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DYNAMIC BEHAVIOR OF TRANSMISSION SYSTEMS

by

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1-INTRODUCTION.

When designing a helicopter, one tries to avoid resonance phenomena which might result from the fact that the natural frequency of an assembly would turn out to be located on the excitation frequencies that helicopter blades pass on to the structure.

For instance the natural frequency of the tail rotor drive must be kept away from the torque excitation generated by the main rotor blades, whose frequency is a multiple of the main rotor rotation speed and of the number of rotor blades (kb Ω)

Yet other oscillatory phenomena are likely to occur during the first flight tests of the aircraft: torsional oscillations of the drive system at relatively low frequencies (on the order of 3 to 6 hertz) generally excited by a slight disturbance of the resistant aerodynamic torque applied on the tail rotor. Depending on their specific amplitude and damping these angular oscillations can be deemed excessive and require that the characteristics of the entire linkage be adjusted in flight.

2-REMEDY.

Given the sophistication of the drive system, the number of parameters likely to be modified is very large. This is why it has become of interest to have available a calculation program for an easier analysis and the dynamic adaptation of the transmission.

In fact, the methods used until recently to reduce the scope of the oscillations were essentially empirical and most of the time consisted in trying to increase the system damping by increasing engine governor damping. This was done by acting on the fuel metering valve for example while trying not to affect the governor performance that had been pre-set on the test bench to perfectly suit the engine on which it was fitted. The drawback with such methods is that fabrication scatter affecting drive system components led to the problem appearing now and again during acceptance tests for production aircraft since the stability margins gained thanks to the new setting of the governor were too small for lack of a theoretical and global approach to the problem.

Calculation methods have therefore been set up progressively thanks to cooperation between helicopter and engine manufacturers

A first approach was made by introducing right from the start a restriction to the effect that the model would only be valid for small variations about a stabilized position.

It was thus possible to linearize the fundamental equation:

ENGINE TORQUE = Σ RESISTANT TORQUES

and therefore to use simplified modes for governors and engines. For a given flight condition, one calculates along conventional lines the complex eigenvalues of the characteristic equations expressing the torque equation mentioned above. The variables selected are the torsional angular displacements of the various flexible elements of the drive system. In this manner, one obtains the natural frequencies of the coupled system constituted of engine, rotors, transmission and the damping related to each of them. The result of this is a calculation tool which makes it possible to estimate the effect of each drive system component on the overall stability of the system and to envisage parametric studies which will eventually enable us to perform final adjustments on the helicopter.

However, the need for a finer analysis of the transient response of the drive system to a given excitation (rotor droop after a substantial pitch increase, for example), the availability of adjustment diagrams and of complete and largely non-linear diagrams of engine controls and of engines have led to envisaging a more detailed and easier to use calculation model that would be capable of processing any non-linear system provided its detailed mathematical model is available. It results in a numerical simulation which gives the response as a function of time of any parameter for a variation in flight parameters (collective pitch, for example) introduced as input. This procedure is particularly useful when performing calculation-based adjustments subsequently supplemented by test flights as it makes it possible to estimate directly the effect of a change in system characteristics on the in-flight behavior of the helicopter. It therefore makes it possible to study rapidly the positive or negative trends of the phenomenon that various modifications can generate. This will make it possible to obtain angular velocities or torsional angles of power drive components, for example or if one prefers, the rotation speeds, fuel flows and control pressures of engine and governor.

A more conventional analysis based on natural frequency and damping calculations will make it possible to fine-tune and quantify more accurately the resulting effects.

For the time being, the aerodynamic part of our model is not complete yet, but we have had the opportunity to use this program to solve two problems that had cropped up during the first tests on an aircraft.

The rest of this paper deals with the first of these applications. We first give a brief description of the model for a better comprehension of the application.

3-THEORETICAL MODEL

In our study of the drive system stability, we look into very low frequency phenomena. Therefore, relative torsional motions are represented by a limited number of degrees of freedom.

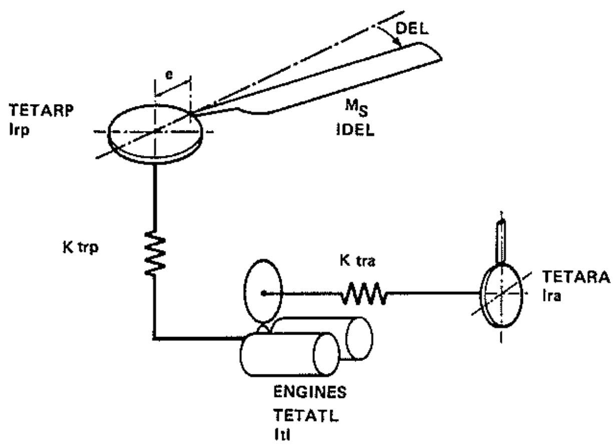

FIG. 1 : THEORETICAL MODEL OF THE DRIVE SYSTEM

The model comprises a main rotor, a main rotor drive system, an engine/governor assembly, an anti-torque rotor drive system, an anti-torque rotor.

