algorithm (Figure 15), up to satisfactory identification of matrix S.

However, after optimization of parameters, the identification sequences are initiated only when modifying the flight conditions (accelerations), and do not necessarily generate high vibration «peaks» : the direction of variation of every control is selected with respect to the previous matrix S in order to reduce the Global Vibratory Level.

Considering the permanent identification of matrix S (and Z_0 for RASEV), the stochastic algorithms showed very good self-adaptivity performance.

The characteristic example presented in Figures 18 and 19 corresponds to a turn (load factor n_z : 1.5 g) at a speed of 200 km/h, the RASEV algorithm being in operation with a multicyclic control authority of +/−0.8 degrees.
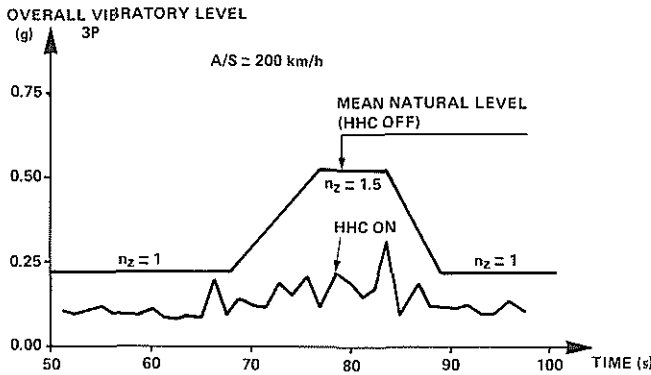

Fig. 19 : SELF-ADAPTIVITY PERFORMANCE IN LOAD FACTOR
(RASEV ALGORITHM TRAVEL ± 0,8°)

COMPARISON WITH A PASSIVE SUSPENSION

If the performance of the system for active control of vibrations is compared with that of the SA 349 GAZELLE passive suspension (Figure 20), it could be noted that the active system leads to vibration levels equivalent to those of passive system where the latter is more efficient (pilot and copilot seats especially), the active system showing much greater performance at the other stations (nose cone and cabin rear section).

Fig. 18 : RESPONSE OF THE SYSTEM IN LOAD FACTOR
(RASEV ALGORITHM TRAVEL ± 0,8°)

Figure 18 shows that the vibratory level was not disturbed during helicopter turn ; Figure 19 allows demonstrating that this stability was obtained thanks to the modification of matrix S during turn (the sensitivity of a vibratory vector component to the variation of higher harmonic control in pitch and the evolution of the corresponding component of the control vector are presented).
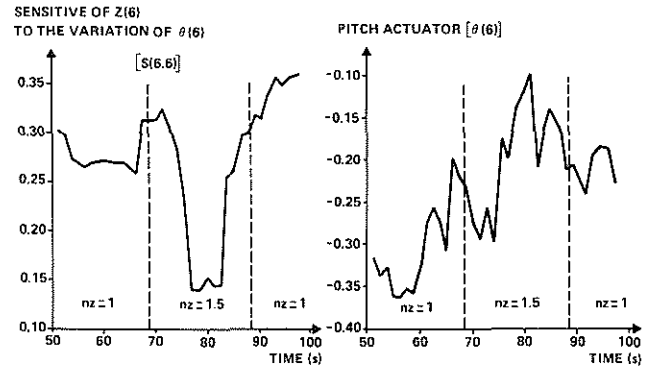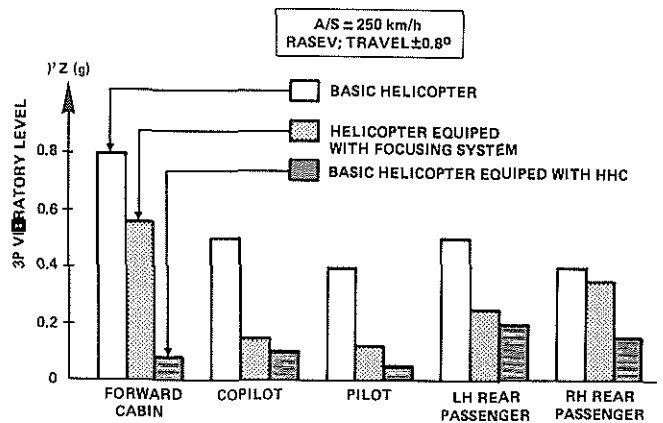

Fig. 20 : COMPARISON WITH PASSIVE-TYPE SYSTEM

In the same figure, it is checked that the higher harmonic control system acts not only at the locations corresponding to those measurements included in its optimization but also at points not taken into account by the algorithms (cabin rear section). This is due to the action of the system directly where vibrations are generated (rotor head loads).

