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FUTURE OF HELICOPTER ROTOR CONTROL

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ABSTRACT

The projection into the future of past achievements in the field of rotor control shows an ever increasing use of feedback techniques to extend the helicopter flight envelope. Limitations of the present monocyclic swashplate will have to be overcome by the use of new types of control.

The paper presents experimental and theoretical results of research directed towards the extensive use of active control. It discusses self-adaptive automatic systems for reducing vibration and stress levels at high load factors and high speeds.

Tests on stall barrier feedback show the effectiveness of sensing the local pressure distribution over the blades of a rotor to remove stall from the normal working conditions of a rotor. Fast response action is used to absorb aerodynamic disturbances and gust effects. Rotor instabilities can be entirely eliminated. New types of control required by this technique result in the elimination of present swashplate and mechanical controls by the installation of fast-response electrohydraulic actuators on the rotating part of the rotor and by the introduction of electrical transmission of control signals.

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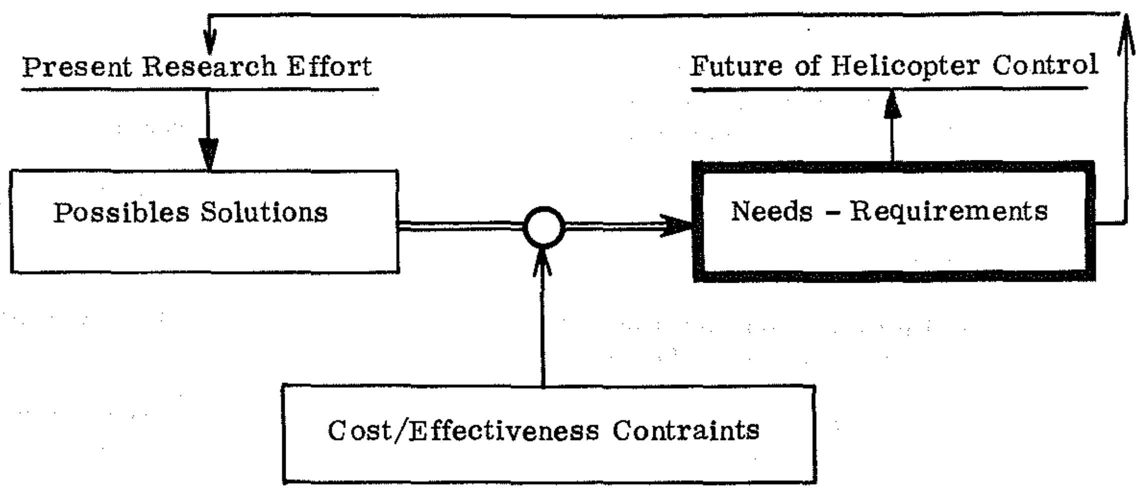
1. FORESEEABLE FUTURE

Discussing the future of helicopter control is a very attractive pastime for someone who has been dabbling with these problems for thirty years. Since all my statements about the future are perfectly unverifiable, I am nevertheless fully aware that my imagination can very well meander in the realms of the unknown. I will therefore endeavour to stay as closely as possible to a rational procedure which will guide our projections into what might happen in the next ten or twenty years. Figure 1 helps me to explain this attitude. The future, in my and many other engineers' opinion, is equivalent to continuous progress, progress that is governed by incentive born of present-day "Needs and Requirements". Once these are identified, we plan vigorous research programmes to satisfy these very needs. We have to define precise objectives and list possible solutions. Since "Need is the Mother of Invention", there is no doubt that if needs are sufficiently acute, high-quality solutions will be forthcoming. A filtering process must therefore be initiated to make the appropriate choices. We must also pay attention to any "Cost/Effectiveness Constraints". We must analyze the trade-offs to reach a satisfactory result. By following this progress, we can predict the future from the possible solutions in a completely rational manner. So let us review and analyze the present situation with respect to the future of helicopter control. This leads us to a foreseeable future. We will start with rotor limitations and analyze their origins. We will then define our objectives and propose possible solutions. Finally, we will risk a few shots into the future.

2. POTENTIALITIES OF ACTIVE CONTROL

Figure 2 illustrates typical rotor working conditions (Ref. 10). The local blade lift coefficient is plotted against Mach number. It is seen that the blade moves into forbidden areas beyond the stall angle and beyond drag divergence. Such conditions are normally tolerated during manoeuvres, during flight at high load factors and at high speed. However, as is well known, the entry into such forbidden areas limits the helicopter flight envelope by causing violent increase of vibration, stress and power consumption. There are, however, two ways of improving the situation : the first consists of pushing back limits by improved aerodynamic profiling. We will not discuss this aspect here, but we will concentrate on the second solution, which consists in paying closer attention to rotor limitations in order to reduce vibration, stress and, at the same time, the power input. This can be achieved by improved control of aerodynamic forces. Remember that today's helicopter uses direct monocyclic control. Thus no attempt is made to prevent the blade from entering the stall, a situation that would hardly be tolerated for a fixed-wing aircraft. No information is available or used for improving this situation. However, it is basically feasible to hold the blade at the stall and compressibility limits without ever allowing boundary layer separation. The solution consists in sensing instantaneous rotor behaviour and acting through additional or new controls to maintain healthy aerodynamic flow all over the rotor disc area. The answer is active rotor control. At least two conditions must be satisfied in order to implement active control : first we must overcome the limitations of the present swashplate that couples the blade pitch angles

Need is the mother of invention
Where there's a will, there's a way.