The aerodynamic loads are introduced at the two rotors.

3.1.Rotors, transmission.

The motion of the main rotor is schematized in the form of an overall torsion of the shaft and by the lag motion of the b blades, supposed to be rigid and vibrating in phase. The tail rotor is represented by its inertia.
The two rotors are connected to the free turbines of the engines via two transmission assemblies whose inertias are overlooked. These assemblies can therefore be considered stiffness factors.
Viscoelastic lead-lag dampers are represented at the blades-to-main-rotor connection.

3.2.Aerodynamics.

Aerodynamic drag loads at the blades are represented by their damping effect on the degrees of freedom related to the rotors. The data necessary for calculating these damping coefficients is obtained for each case of simulated flight through a specific aerodynamic computer program available at AEROSPATIALE (induced velocities, cyclic pitch variations, ..)

3.3 Engines/governors.

TURBOMECA have proposed, within the framework of the design of the SA 365 N1 DAUPHIN, the representation of the dynamic behavior of the ARRIEL 1C engine and of its governor.

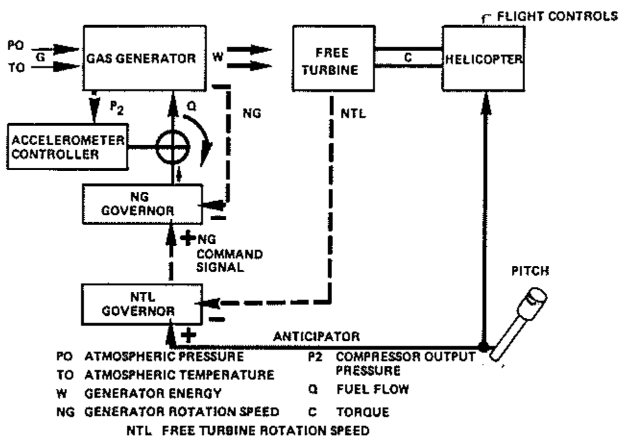

FIG. 2 : ENGINE AND GOVERNING SYSTEM - SIMPLIFIED SCHEMATIC DIAGRAM

The engine model makes it possible to calculate the behavior - as a function of the fuel flow delivered by the governor - of the parameters listed below during simulation.

- -gas generator rotation speed
- -compressor output pressure
- -torque delivered at the free turbine

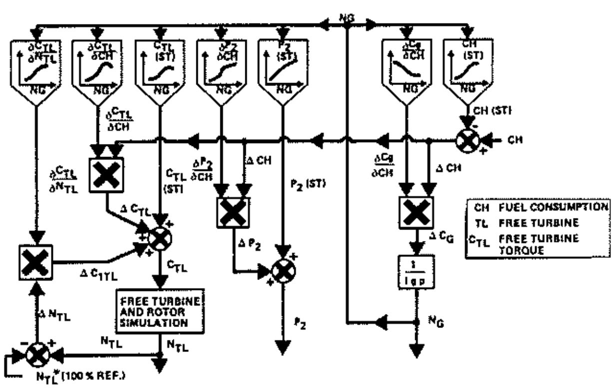

FIG. 3 : ARRIEL 1C - TURBOSHAFT ENGINE SIMULATION

In effect, these characteristics are the stabilized operating lines of a given engine. Some care should therefore be exercised when using this data.

-on the one hand, the study of transient thermodynamic phases is not feasible with this type of model, which is not designed to be used for performance calculation. Other models have been designed for that purpose.
-on the other hand, it is difficult to determine the engine performance scatter and therefore to arrive with certainty at a stable configuration for all engines when studying the drive system stability.

The transfer functions of the power-turbine governor and of the generator governor are determined by TURBOMECA on a governor bench.

