Paper No. 3

RESEARCH IN MULTICYCLIC AND ACTIVE CONTROL OF ROTARY WINGS

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The paper relates the research work initiated by the French Government Research Agency, Direction des Recherches et Moyens d'Essais, DRME, since 1971 in the domain of active control directed towards applications to rotary wings. The programme stems from previous studies and tests performed on experimental 40-foot diameter DH 2011 jet flap rotor built for the U.S. Army and NASA. The particular feature of this rotor was its capability to introduce multicyclic effects to improve performance and dynamic behaviour of the lifting rotors. The impact of the fly-by-wire and of the control-configurated-vehicle techniques bore heavily on the promotion of this research whose aim is to abandon the conventional swash plate in the new generation of helicopters.

The analysis of rotor behaviour at high advance ratios shows that the rotary wings suffer from severe speed limitations. Fig. 1 illustrates a typical example of divergent rotor characteristics, control loads in this case. When the divergence boundaries are reached not only ride conditions become prohibitive but all helicopter elements subjected to alternating stresses exhibit time fatigue and wear with detrimental effects on operating costs, ref. 1. At still higher u values, at still higher load factors the rotor will experience dynamic instabilities and stall flutter will appear. We feel that we are facing conditions pushing towards conceptual break-trough if present helicopter speeds are to be exceeded. This situation calls for a broad research effort. Our meeting is an excellent example of efforts deployed.

In this paper I will endeavor to show that one of the means to achieve a shift of helicopter limitations is to introduce generalized feedback control of the blade. This approach leads to a new definition of the rotor control system characterized by the fact that each blade is governed independently by a feedback system comprising an electrohydraulic actuator as the main power element. In this respect the development of fly-by-wire and CCV techniques for fixed wings open new possibilities for rotorcraft. Their application will not only eliminate the mechanical linkage between the stick and the rotor head but also eliminate the swash-plate itself. In fact, the swash-plate introduces one of the most stringent limitations to the rotor control by coupling the blades and imposing monocyclic pitch variation. The freedom of the blade to counteract an external disturbance does not exist. At present the best we can do is to optimize the blade, the hub, the suspension system and accept in best tolerable conditions the heavy dynamic inputs the rotor receives at high forward speeds. In fig. 2, which is 14 years old now, ref. 2, is an outcome of comparison of two theoretical helicopters, an Advanced Vertol 107 and a jet flap DH 2011, our company was building in 1961. At an advance ratio of 0.45 the blade lift moment of the conventional rotor exhibits dynamic variations of $\pm$ 164% of its mean value. The jet flap rotor, having the capability of introducing multicyclic lift variations reduces this dynamic input to $\pm$ 45%. We can see clearly from the figure that not only the peak-to-peak values have been reduced but the multicyclic components of the aerodynamic moment have been largely eliminated. The experimental work on the DH 2011 jet flap rotor has proven that the theoretical considerations were correct. The rotor was tested several times in the NASA Ames 40 x 80 wind tunnel. The 1971 tests, ref. 3, have been directed to highlight the ability to alleviate vibration and stresses by modulating the control inputs. An example of recordings presented in fig. 3 shows the benifits obtained by introduction of multicyclic effects. 48% reduction of vibration and 40% reduction of blade stresses have been obtained at an advance ratio of 0.4. These results encouraged analytical work. An early attempt was made to find a mathematical model of the jet flap rotor, which gave an agreement not extending beyond 2 P variations. At that time our knowledge of unsteady jet flap forces was rather poor. Faced with an inextricable problem due to the large number of parameters involved, a new approach to the analysis of rotor dynamics has been developed. Based on matrix calculus, this method lead to the discovery of a particular transfer matrix replacing the rotor as a unique mathematical model, easy to handle, ref. 3. The transfer matrix has the particularity of being practically insensitive to widely varying flight configurations, thus permitting to proceed to optimization of multicyclic laws, fig. 4. The basic matrix has been obtained by identification method extended over 30 different test conditions at an advance ratio of 0.4. The example shows 80% reduction of stresses. Similar results have been obtained for vibratory loads. The work presently under way takes into account a simultaneous optimization of stresses, vibrations and power inputs. The method of ref. 4 established the computer programme ROMULAN allowing generalized optimization of multicyclic laws. The problem is thus solved theoretically and will be checked experimentally by the use of preprogrammed multicyclic laws.

The results presented here correspond to a specific jet-driven and jet-controlled rotor. The question arises to what extent other circulation control means would permit a similar reduction of stress levels and vibratory loads. Such systems as mechanical flaps, servo-flaps controlling the twist of the blade, low powered jet-flaps, conventional rotor blades having a multicyclic control in addition to the swash-plate control, introduce multicyclic lift effects and are, at least theoretically, capable of producing some degree of stress and vibration alleviation. The various systems differ only by their unsteady flow characteristics and are similar in introducing high frequency lift inputs of up to at least 4P signals. Since lift variation is the common factor for these systems, we will use non-dimensional lift :

$$\frac{C_L(\Psi)}{\overline{C}_L} \qquad \Delta C_L \text{ half peak-to-peak value}$$

for comparing them. This approach will provide us with an initial idea of the amount of lift variation we need to obtain the required stress and vibration alleviation.

