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A CRITICAL COMPARISON BETWEEN DIFFERENT METHODS OF FLAP SYSTEMS ACTUATION SPEED LIMITATION

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Abstract

The aerodynamic loads on the flap controls generally act in the same orientation: opposing loads during the deployment, aiding loads during the retraction. As a consequence the actuation speed and the required flow rate can be markedly higher in the latter case than in the former one, eventually causing a critical supply pressure reduction in the hydraulic system or even a block-lift condition in the hydraulic motor; therefore some device acting as speed and flow rate limiter can be recommended.

The purpose of this paper is to critically compare four different methods usually employed in the flap control system actuation speed limitation:

- reduced valve spool maximum stroke in the retraction mode
- flow limiter
- non-linear speed feedback
- command ramp generator.

In order to analyze the above mentioned methods a mathematical model and related computer program, concerning a typical flap control system, have been developed. The computer program contains the simulation algorithm for the dynamic behaviour of the control system and the considered actuation speed limiters.

The results emphasize the different dynamic behaviour of the control systems employing each above mentioned device.

Introduction

The flap actuation systems of most commercial and military aircraft consist of a centrally located Power Drive Unit (PDU), a shaft system and a certain number of actuators (normally two for each flap surface). Depending on the performance requirements and on the specified interface with the other aircraft systems and structure, several different configurations have been used in the design of such actuation systems. PDUs can be either hydromechanical or electromechanical and be either of a single or dual motor type. In the last case the outputs of the two motors can be either torque summed or speed summed. The shaft system generally consists of torque tubes connecting the PDU output with the right and left wing actuators (Figg. 1, 2, 3); however, the flap actuation systems of small commercial aircrafts often use flexible drive shafts rotating at high speed in place of the low speed rigid shafts. The actuators are normally linear and are based on ballscrews, though some flap actuators use an ACME screw; some flap actuators are of a rotary type. The system must be able to prevent asymmetries between the left and right wing flaps in case of a shaft failure (detected by a proper asymmetry monitoring system) and to hold the surfaces in the commanded position following the shutoff command given when no actuation is required.