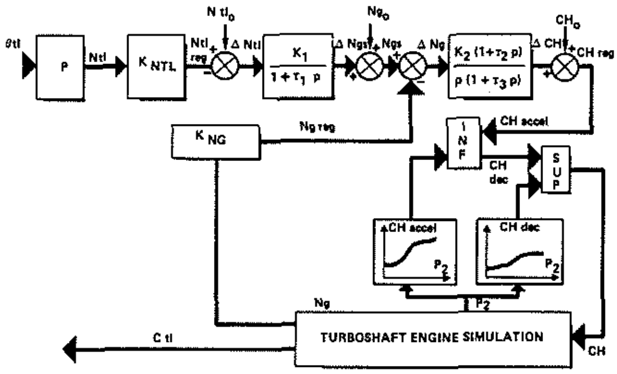

FIG. 4 : ARRIEL GOVERNING SYSTEM SCHEMATIC DIAGRAM

The model dealt with here has simple curves of the

output = f (input)

type which have been analyzed as a function of the governor concerned. (e.g. proportional type for the power-turbine governor and integral proportional type for the generator governor).
Characteristics like gains and global response times for each loop were deduced from this analysis. In this case and like for engines, such a model can in no way be used for setting the governors.
In practice, if one wishes to fine-tune the development of the regulation and its adaptation to the helicopter, it is necessary to have a diagram showing how the mechanical, hydraulic or pneumatic systems have been translated into equations. This is the type of model that we used for the application to the US Coast Guard SRR helicopter. We will return to it later.

The transfer functions are introduced into the program in the form of transfer functions in Laplace parameters.

It should be pointed out that the two engines are supposed to operate in phase and at the same power output, which corresponds to normal operation

3.4. Equations

The equational expression of the system is that already touched upon in paragraph 2. Using the following variables:

-torsional angle of power turbine,
-blade lead-lag angle,
-main rotor torsional angle,
-tail rotor torsional angle,

the system that must be solved is:

$$P^2[I]TETA + P[A]TETA + [K]TETA = C$$

with

$$TETA \begin{pmatrix} TETATL \\ DEL \\ TETARP \\ TETARA \end{pmatrix}$$

$$[I] = \begin{bmatrix} Itl & 0 & 0 & 0 \\ 0 & BxIdel & B(Idel+ExMs) & 0 \\ 0 & Bx(Idel+ExMs) & Irp & 0 \\ 0 & 0 & 0 & Ira \end{bmatrix}$$

$$[A] = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & BxAdel & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$[K] = \begin{bmatrix} KtraxNtltr^2 + KtrpxNtlrp^2 & 0 & -Ktrp \times Ntlrp & -Ktra \times Ntltr \\ 0 & BxKdel & 0 & 0 \\ -KtrpxNtlrp & 0 & Ktrp & 0 \\ -KtraxNtltr & 0 & 0 & Ktra \end{bmatrix}$$

$$C \begin{pmatrix} Ctl \\ -Cdel \\ -Crp \\ -Cra \end{pmatrix}$$

4 - STUDY OF THE SA 365 N1 DAUPHIN TRANSMISSION

During development of the new larger-diameter fan-in-fin Fenestron of the Dauphin, substantial torque oscillations - at 4.4 and 5.8 Hz - were noticed in very particular flying conditions: high speed with slip upon a sudden tail rotor pitch increase.

To analyze this problem we resorted to the drive system numerical simulation program.

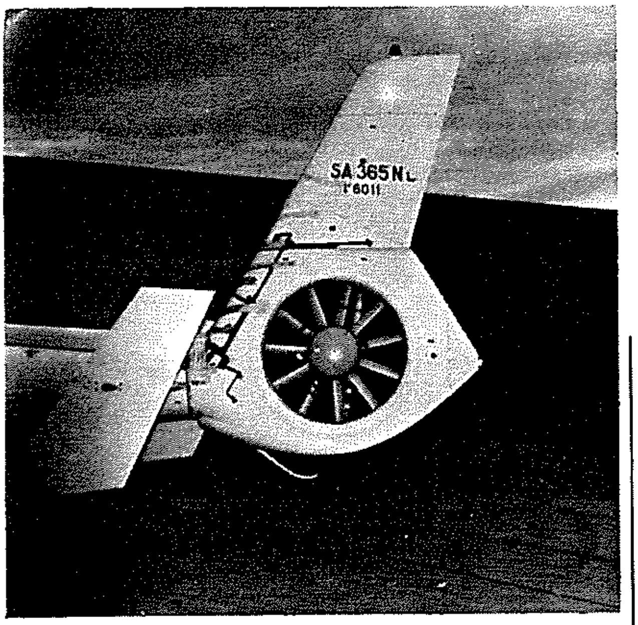

FIG. 5 : DAUPHIN SA 365 N_1 – NEW «FENESTRON»

We simulated through calculations the response of the system to a tail rotor torque step reproducing the flight conditions mentioned under the preceding paragraph.