To qualify the efficiency of a reduction schedule we introduce a reduction factor, RF, defined as follows :

$$RF = \underset{\text{Stresses}}{\frac{\dfrac{\Delta\sigma}{\sigma}}{\dfrac{\Delta C_L}{\overline{C}_L}}} = \underset{\text{Vibrations}}{\frac{\dfrac{\Delta F}{F}}{\dfrac{\Delta C_L}{\overline{C}_L}}}$$

and use half peak-to-peak values. The correlation of the results from the jet flap tests are presented in fig. 5. The straight lines represent the maximum value of RF obtained. Only one test point is shown ; all other points are located to the right of the straight line. The lines are drawn as first-order approximations and there is no evidence as to the shape of the envelope. The lines should be considered as being tangential to the envelope. The highest RFs obtained are : 1.65 for vibratory loads and 1.0 for blade stresses.

From the conceptual point of view the use of a jet flap constitues a considerable technological break-through. Solutions using conventional rotor blades are also investigated. The simplest of these solutions being the control configurated rotor, CCR, introduces the modification at the rotor head by eliminating the swash-plate and by replacing it by a new control system actuating each blade independently. This solution, when regarded from theoretical point of view, resembles the fixed wing gust suppression system. In fact the problems are identical if an actuator can be developed that operates fast enough to correct blade variations while the blade rotates. It thus becomes evident that whatever the control system envisaged it has to be characterized by :

1) a very short response time,

2) an aerodynamic capability to counteract rapidly varying lift forces.

Following these conclusions basic research work was initiated in 1971 by the French Government Research Agency, DRME, known as the E 44 programme. A two-dimensional model was built having as primary goal the feedback control of unsteady aerodynamic forces. By changing the trailing edge, the model can be fitted with jet flaps, as shown in fig. 6, or with mechanical flaps, or it can be used as a pure airfoil. The model has a 0.4 m chord and is 1.0 m in length. Excited by an eccentric device driven by a variable speed electric motor, it can oscillate about its quarter chord at frequencies of up to 40 Hz. Most of our tests have been performed by detecting the pressure field on a given airfoil section. Thirteen pressure pick-ups were converted to electrical signals by ONERA 20 H 130 transducers, then weighted and filtered as shown in the block diagram of fig. 7. The weighted signals (generally the integrated lift) were then compared with the desired reference signal before entering the electrohydraulic actuator. The actuator constitues the power transformer acting on the aerodynamic control means : in our case on the flaps or on the whole profile. The E 44 electrohydraulic actuator has been designed for applications to full-scale helicopter blades. Its performance is unaffected by 2 kN friction loads (approx. 100kg force) and 5 kg mass load. Its response time of 3 milliseconds corresponds to travelling one meter at a Mach Number of one. It is thus capable of controling 6 P signals at a rotor speed of 300 r.p.m. Losing roughly one degree per Hz, its useful frequency range extends to 30 Hz. A typical result obtained when tested as a gust absorber is shown in fig. 8. The model has been placed down-stream of the ONERA S2L gust generator producing $\pm$ 0.03 C_L variations. The lift variations have been absorbed by acting on a 10% chord mechanical flap. We can see that at 20 Hz gust alleviation reaches 63%. The control of the unsteady forces has been extensively explored for the two other configurations : jet flap and oscillating profile. The jet flap control has been investigated more particularly. We can see from the comparison of the results shown in fig. 9 that the correlation with ref. 5 is fairly good. However, the two test results differ from the theoretical predictions of Spence, ref. 6. The feedback control of unsteady forces, analysed in the linear domain of lift variations has been found practically identical when careful account is taken of aerodynamic transfer functions for each configuration, ref. 7. The useful band-width extended to 20 Hz and no attempt has been made to go well beyond this frequency range as the research undertaken is for covering as wide a field as possible without performing lengthy in-depth studies.

Our next task was to test the ability of the E 44 system to control the air loads under stalled conditions. We knew from related work, ref. 8, that the stall crossings appear in form of loops of C_L and C_m coefficients. An attempt to control the lift forces in a way we proceeded when the lift varied linearly, failed to give satisfactory results. Upon analysing the tests of ref. 8 we noticed a degree of loop shape similarity between the unsteady lift variations in the linear domain and the aerodynamic moment variations under stalled conditions. This lead to the idea of using a double loop feedback, with switching from unstalled to stalled conditions when the aerodynamic moment reaches a certain predetermined pitch-down value. Working on these lines has produced some remarkable results, enabling the aerodynamic moment to be controlled at frequencies of 15 Hz without excessive distorsion, fig. 10. The situation changed, however, when we attempted to repeat the tests accross the stall conditions. At 5 Hz, fig. 11, the output signals (pressure field) became very rich in harmonics and an apparent natural periodicity appeared, making it particularly difficult to continue experiments. Moreover, a very pronounced lack of periodicity appeared when the amplitude accross the stall decreased to $\pm$ 2°. In fig. 12, we can see that during one of the periods the model did not unstall at all. This result being a typical one, we repeated the unsteady tests with return to the unstalled region when the feedback is applied, fig. 13. The randomness seems to be a characteristic feature of most unsteady stall conditions. A similar example is reported in ref. 9. To obtain a better insight into the dynamic aspects of the stall, we applied a series of step inputs. The responses to steps of 0.02 sec are not symmetrical and the time delays are unequal. The time lags of several hundredths of a second explain the difficulty in controlling the stall beyond frequencies of 5 Hz. Fig. 14 shows a typical result for step inputs. The stalling transient has a much longer duration than the unstalling sequence. The lift is first rapidly established and maintains its value with a sudden break-down characterized by a certain oscillatory variation. During restablishment, the lift shows a curious inversion before reaching again unstalled conditions. The lack of periodicity of stall crossings and the oscillatory transient when the airfoil enters stall after a step input are not yet well understood. There remains still a wide field of investigation to explain all aspects of the stall phenomena.