FIRURE 1 - PROCESS CONDITIONING THE FUTURE

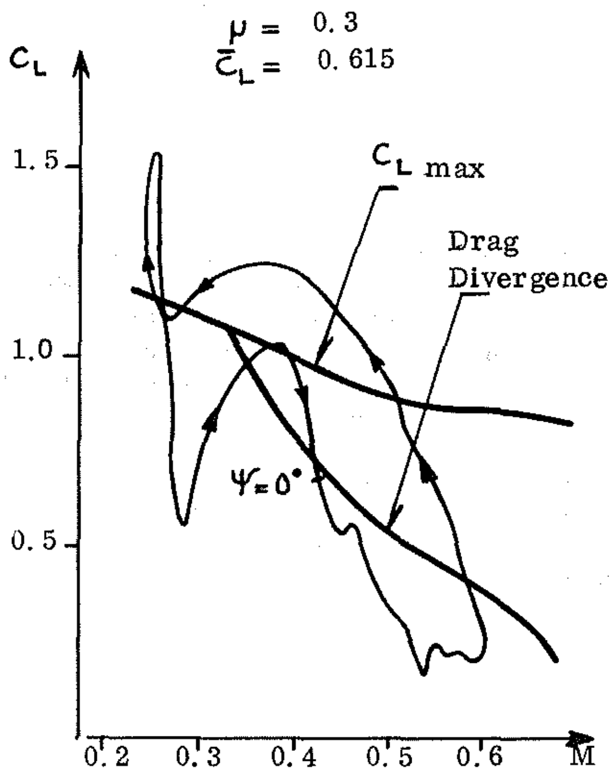


FIGURE 2 - WORKING CONDITIONS OF A ROTOR BLADE ELEMENT AT 0.71 RADIUS - REF. : 10

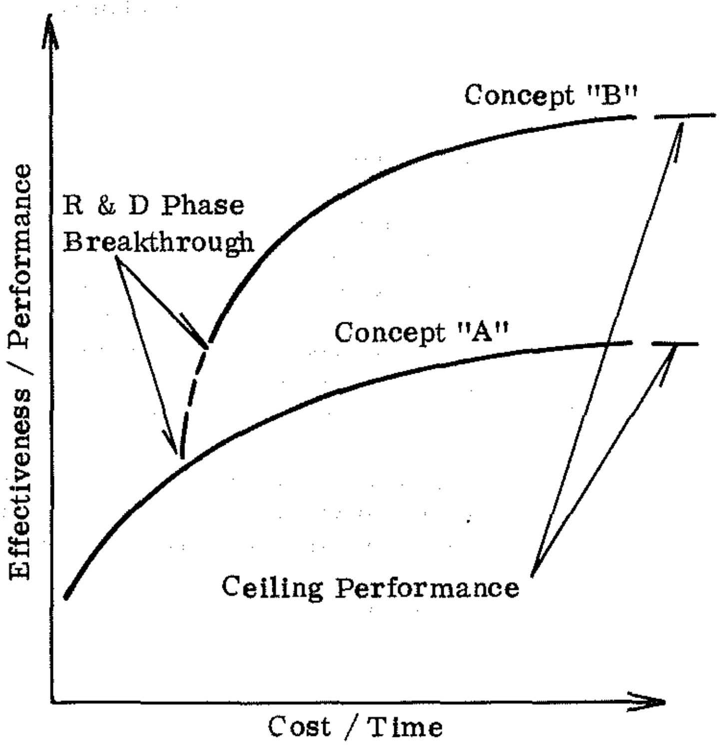


FIGURE 3 - GENERAL TRENDS OF TECHNOLOGICAL PROGRESS.

and provides only monocyclic pitch variation ; secondly we need fast-response actuators to allow extension of the control spectrum to higher-order harmonics. We can then take the next step. Requirements having generated research objectives and orientations, we can list the possible solutions. Figure 4 shows the potentialities of active control. The "Broadening of Flight Envelope" objective can be met by four distinct feedback systems :

- Instantaneous action within the linear range of lift variation to eliminate gust effects, disturbances and interactions.
- Stall and compressibility barrier feedback effectively preventing the blade from entering the forbidden areas of drag divergence due to boundary layer separation.
- Introduction of multicyclic lift variation for modulating the highly variable forces on the blade to reduce them to more acceptable levels. This approach does not necessitate instantaneous action. The solution consists in self-adaptive automatic generation of multiharmonic control inputs. This solution seems highly attractive and corresponds to research effort (Refs. 1 to 7) scheduled for the near future.
- Instantaneous action for eliminating instabilities. The origin of the latter can be attributed to high load factors, high advance ratios, and mechanical and aeroelastic coupling typical of a rigid rotor.

3. TECHNOLOGICAL JUMP

The introduction of active control is a multipurpose technique and will require complete reorientation of technological concepts, against which the present helicopter industry is resisting. Figure 3 schematically illustrates the law of technological progress. The introduction of a new concept must be highly cost-effective to be justified. The continuous line is the road along which industry is travelling, general improvement resulting from the accumulated effect of successive perfections. If we wish to jump from the "low road" to the "high road", a breakthrough, a change of orientation is required. The jet turbine, the composite blade, the bearingless rotor, the fenestron, can be quoted as major performance jumps, and today we are certainly on the threshold of another major jump. Research has already produced results that bear promise of substantial performance advantages due to active rotor control. We will now concentrate on the time scale for introducing a new technique. The future is defined by new concepts that become operational through the arduous process of RDT and E. Having demonstrated the usefulness of the concept and its cost-effectiveness, we must also demonstrate its feasibility and anwser the question : is the present state-of-the-art ready to integrate the concept into a system. In order to substantiate all the benefits that active control can bring to helicopters, we must satisfy at least two conditions essential to this technique :

1 - Extremely fast-response actuators, having satisfactory response up to at least 30 Hz.

2 - Location of the actuators in the rotating part of the rotor.

Today's technology is ready for the R and D phase, but is not yet ready to render the concept operational. The time needed for the integration of this technique into an operational vehicle depends on two factors : the readiness of present-day technology and the requirement for much higher performance. These are the basic reasons that are now dictating the introduction of multicyclic pitch control by a self-adaptive automatic system, this being the first step of the active control concept implementation.

4. FUTURE ORIENTATIONS

The control system of the present conventional helicopter has survived since the earliest days of its practical use, without major structural or functional modification. Autopilots, SAS's and hydraulic boosters have appeared, considerably improving flight characteristics. However, there are two problems requiring solutions in which the control system plays a critical role : reduction of vibration level, reduction of vulnerability of military helicopters. The answer, that would at the same time result in cost and weight savings as well as reduced maintenance, is provided by the introduction of active control using fly-by-wire and/or fly-by-optical fibre techniques with elimination of the swashplate.