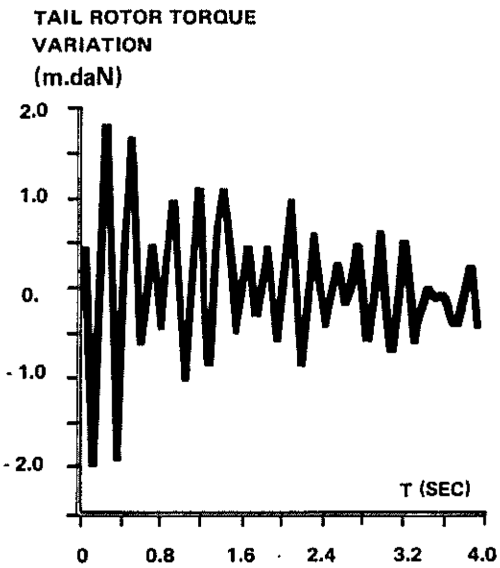

FIG. 6 : TORQUE OSCILLATION ON TAIL ROTOR TRANSMISSION MEASURED IN FLIGHT.

First of all we notice that the torque delivered by the engine to the free turbine has a noticeably lower frequency than those of the phenomenon encountered in flight. It responds on its natural frequency which we had measured on the bench and seemingly is not affected by the higher frequencies.

Moreover the analysis of the phases and of the amplitudes of the response of each degree of freedom has evidenced a preponderant participation of the degrees of freedom associated with the tail and main rotor at two modulated frequencies: 4.6 Hz and 5.9 Hz.
In this case the engine could not be the major contributing factor to the oscillatory phenomenon studied. Therefore our analysis concentrated on the dynamic behavior of the transmission.

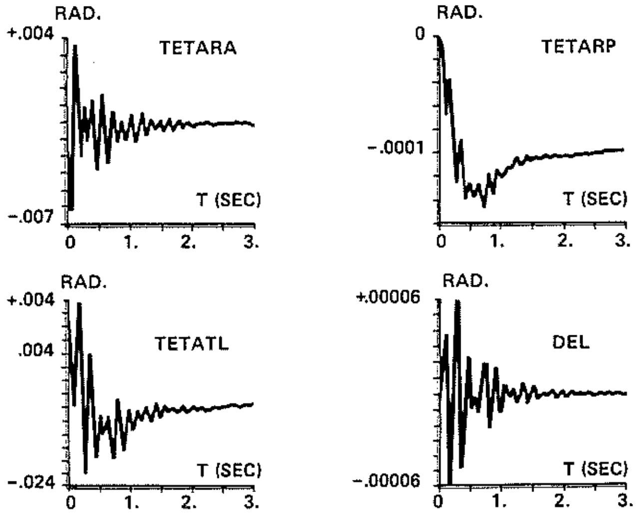

FIG. 7 : SYSTEM RESPONSE AT A GIVEN TAIL ROTOR TRANSMISSION TORQUE STEP

One can observe on the calculated signal (see figure) that the first frequency at 4.6 Hz is damped less than the second frequency and that the amplitude of the tail rotor response at that frequency is large.

Therefore, the oscillatory phenomenon encountered was essentially attributable to an insufficiently damped response of the tail rotor at 4.6 Hz, very much coupled with the main rotor.

Two modifications were tested in flight with no result and confirmed our analysis: the first modification consisted in decreasing the stiffness of the viscoelastic lead lag dampers of the main rotor blades, the second in increasing the response time of the turbine governor (these results had been predicted through calculations). This also proved that the second modification does not systematically give good results.

As a solution to the problem, increased tail rotor transmission damping was not easily feasible from a practical standpoint.