As far as rotary wings are concerned, the research performed was successful in showing that it will be possible in the future to keep the blade out of the stall whatever the flight configuration. In fact it is feasible by detecting the aerodynamic pressure field on the blade to control the aerodynamic forces in such a way that the retreating blade is maintained at the highest prescribed C_L value without ever exceeding it. We can thus eliminate one of the main sources of vibrations of helicopter rotors. The two dimensional tests were highly instructive in the development of the feedback techniques to be used to control the blades in the domain of linear variation of lift and in the stalled conditions. Moreover, it could be demonstrated that the control can be applied effectively over a wide frequency band up to 30 Hz. These results encouraged further research that has been initiated on a 1.5 m diameter two-bladed rotor, model E 50, seen installed in the ONERA S2Ch wind tunnel in fig. 15. The rotor, a typical case of control configurated rotor, CCR, possesses independently controlled blades, of conventional type. Two electrohydraulic actuators mounted on the non rotating part of the rig, beneath the floor of the tunnel, command the pitch of each blade according to laws generated by the feedback system. The actuators and the electronic feedback apparatus are of the same types as those used in the 2-D tests. The first experiments on this model were performed in 1975 and covered the simplest cases of rotor feedback, related to the flap angle control at high advance ratios. Fig. 16 shows the test envelope. The domain investigated is confined within the values 1 and 3 for μ. The hover and stopped rotor - Ψ = constant = 90° - configurations have also been investigated. By detecting the flap angle it could be demonstrated that the typical rotor instabilities at advance ratios up to 3 and at wind tunnel speeds of 90 m/s can be eliminated. The accuracy of the flap angle control has exceeded during these tests ± 0.2 degrees. This research work represents the preliminary stages of the tests on the CCR, model E 50, and will be followed by optimization studies to reduce vibratory loads, blade stresses and power inputs for advance ratio values in the range μ = 0.3 to 0.7.

The immediate objectives persued are oriented towards conventional rotors equipped with unconventional controls. It appears that the control configurated rotor, CCR, will become the next step present helicopters will have to face to overcome, 1°, their speed limitations due to high vibration levels and, 2°, to eliminate their inherent instabilities at high advance ratios and at high lift coefficients. Let us conclude by looking at fig. 17 showing a project of a specific type of CCR full scale test model, a possible solution for conventional helicopters having fly-by-wire controls. Fig. 17 shows the Alouette II rotor head having its swash plate replaced by a non tilting plate. The outer rim of this plate is rotating and carries three, type E 44, electrohydraulic actuators. The oil pump driven by the rotor shaft is also rotating to avoid rotating joints. Each actuator controls the pitch of a corresponding blade in a manner that is mechanically separate and independent of the control of the other blade. The actuators are fed via slip-rings with the command signals from a generalized feedback system placed in the non-rotating part of the rotorcraft. Such a solution can be used for test purposes in the very near future and become operational in few years when electronic controls will become fully reliable.

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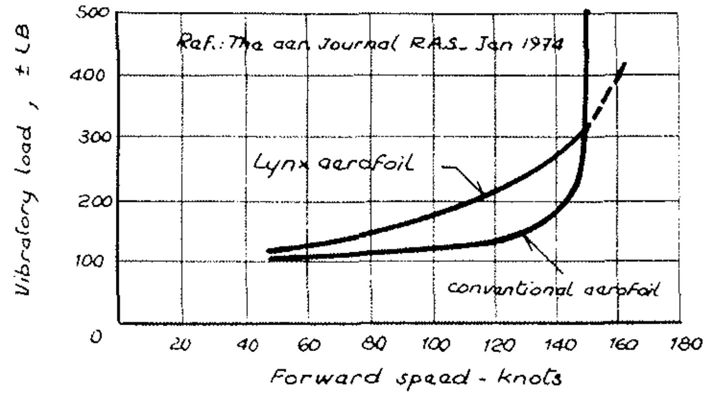


Fig. 1 - Example of helicopter speed limitations. Control loads.