This approach has been proposed at the 1st European Forum in 1975 (Ref. 3). The research with its near-future applications is being vigorously pursued at the present time (Refs. 4 to 7). I would like to quote General S.C. Stevens addressing the Specialist Meeting on Flight Controls in October last year : "The elimination of the swashplate and all other rotating controls is one area where progress may be made. The actuators could be placed in the rotor hub or blade grips using fly-by-wire or optical control systems and hydraulic power could be generated in the rotor head, thus eliminating plumbing and leak points" (Ref. 8). We are thus heading towards major conceptual and functional modification of the control system. The new concepts of control activation are on the way, the main effort being oriented towards automatic self-adapted multicyclic effects. In its present phase, this effort conserves the swashplate, to avoid radical technological changes, and creates the required multiharmonic pitch variation by adequate higher-harmonic control of the conventional swashplate. The theoretical tools are being prepared to allow the study and analysis of this technique and its benefits (Refs. 1 and 2).

5. PROGRESS ACCOMPLISHED

Our work on active control was initiated in 1970 under French Government Research Agency (DRET) contracts. Our first objective was to develop an electrohydraulic actuator (the E44) capable of varying the pitch of a light-weight helicopter blade at frequencies of up to 30 Hz. A series of tests was performed on a 2-D model to assess the capability of this actuator to control unsteady aerodynamic forces in stalled and unstalled conditions (Ref. 3). In 1974, we started research on a rotor model more particularly equipped for the study of active control problems. This rotor was named

F-ROTOR, F for feedback. The tests performed since then were directed towards broadening of the helicopter flight envelope.

The F-Rotor is a 1.5 m (5 ft) diameter rotor built for wind-tunnel testing of active control principles. Its special features include the absence of the swashplate, the latter being replaced by a linkage controlling each blade pitch angle independently. Type E44 electrohydraulic actuators having a response time of 3 milliseconds can impose harmonics up to the 6th order. The tests performed on the F-Rotor were first directed towards achieving full control and stability at very high advanced ratios, exceeding unity, and in rotor stopped conditions. Later tests were oriented towards the development of multiharmonic techniques to reduce vibration and stress. This approach promises considerable progress in the control of dynamic behaviour of the rotor in steady flight by the use of a self-adaptive closed-loop system (Ref. 4). In dealing with steady-state dynamics, we needed an analytical support that would simulate the rotor in a simple and flexible manner. This has been achieved by the identification methods reported in Ref. 1 and 2, and has considerably facilitated the treatment of all problems of a multicyclic character.

Following the tests on the 40-foot diameter rotor in the NASA Ames 40 x 80 wind tunnel in 1971 (Ref. 1), where the multiharmonic control inputs were experimented on a jet-flap rotor at advance ratios of up to 0.6, we were faced with a mountain of information of very complex nature, forcing us to look for a new method of analysis and of processing the dynamic behaviour of rotors. The solution was found in the introduction of the transfer matrix having properties relating to a certain extent to the transfer function. In fact, the transfer matrix constitutes a multiplicative operator for deriving the multicyclic output from a multicyclic input. The difference between the transfer matrix and transfer function consists in the selection of input frequencies, which in the case of the transfer matrix must be multiples of the basic rotor frequency and not merely arbitrary. This in turn stems from the nature of the rotor dynamics described by a set of linear differential equations having periodic coefficients, these being Hill type equations.

The presence of periodic coefficients naturally modifies considerably and complicates the treatment of rotor dynamics. We can see in Figure 5 the difference with conventional type equations having constant coefficients, where a sinusoidal signal, e.g. 2P, gives rise to a multiharmonic output, a Fourier series rich in all harmonic components. The linear aspect of both types of equation must not, however, be neglected, as it simplifies analysis by allowing the linear addition of partial responses. We can see that amplitude proportionality exists in both cases and allows the introduction of proportionality coefficients corresponding to partial derivatives between the input amplitude, a sine or cosine of nP, and the output Fourier series whose coefficients can be represented as one of the columns of a matrix, the so-called transfer matrix (Figure 6). One of the ways of constructing the transfer matrix of the rotor therefore consists in exciting it at a given multiple of its basic frequency and recording the selected output, whose Fourier coefficients constitute the corresponding column of the transfer matrix. This approach has been used with success on the F-Rotor test results obtained in 1978 (Ref. 9). However, certain precautions have to be taken because of the non-linear behaviour of the rotor at high load factors and at high advance ratios, the tests having been performed for $0.5 < \overline{C}_L < 0.8$ and $0.3 < \mu < 0.5$. The objective of the tests was to