Conversely, since we had two coupled frequencies, it was easier to modify the stiffness associated with the degree of freedom of the tail rotor so as to bring closer the existing two modes, thus stabilizing the lower

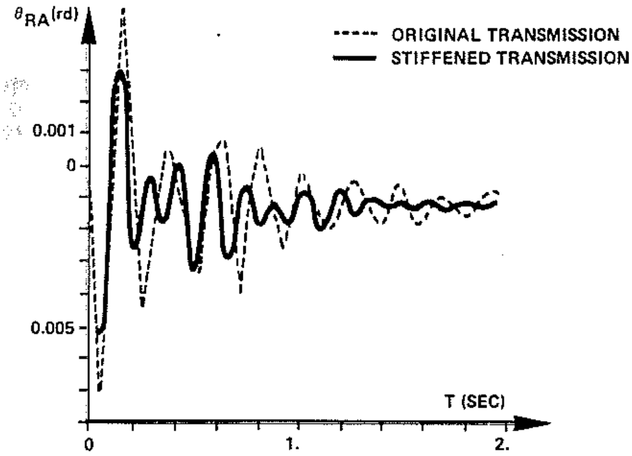

FIG. 8 : RESPONSE TO A GIVEN TAIL ROTOR TRANSMISSION TORQUE STEP

frequency - which was the more critical - to the detriment of the higher frequency which was damped.
This hypothesis was confirmed by a new simulation exercise where the stiffness of the tail transmission had been stepped up by 33%.

The calculated overall response of the system was acceptable then. The original duralumin central tail transmission shaft was then replaced on the aircraft by a steel shaft. This modification made it posssible to obtain the 33 % increase in stiffness proposed on the basis of calculations.
Subsequent flight-test results confirmed the validity of the solution and hence of the calculations.

The solution that was finally adopted for production consists simply in thickening the light-alloy shaft, which gives lower transmission stiffness and a less penalizing weight increase. The resulting stiffness is still sufficient to suppress the oscillatory phenomenon.

5 - OTHER POSSIBLE APPLICATION

In the case of the AS 365 N1 DAUPHIN mentioned previously, we presented an application dealing more precisely with the dynamic adaptation of the drive system.
In effect, this program can also turn out to be a valuable instrument for the study of engine fuel flow control provided a few modifications are introduced in the field of the representation of dynamic loads on the one hand and in that of the collective-pitch-control to main-rotor and collective-pitch-control to fuel-flow-anticipator couplings on the other hand.
We used this instrument for the adaptation of Lycoming's LTS 101 engine on the US Coast Guard AS366 G helicopter. It allowed us to identify the gain adjustments that permit a satisfactory operation of engine regulation.

6 - CONCLUSION

The study of the dynamic stability of drive systems has thus evolved in the recent years from a purely experimental stage to a more theoretical one where mathematical analysis precedes the experimental verification of the validity of technical modifications.

During this evolution, we realized that - provided relatively complete engine and governor models are available - the type of program developed allows to go far beyond the solving of drive system oscillation problems.

In fact, we presently envisage applications like the calculation of performance or the transient behavior of the transmission system of the helicopter in flight (rotor droop subsequent to a sudden increase in collective pitch). However the representation of the aerodynamic loads used so far is no longer sufficient for these studies and, in particular, it is necessary to introduce transient effects at the rotor.

Moreover mechanical couplings with the airframe behavior will also be represented (yaw response in particular).

Finally, the simulation of the behavior of the fuel governor, which was hard to modelize in the case of mechanical systems will become simpler thanks to the appearance of electronic governors presently under study.
The program presented will then be a very valuable development tool.

NOTATION

- Blades:
  - Ms: Static moment of a blade as against lead-lag articulation
  - Idel: Weight inertia of a blade as against lead-lag articulation
  - b: Number of blades
  - e: Lead-lag eccentricity
  - Del: Degree of freedom related to blade lead-lag motion
  - Kdel: Angular stiffness of lead-lag adaptor
  - Adel: Lead-lag adaptor damping
- Main rotor:
  - Irp: Main rotor inertia

- TETARP: Torsional degree of freedom related to main rotor
- Ktrp: Main rotor/engine transmission stiffness
- Ntlrp: Main rotor speed/power turbine speed

- Tail rotor:
  - TETARA: Torsional degree of freedom related to tail rotor
  - Ira: Tail rotor inertia
  - Ktra: Tail rotor/engine transmission stiffness
  - Ntlra: Tail rotor speed/power turbine speed

- Aerodynamics:
  - Cdel: Aerodynamic damping torque on blade
  - Crp: Aerodynamic damping torque on main rotor
  - Cra: Aerodynamic damping torque on tail rotor

- Engine:
  - TETATL: Torsional degree of freedom related to free turbine
  - Itl: Free turbine inertia
  - Ntl: Free turbine rotation speed
  - Ntlreg: Free turbine rotation speed at governor
  - Ng: Gas generator rotation speed
  - Ngreg: Gas generator rotation speed at governor
  - CH: Fuel flow
  - P2: Pressure
  - Cg: Torque applied at gas generator
  - Ig: Gas generator inertia
  - Ctl: Torque applied at free turbine