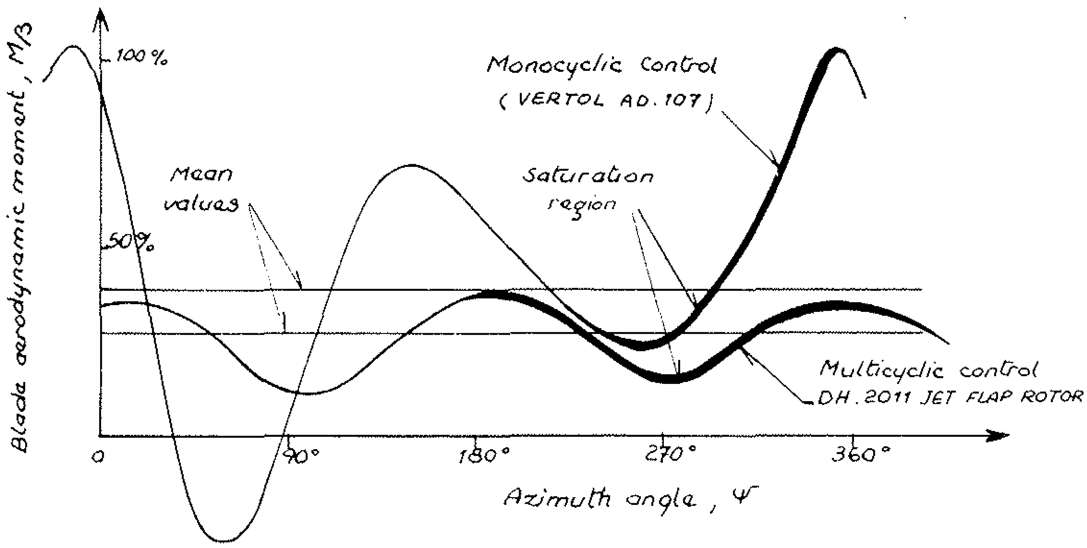
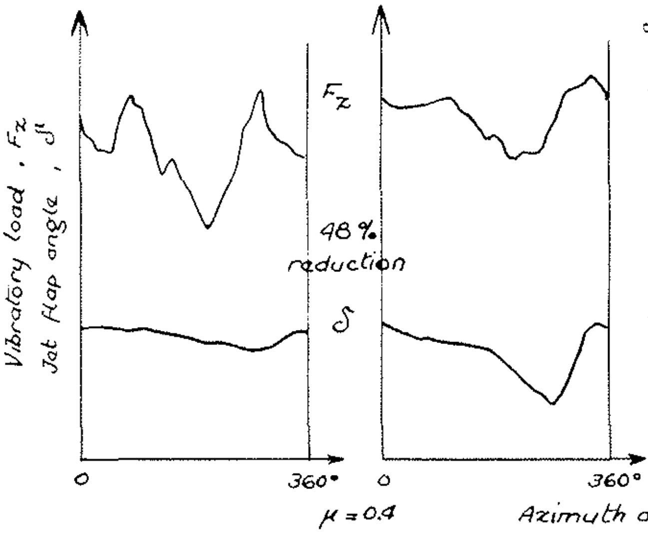


Fig. 2 - Reduction of dynamic loads by multicyclic lift control. V=95m/s, =0.45.



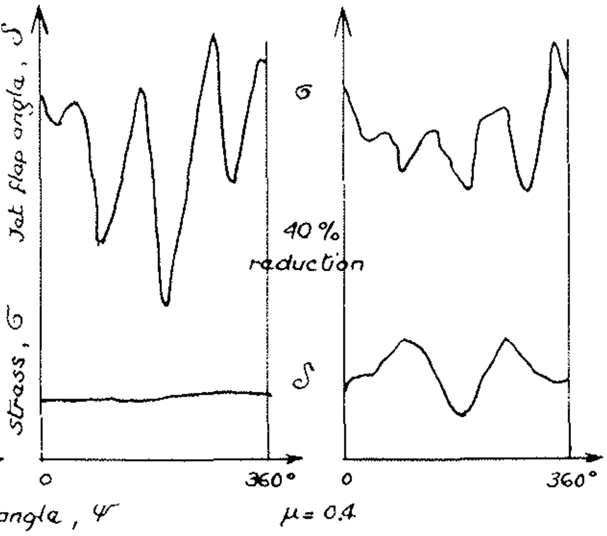


Fig. 3a - Reduction of vibratory loads Fig. 3b - Reduction of blade stresses

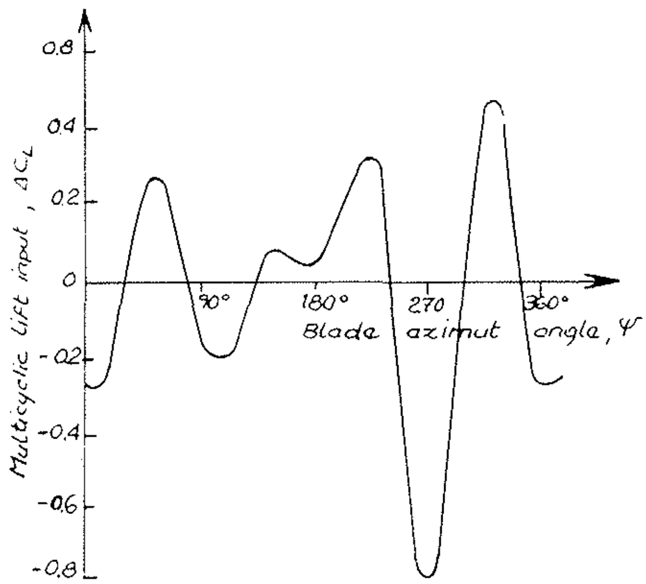


Fig. 4 - Optimal law for stress reduction.
$\overline{C}_L = 0.6$

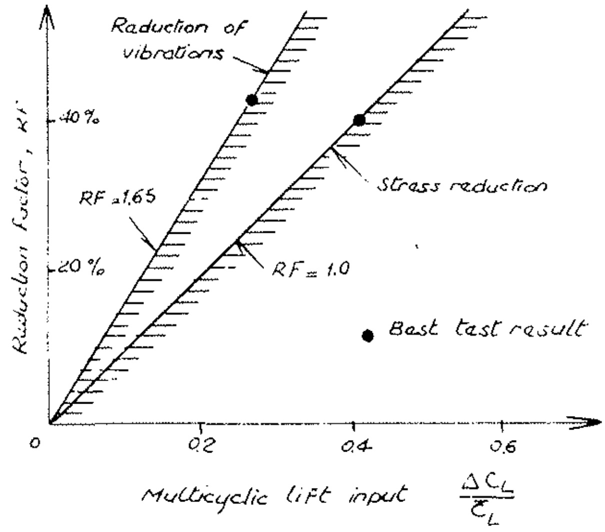


Fig. 5 - Vibration and stress reduction factors *v.* multicyclic lift input.
$\mu = 0.4$