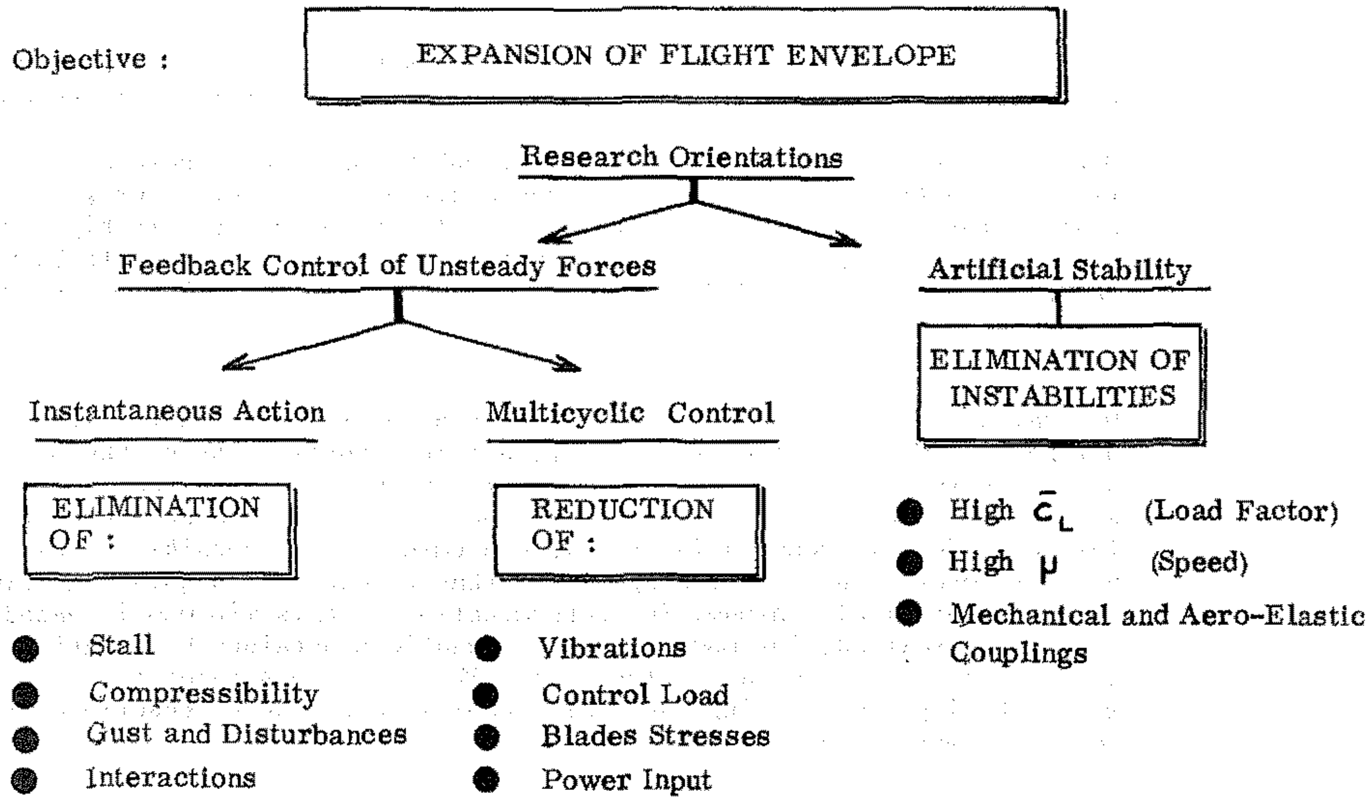


FIGURE 4 - ACTIVE CONTROL OF HELICOPTER ROTORS

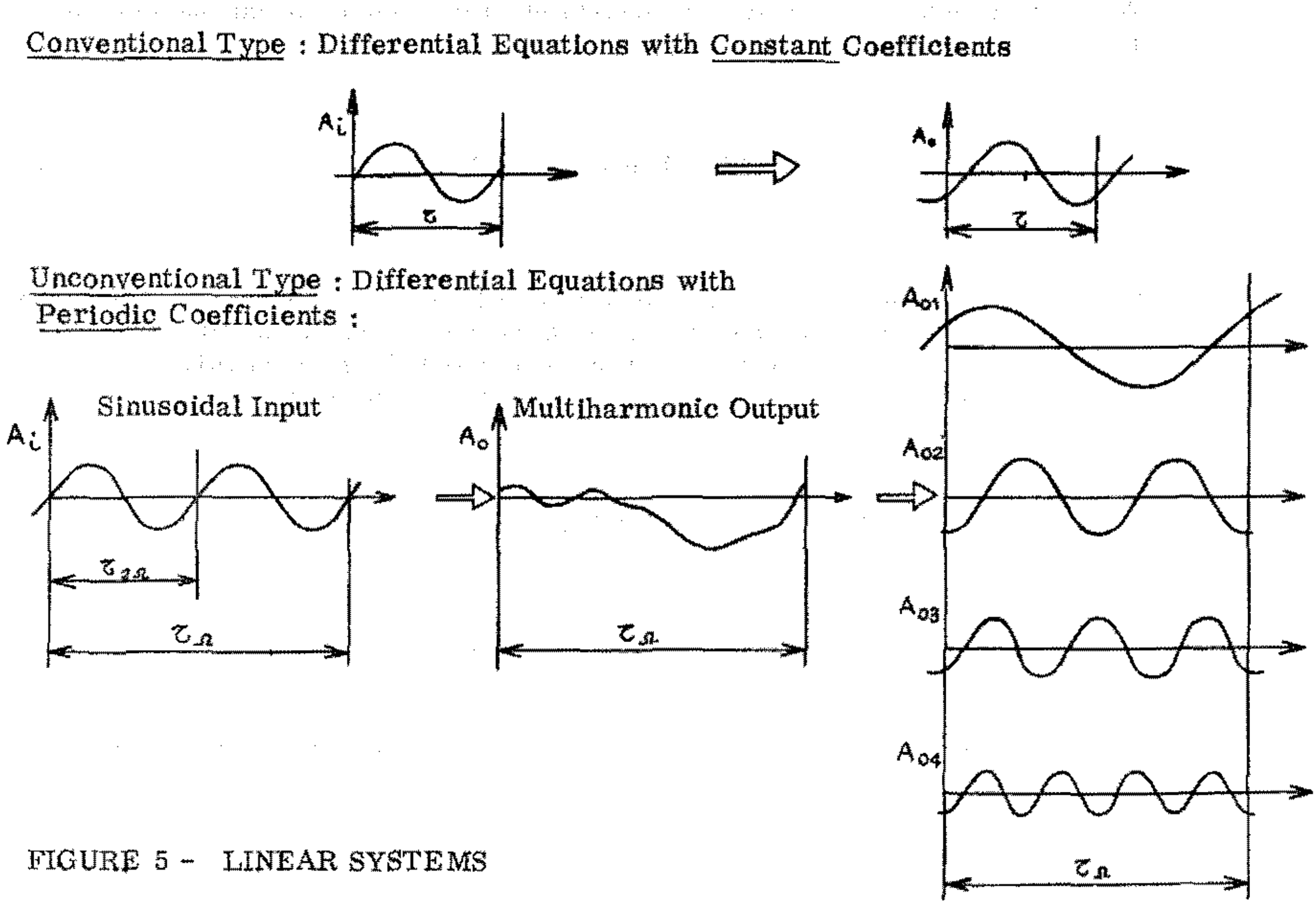


FIGURE 5 - LINEAR SYSTEMS

establish multicyclic control laws reducing vibration, in our case the vertical force at the hub and stresses in the blades (flapping bending moment).