EFFECTS OF THE SYSTEM ON THE LOADS AT ROTOR HEAD AND ON CONTROL CHANNEL (Ref (12))

It was possible to show through the analysis of higher harmonic control effects at various vibration generation levels that the major effect of the system was the reduction of 2/rev harmonic of dynamic forces and moments at centre of rotor which is the component with the greatest effect on cabin vibrations for the SA 349 helicopter, thanks to a higher harmonic control which is rich in 2/rev harmonics on rotating swashplate.

This reduction is also found on non-rotating swashplate at 3/rev frequency, on the introduction of dynamic loads in airframe (loads on struts attaching the main gearbox to airframe).

The auxiliary effects, especially on the dynamic loads withstood by the control channel, were significant during the identification flights where all higher harmonic controls combinations are generated (thus causing an amplitude limitation of 1 degree), but very low during operation of the system in closed loop where the generated controls are optimum for reduction of vibrations.

CONCLUSION

The development of the experimental system for active control of vibrations through higher harmonic controls whose major steps have been presented, led to :

- demonstrate the significance of a methodology both for the design and development of an airborne system and performance of tests which have to lead to the development of a software,

- to have a better knowledge of the vibratory behaviour of a helicopter and more precisely to obtain an in-flight «data base» allowing the rotor and structure modelings to be reset,

- to prove the efficiency of a system in closed loop for reduction of vibrations on a helicopter throughout the flight envelope.

In addition to the extension of the data base on the higher harmonic controls (new test flights), this action is currently continued on the study of pre-project of series systems in order to evaluate the cost of such a system for a series helicopter.

Lastly, this experimentation is an important application of digital techniques on a helicopter and shall lead to other aspects of the Generalized Automatic Control on Helicopter (CAGH).

REFERENCES

(1) F.J. McHUGH and J. SHAW, Jr., «Benefits of Higher-Harmonic Blade Pitch : Vibration Reduction, Blade-load Reduction and Performance Improvement», Proceedings of American Society Helicopter Region Symposium on Rotor Technology, August 1976.

(2) KRETZ, M., «Research on Multicycle and Active Control of Rotor Wings», Vertica, Vol. 1, No. 2, 1976.

(3) WOOD, E.R., R.W. POWERS and C.E. HAMMOND, «On Methods for Application of Harmonic Control», Vertica, Vol. 4, No. 1 - p. 43-60, 1980.

(4) HAMMOND C.E., «Wind Tunnel Results Showing Rotor Vibratory loads reduction using Higher Harmonic blade pitch control», J. of Am. Hel. Soc. Vol. 28 No. 1 (January 1983).

(5) WOOD, E.R. and POWERS R.W. «Practical design considerations for a flightworthy higher harmonic System», AHS Forum, 1980.

(6) WOOD, E.R., R.W. POWERS, J.H. CLINE, and C.E. HAMMOND «On Developing and Flight Testing a Higher Harmonic Control System», J. of Am. Hel. Soc. Vol. 30 No. 1 (January 1985).

(7) JACOB, H.G., & G. LEHMAN, «Optimization of Blade Pitch Angle for Higher Harmonic Control», Vertica 7, No. 3 - 1983.

(8) HAM, N.D., «Helicopter Individual Blade Control and Applications», Annual AHS Forum, 1983.

(9) DAVIS M.W., «Development and Evaluation of a generic active helicopter vibration controller», AHS Forum, 1984.

(10) O'LEARY J.J., SESI B.R. KOTTAPALLI, DAVIS M., «Adaptation of a modern medium helicopter (Sikorsky S76) to higher harmonic control», NASA CP 2400, November 1984.

(11) SHAW J., ALBION N., HANKER E.J., TEAL R.S., «Higher Harmonic Control : wind tunnel demonstration of fully effective vibratory hub force suppression», AHS Forum, 1985.

(12) POLYCHRONIADIS M., ACHACHE M., «Higher Harmonic Control : flight tests of an experimental system on SA 349 Research GAZELLE», AHS Forum, 1986.