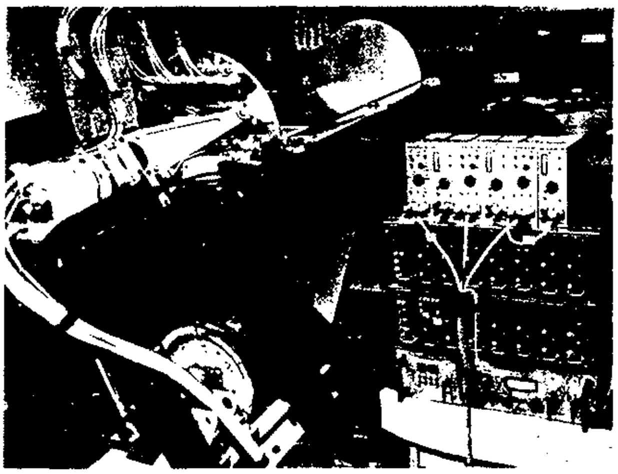


Fig. 6 - Test model E 44

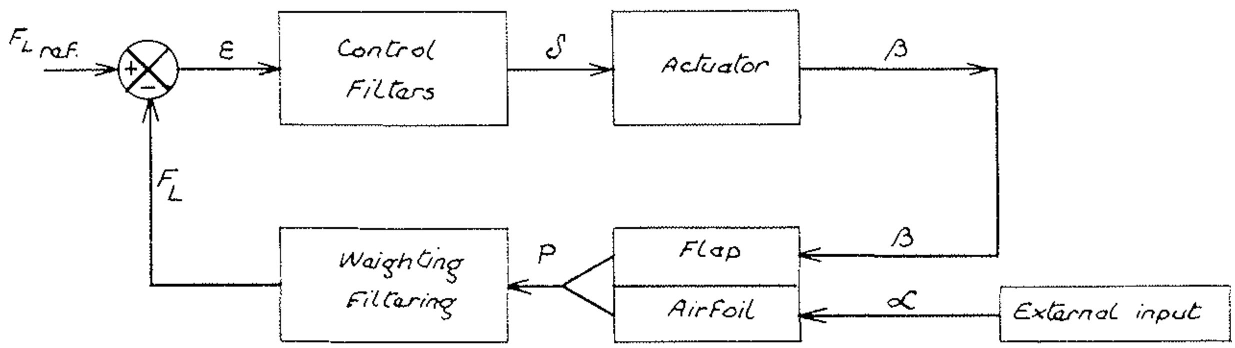


Fig. 7 - Feedback block diagram. E 44 model

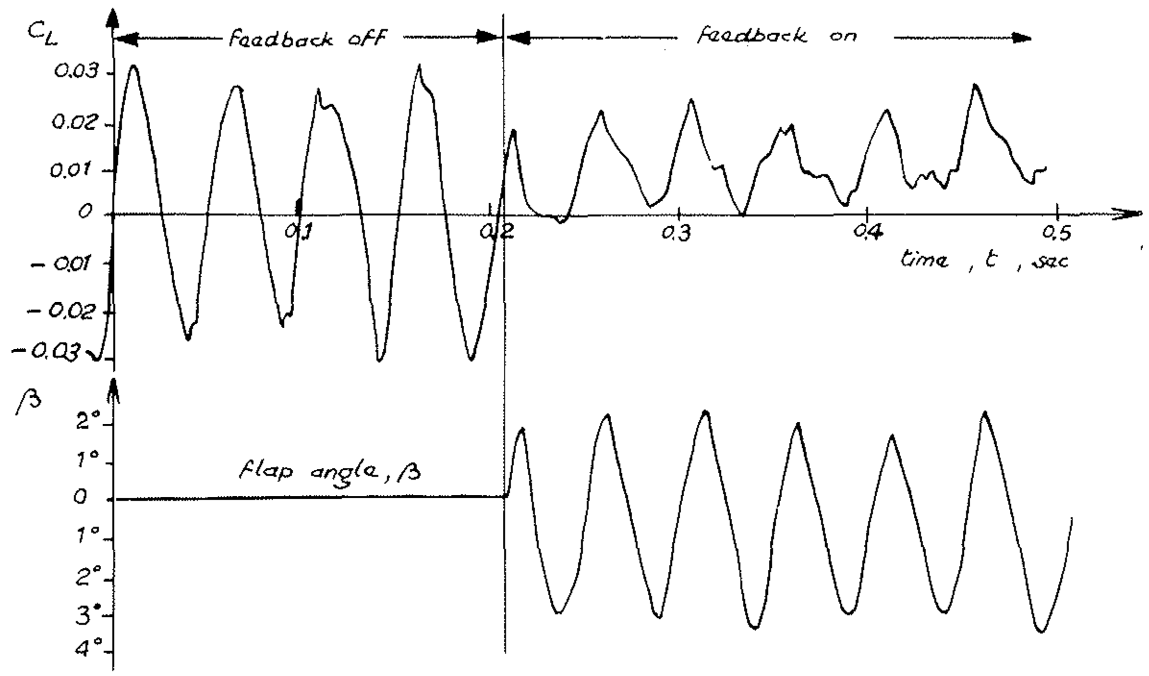


Fig. 8 - Gust absorbtion at low C_L values. Frequency 20 Hz.