With the linear approach, it is theoretically possible to determine a multicyclic control schedule that reduces a given output, e.g. vertical vibration force, to zero. In practice, this led to prohibitively high input amplitudes. A careful study showed that strong correlation exists between the norm of the input (RMS of the control amplitude) and that of the output, (Figure 7).

Determination of the ideal active rotor control transfer matrix from experimental data constitutes, however, a major problem. One of the procedures, as reported in Ref. 4, is to apply in succession as many purely sinusoidal input signals as there are coefficients in the multicyclic law. This procedure is comparatively time consuming. It is possible to use another rotor identification approach, that reduces the acquisition time to its theoretical minimum. The determination of this minimum is based on the use of self-adjoint modified state equations obtained by identification methods and model simulation (Ref. 11). The rotor considered as a linear system having time-varying (periodic) coefficients can be described in the form of a matrix equation.

$$\dot{x} = A(t)\,x + B(t)\,e \qquad (1)$$

The corresponding self-adjoint modified state equation can be written in this case as follows :

$$\frac{dy}{d\theta} = A^{T}(T-\theta)\,y + e^{*} \qquad (2)$$

There is an advantage in using equation (2) as it is easily deduced from equation (1) by the transposition of matrices A and B, as shown in Figure 8, and due to the fact that the transition matrices containing the step responses are also related by the transposition procedure :

$$\Phi^{\Theta}(T-\tau, 0) = \Phi^{T}(T, \tau) \qquad (3)$$

The number of step inputs can thus be minimized by reducing it to the number of degrees of freedom of x, equal to the number of components of the x vector. The theoretical minimum time required for acquiring the transfer matrix is equal to the number of rotor periods multipled by the number of components of the output vector x.

$$\sigma = T \, \delta$$

$$\begin{vmatrix} \sigma_{1c} \\ \sigma_{1s} \\ \sigma_{2c} \\ \sigma_{2s} \\ \sigma_{3c} \\ \sigma_{3s} \end{vmatrix} = \begin{vmatrix} T_{11} & T_{12} & T_{13} & T_{14} & T_{15} & T_{16} \\ T_{21} & \cdot & \cdot & T_{24} & \cdot & \cdot \\ T_{31} & \cdot & \cdot & T_{34} & \cdot & \cdot \\ T_{41} & \cdot & \cdot & T_{44} & \cdot & \cdot \\ T_{51} & \cdot & \cdot & T_{54} & \cdot & \cdot \\ T_{61} & \cdot & \cdot & T_{64} & \cdot & \cdot \end{vmatrix} \begin{vmatrix} \delta_{2c} \\ \delta_{2s} \\ \delta_{3c} \\ \delta_{3s} \\ \delta_{4c} \\ \delta_{4s} \end{vmatrix}$$

$$\sigma = [T_{14} \cos \Psi + T_{34} \cos 2\Psi + T_{54} \cos 3\Psi \quad T_{24} \sin \Psi + T_{44} \sin 2\Psi + T_{64} \sin 3\Psi] \, \delta_{3s}$$

$$T_{14} = \frac{\partial \sigma_{1c}}{\partial \delta_{3s}} \qquad T_{34} = \frac{\partial \sigma_{2c}}{\partial \delta_{3s}} \qquad T_{54} = \frac{\partial \sigma_{3c}}{\partial \delta_{3s}}$$

$$T_{24} = \frac{\partial \sigma_{1s}}{\partial \delta_{3s}} \qquad T_{44} = \frac{\partial \sigma_{2s}}{\partial \delta_{3s}} \qquad T_{64} = \frac{\partial \sigma_{3s}}{\partial \delta_{3s}}$$

FIGURE 6 - TRANSFER MATRIX OF A ROTOR

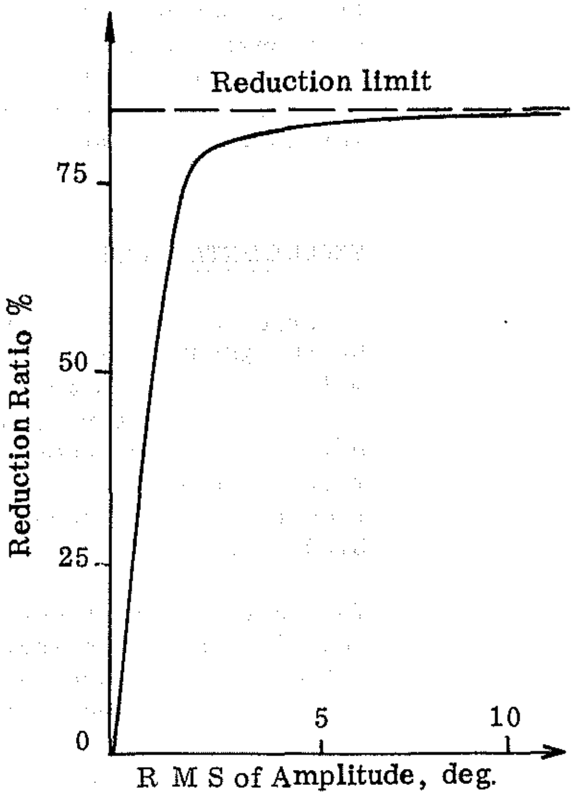


FIGURE 7 - ROTOR NON-LINEAR BEHAVIOUR

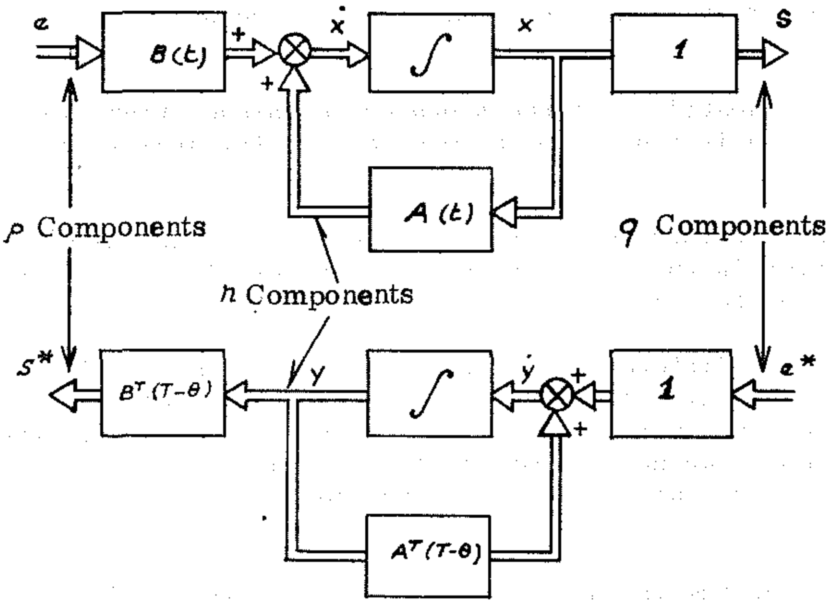


FIGURE 8 - SIMULATION OF SELF-ADJOINT MODIFIED SYSTEM

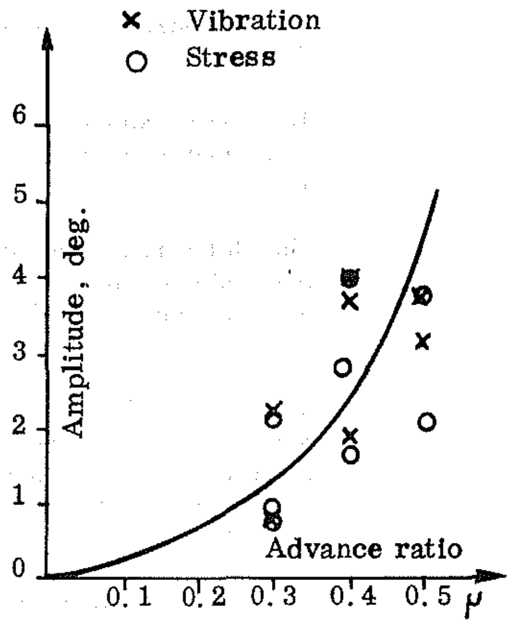


FIGURE 9 - PITCH AMPLITUDE DIVERGENCE

Part of our present research effort is directed towards reducing the time of transfer matrix acquisition and reducing the computational load. These two objectives not being necessarily compatible, there exist different possible compromises, resulting in different procedures, often equivalent, for solving the problem of transfer matrix acquisition.

6. EXPERIMENTAL APPROACH

A series of tests was run in 1978 to verify to what extent linear treatment by the ROMULAN procedure (Ref. 2) can be used to solve the problem. As we will see later in more detail, the non-linear aspects of rotor behaviour lead to prohibitively high input amplitudes, when the adopted optimization criterion is the complete nulling of the output. In fact, under given flight conditions, there exists a practical limit to vibration and stress reduction, which cannot be exceeded because of saturation of the retreating blade lift.

This particular aspect of rotor behaviour results in excessive input amplitude increase with increasing advance ratio as shown in Figure 9. When attempting to reduce vibration or stress or power, a compromise must be found, keeping conflicting requirements within practical limits.

In the 1978 test programme, multicyclic effects were introduced by a manually controlled multiharmonic generator. The output signals : the vertical force F_Z and the blade stress σ, have been computer-processed to obtain the harmonic analysis of the input and output signals, the transfer matrix and the multiharmonic input, by using the ROMULAN programme, minimizing the dynamic components of vibration and stress.

In order to reach these objectives, the approach followed two directions. On the one hand, we tried to obtain the required reductions by the introduction of experimental matrix laws, based on the ROMULAN programme, and on the other hand, we proceeded by output inspection and manual adjustments of the harmonic generator, resulting in determination of the so-called "empirical" law.

The tests showed the high capability of the proposed technique, vibration and stress being simultaneously reduced by as much as 80% (Figures 10 and 11).

The determination of transfer matrices by the introduction of pure harmonics showed non-linearities in the rotor response, particularly pronounced at low input amplitudes, of the order of 0.5°.

This phenomenon explains the differences recorded between the matrix laws and the empirical laws. The analysis of test results indicates that the practical determination of the optimum multicyclic control law based on the transfer matrix should impose an upper limit of output reduction. It is necessary to tolerate residual output because of the low sensitivity of the transfer matrix.

A practical-constraint algorithm (penalty function) must be inserted between the multiharmonic input and the transfer matrix, to take into account the practical aspects of the control problems. As in many cases of control