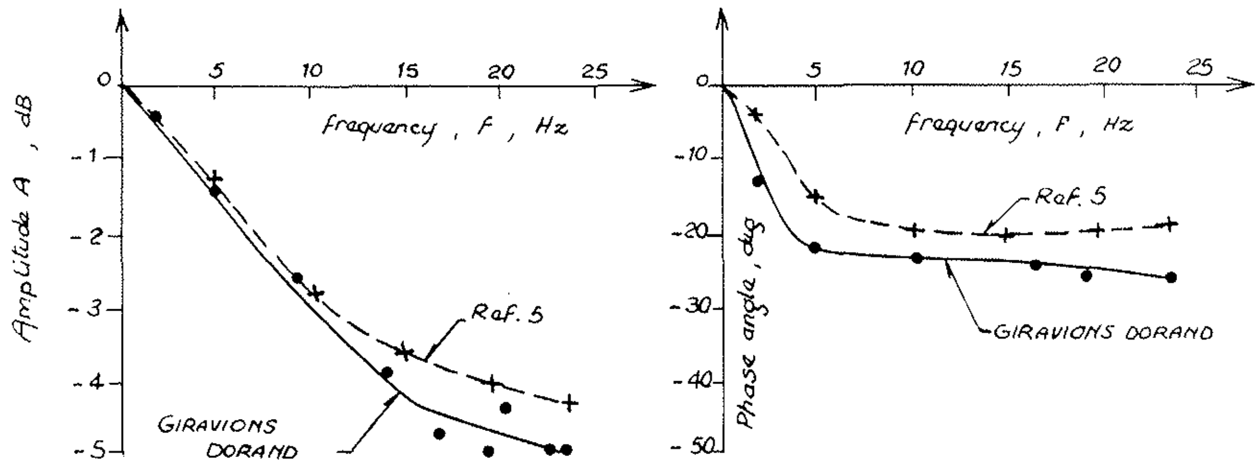


Fig. 9 - Unsteady frequency response of jet-flap. Correlation of test results.

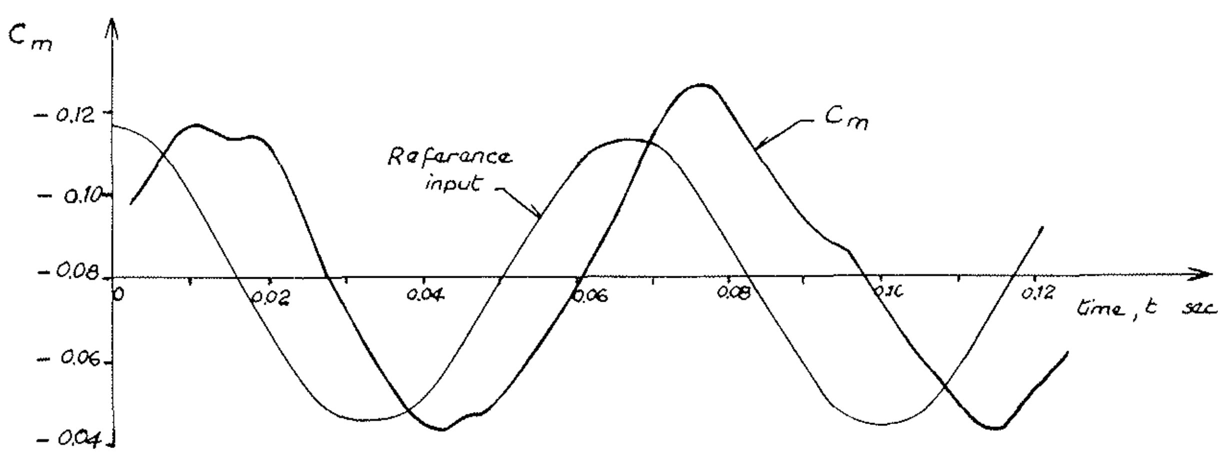


Fig. 10 - Feedback control of aerodynamic moment, in stalled conditions. Frequency 15 Hz.

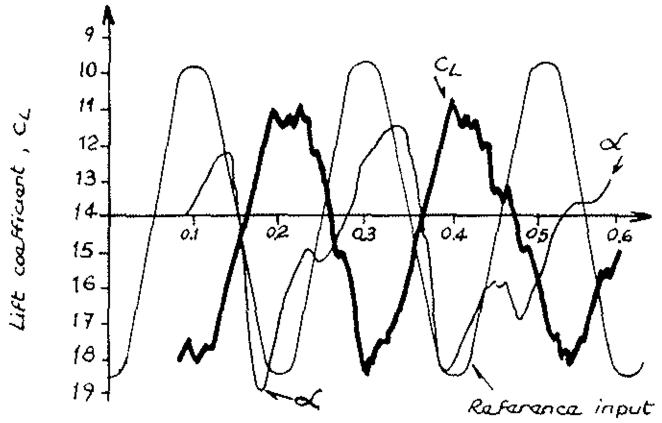


Fig. 11 - Feedback control of lift forces accross stall. Frequency 5 Hz.

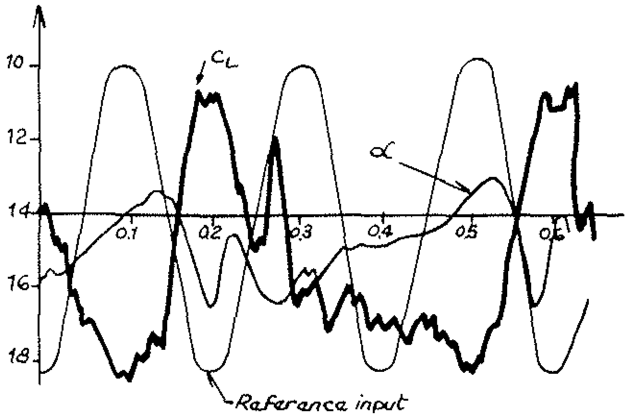


Fig. 12 - Example of non periodic response in fig. 11.

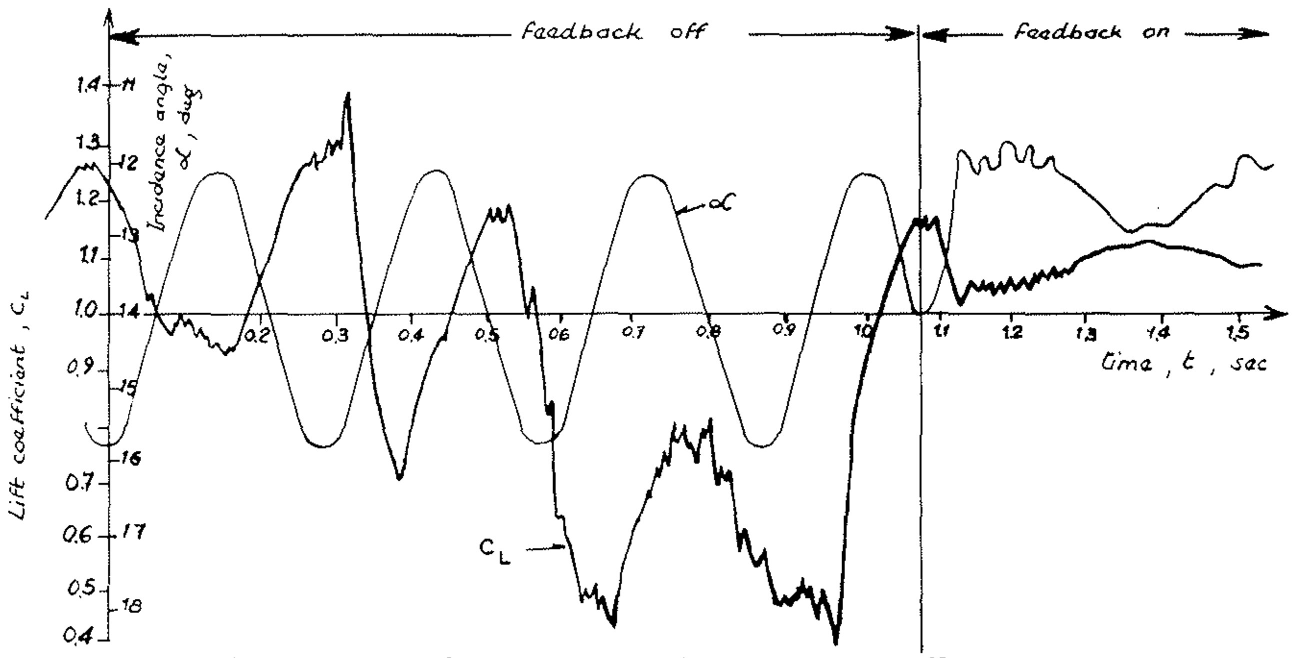


Fig. 13 - Non periodic response and return to unstalled conditions.

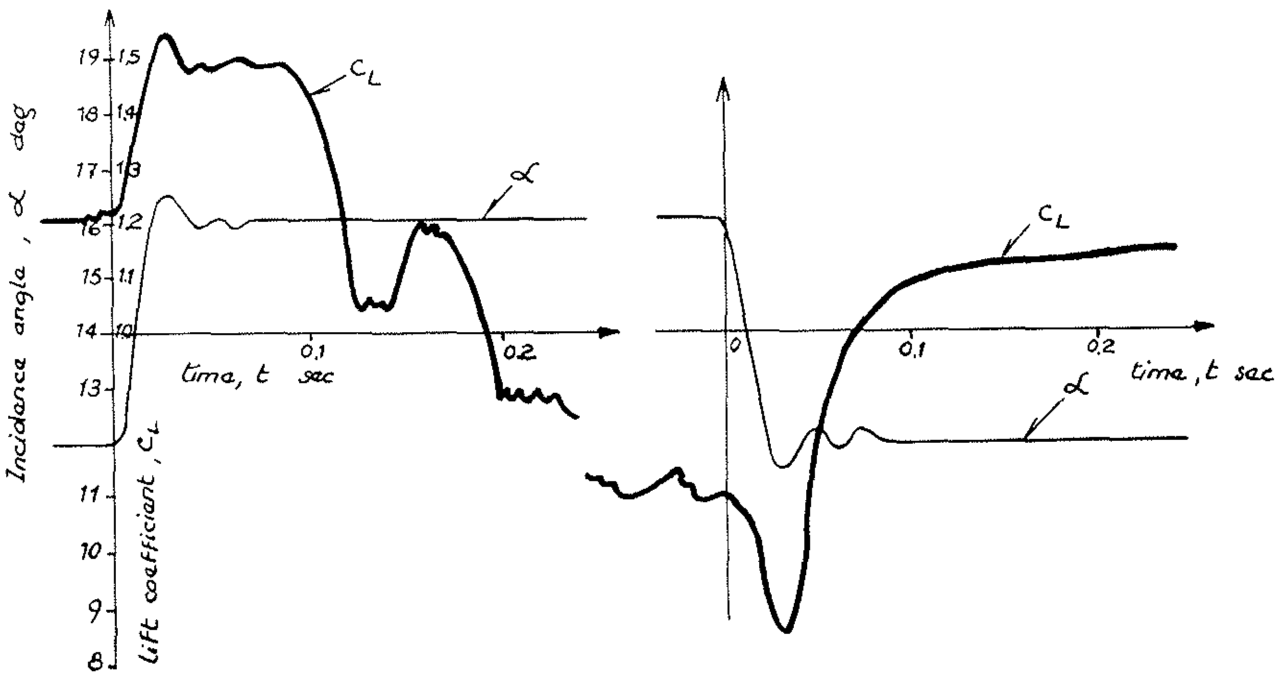


Fig. 14 - Lift responses to step inputs accross stall.