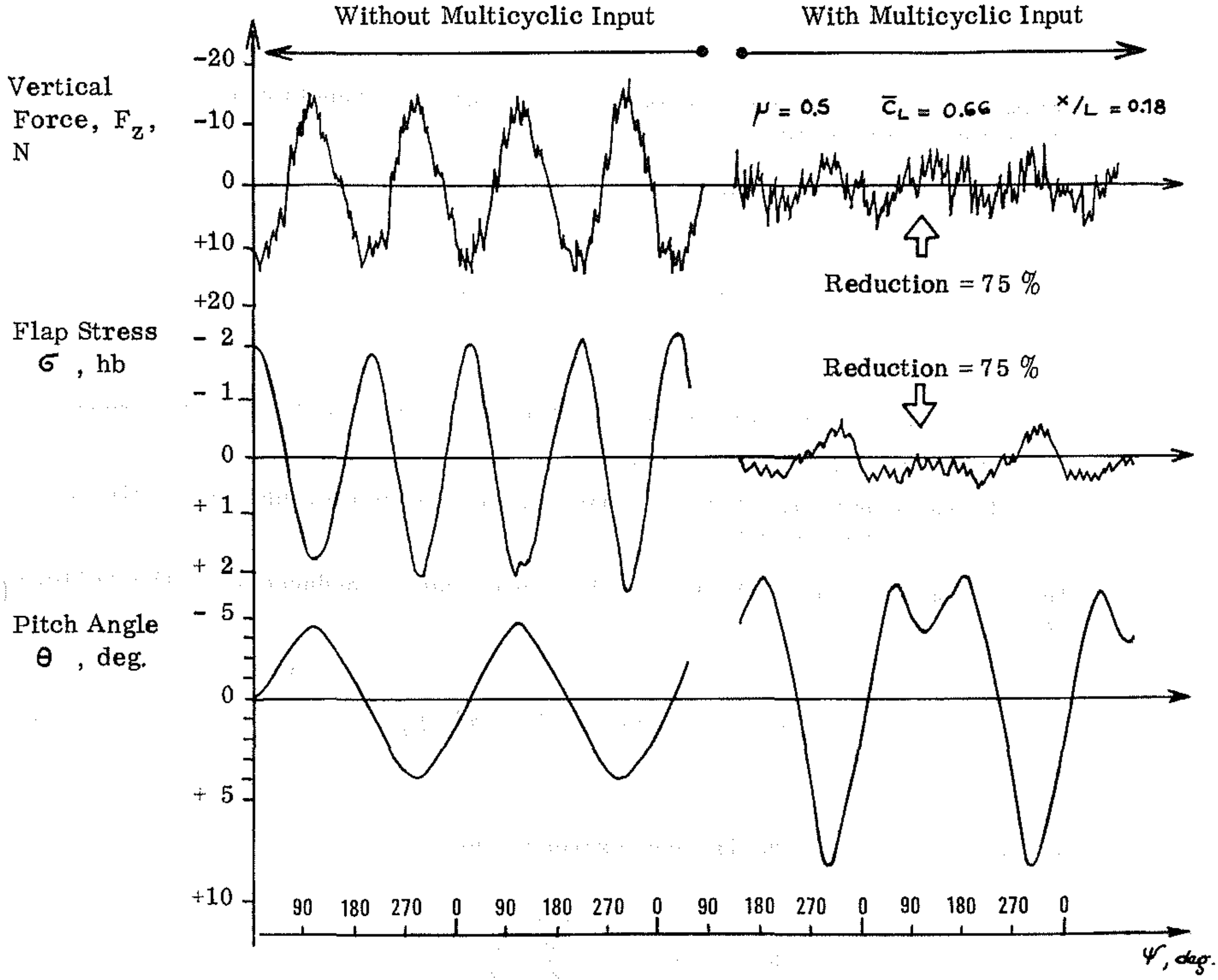


FIGURE 10 - EXAMPLE OF SIMULTANEOUS REDUCTION OF STRESS AND VIBRATION

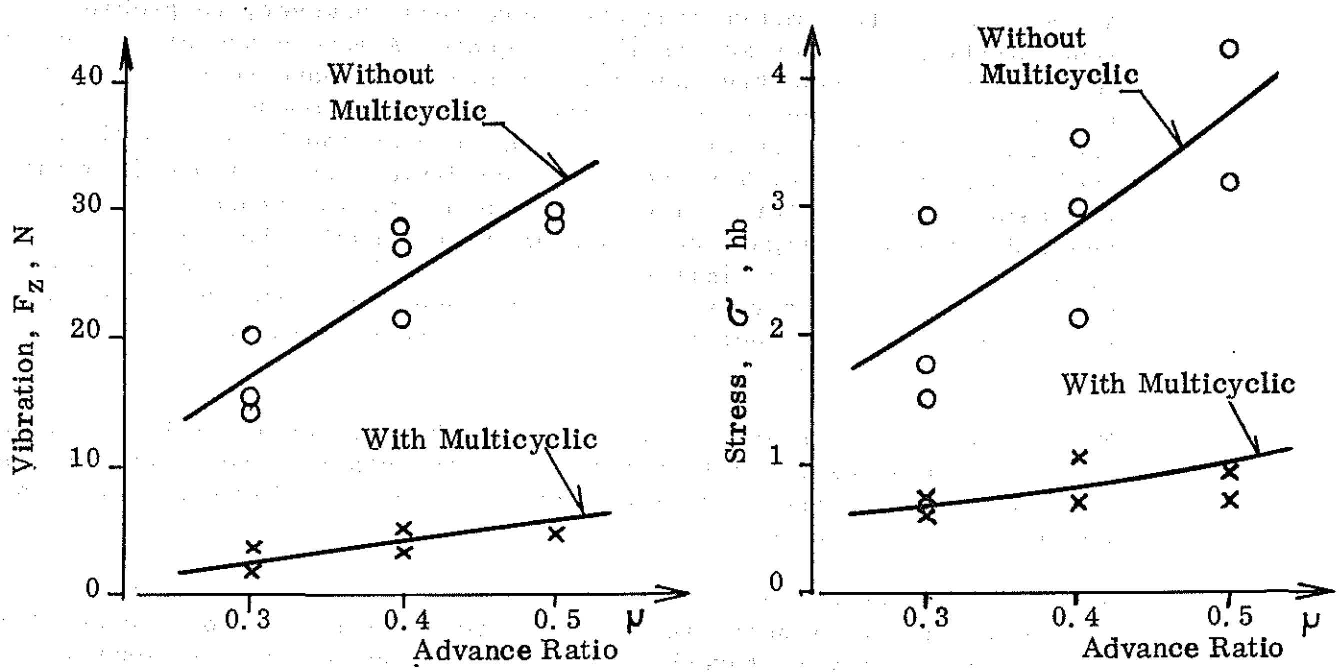


FIGURE 11 - EXPANSION OF FLIGHT ENVELOPE.

optimization, this algorithm must be defined as a function of operating and operational considerations.

The basic ROMULAN relation (Ref. 9) can be written as follows :

$$S = [T]\,E + S_o \tag{4}$$

where S is the output vector having Fourier coefficients as its components.

E is the control vector of the rotor.

[T] represents the transfer matrix, generally rectangular, having more rows than columns.

In the simplest case, the minimizing input can be deduced from the following relation :

$$E_{min} = -(T^T\,T)^{-1}\; T^T\,S_o \tag{5}$$

The reduction ratio RR is then expressed by :

$$RR = 1 - \sqrt{\frac{S^T\;S}{S_o^T\;S_o}} \tag{6}$$

Attempts to use this minimizing procedure lead, however, to prohibitive input amplitudes, when matrix [T] is square. A more elaborate algorithm is required for self-adaptive automatic systems. We have to place a limitation on RR lower than the value given by (6), or impose a limitation on the input amplitude. In either case, we need an additional condition to avoid indetermination. The additional condition can be found in minimizing the input amplitude for a given RR. Such minimizing procedure has been applied for given flight conditions with the result shown in Figure 7. The figure clearly shows a limiting value of RR, 85% in the present case, which leads to excessive values of input amplitude, the RMS value of the E vector. However, a reduction ratio of 75% can be attained with a pitch angle input amplitude of 2°.

This method has been applied to optimize the multicyclic schedules. When the RR obtained empirically was taken as the starting point and the input was limited, the resulting pitch variation compared favourably with manually optimized schedules.

The 1978 series of tests has shown that certain precautions must be taken to accomodate non-linearities due to rotor lift saturation, noise, turbulence and sensitivity thresholds. The main findings can be resumed as follows :

- Multicyclic inputs (MCI's) reduce vibration and stress.
- When calculating MCI's, linear models, such as rotor transfer matrices, can be used, provided rotor and control limitations are taken into account.
- Each RR results from a given RMS value of an MCI, and vice-versa.
- Optimum MCI computation involves the use of several different algorithms that correlate test results.

7. STALL BARRIER FEEDBACK

The stall results in essentially non-linear behaviour of the rotor. This state is tolerated because of present rotor control limitations originating in the swashplate and in the inability of acting rapidly and individually on each blade. Aerodynamically, stall is highly wasteful of power. There is every reason to believe that rotor stall will be completely eliminated in the future by the use of stall barrier feedback. We are presently experimenting and developing such techniques based on the detection of pressure distribution over the blades. They will limit the lift variation to its linear range, preventing the blade from entering the stall by rapidly reducing its pitch angle (Ref. 4).

In practice, the same system, suitably adapted, can be used to prevent boundary layer separation caused by compressibility effects. Stall barrier feedback may be considered as a member of a family of devices controlling the transient states of rotor behaviour, and as such is sensitive to instantaneous changes. This class of feedback can be used for absorbing aerodynamic disturbances and interactions. The considerable advantage of active control is that it is multipurpose. Basically, the same system, capable of introducing rapid pitch changes individually on each blade, can also solve most of the stability problems. The differences in the fields of application consist in the choice of appropriate sensors and adequate computer-processing of sensor data. As these elements are generally lightweight and operate at very low power levels, the incorporation is comparatively inexpensive. Their introduction into already existing active control systems should not constitute a major technological problem.

8. CONCLUDING REMARKS

This review of possible solutions leads to a number of conclusions. Active control of a helicopter rotor can reduce vibration and stress by 50 to 80% at an advance ratio of 0.4, thus broadening the present flight envelope. Rotor instabilities can be eliminated and appreciable power savings of 5 to 10% can be achieved. The new control systems required by this technique may soon lead to elimination of the swashplate and mechanical controls by the installation of electrohydraulic actuators on the rotating part of the rotor and by the introduction of electric or optical-fibre control transmission.

- The lines of research for achieving such ends will be directed towards the automatic application of self-adaptive multicyclic control inputs.

- Stall and compressibility onset will be avoided in the future by the use of stall and compressibility barrier feedback.

- The introduction of artificial stability can improve rotor working conditions in an efficient manner.

- Finally, rotor control will cover a much wider harmonic spectrum, including 5th and 6th harmonics. This in turn will necessitate the use of high-frequency electrohydraulic actuators having a maximum phase lag of 30° at 30 Hz.

Active control promises a substantial performance jump by extending the helicopter flight envelope to higher advance ratios and higher load factor However, intensive research effort is still required to integrate this new technique into an operational helicopter. Such research is presently under way and some of the results obtained are presented in this paper.

9. REFERENCES

1) M. KRETZ, J.N. AUBRUN and M. LARCHÉ, March 1971 Wind Tunnel Test of the Dorand DH 2011 Jet-Flap Rotor, NASA CR 114 693 — June 1973

2) J.L. Mc CLOUD III and M. KRETZ, Multicyclic Jet-Flap Control of Rotary Wings, NASA SP 352 — Feb. 1974

3) M. KRETZ, Research in Multicyclic and Active Control of Rotary Wings, VERTICA, 1976, VOL 1 pp. 95 to 105, Paper presented at 1st European Rotorcraft Forum — Sept. 1975

4) M. KRETZ, Relaxation of Rotor Limitations by Feedback Control, 33rd AHS FORUM — May 1977

5) F.J. Mc HUGH and J. SHAW, Helicopter Vibration Reduction with Higher Harmonic Blade Pitch, 3rd EUROPEAN ROTORCRAFT FORUM — Sept. 1977

6) J.L. Mc CLOUD III and A.L. WEISBRICH, Wind Tunnel Test Results of a Full-Scale, Multicyclic Controllable Twist Rotor, 34th AHS FORUM — May 1978

7) E.R. WOOD, R.W. POWERS and C.E. HAMMOND, On Methods for Application of Harmonic Control, 4th EUROPEAN ROTORCRAFT FORUM — Sept. 1978

8) Maj. Gen. S.C. STEVENS, Army Outlook : Flight Control Systems, AHS SPECIALISTS MEETING ON FLIGHT CONTROLS — Oct. 1978

9) M. KRETZ et M. LARCHÉ, Pilotage multicyclique et contrôle asservi du pas des pales d'hélicoptères GIRAVIONS DORAND INDUSTRIES DE 07-52 E 4 — Nov. 1978

10) J. RENAUD, Pale reculante et décrochage dynamique AAAF 15° COLLOQUE D'AERODYNAMIQUE APPLIQUEE — Nov. 1978

11) R. BOUDAREL, J. DELMAS et P. GUICHET, Commande optimale des processus, DUNOD, EDITEUR, PARIS — 1969