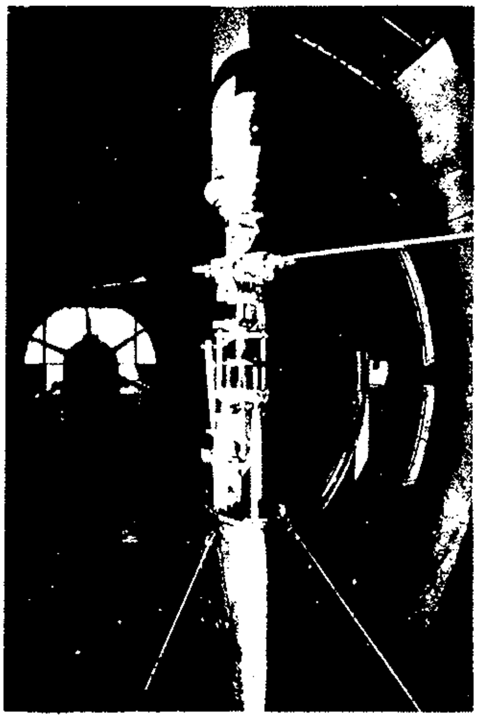


Fig. 15 - Control configurated rotor E 50 in ONERA S2Ch wind tunnel.

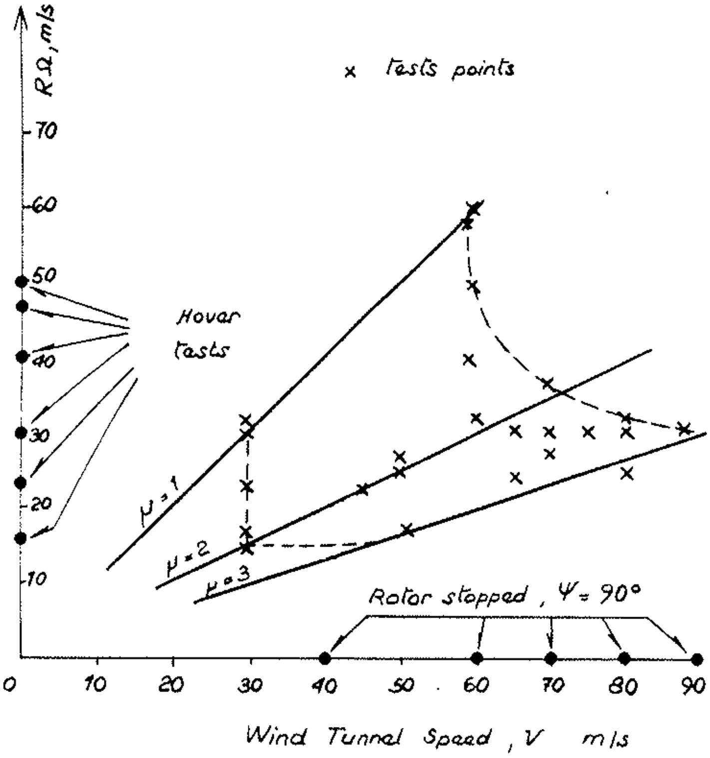


Fig. 16 - Test envelope of the E 50 rotor.

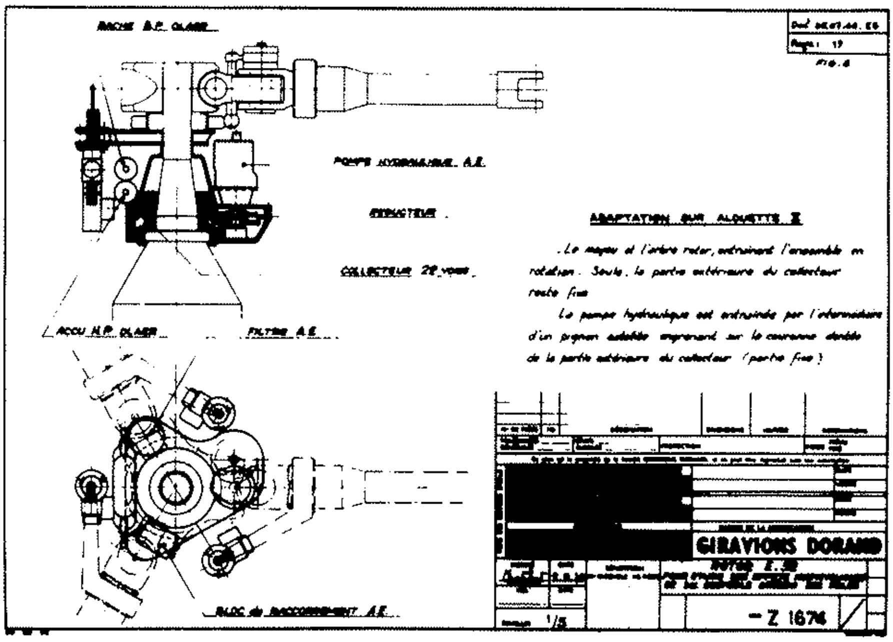


Fig. 17 - Project of full-scale control configurated rotor, E 52.