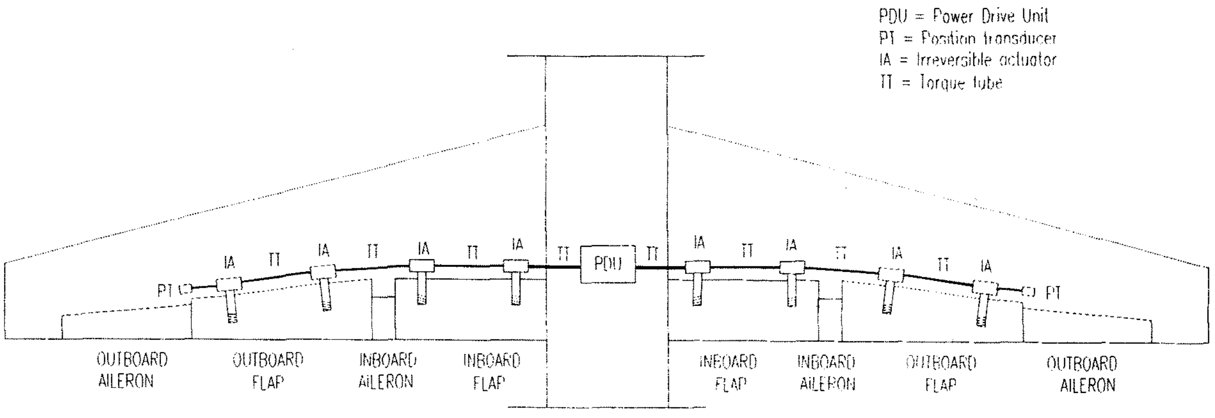

Fig. 1 - Irreversible actuator architecture

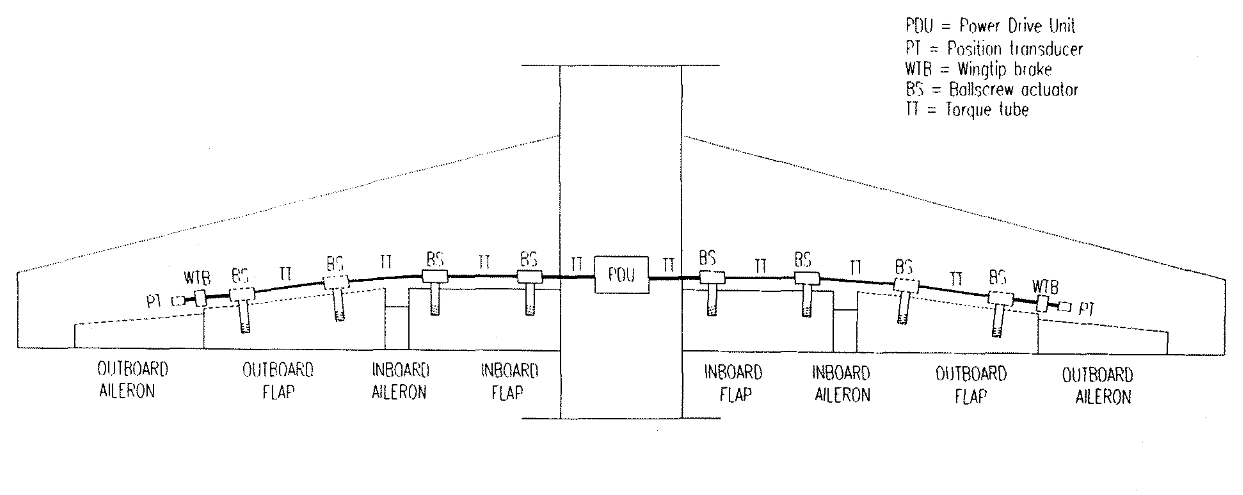

Fig. 2 - Wingtip brakes architecture

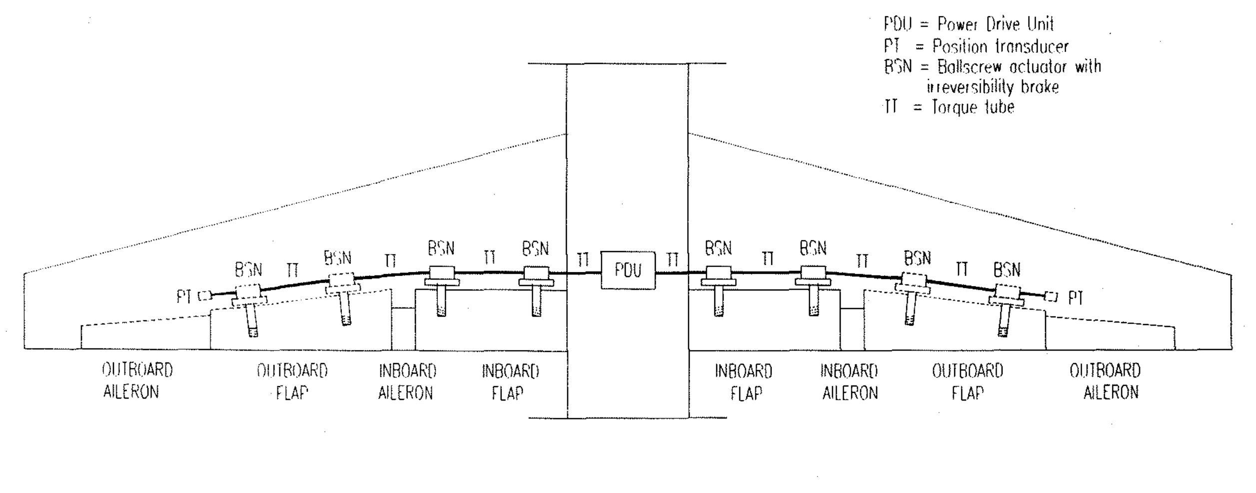

Fig. 3 - Irreversibility brakes architecture

If the actuators use an irreversible ACME screw (Fig. 1), the above mentioned requirements are intrinsically accomplished; if the actuators are reversible (in order to obtain higher efficiency) a brake system is necessary:

- controlled wingtip brakes (one for each wing) located at the end of the transmission line, close to the position transducers (Fig. 2), that become engaged and brake the system after a failure has been positively recognized;
- self-acting irreversibility brakes within each actuator, which self engage when the actuator output overruns the input shaft (Fig. 3).

The relative merits of the three solutions (non-reversible actuators, reversible actuators with wingtip brakes or reversible actuators with irreversibility brakes) and which of the three is better is a long debated matter: the maximum asymmetry in failure conditions is greater with the wingtip brake solution, the solution with non-reversible actuators requires higher hydraulic power owing to its lower efficiency and the irreversibility brake solution, that overcomes the shortcomings of the two previous solutions, is more expensive.

Therefore the most commonly used architecture employes the reversible actuators with wingtip brakes and centrally located PDU (of a dual motor type for operational reliability) (Fig. 2) because it is cheaper and more efficient, neverthless the associated high asymmetries in case of failure.

It must be noted that the aerodynamic loads on the flap controls generally act in the same orientation: opposing loads during the deployment, aiding loads during the retraction. While the above mentioned circumstance affect marginally the behaviour of the architecture shown in Figg. 1 and 3, in the architecture of Fig. 2 the actuation speed and the required flow rate can be markedly higher during the retraction than in the deployment, eventually causing a critical supply pressure reduction in the hydraulic system or even a block-lift condition in the hydraulic motor; therefore some devices acting as speed and flow rate limiters can be recommended.

Four different methods are usually employed in the flap control system actuation speed limitation:

- reduced valve spool maximum stroke in the retraction mode
- flow limiter
- non-linear speed feedback
- command ramp generator.

Aims of the work

The purpose of this paper is to critically compare the four above mentioned different methods usually employed in the flap control system actuation speed limitation.

In order to analyze the above mentioned methods a mathematical model and related computer program, concerning the flap control system of Fig. 2 (the most employed and the only one affected by excessive actuation speed with aiding loads), have been developed. The computer program contains the simulation algorithm for the dynamic behaviour of the control system and the considered actuation speed limiters.

Reduced valve spool maximum stroke

As the aerodynamic loads on the flap controls generally act in the same orientation (opposing loads during the deployment, aiding loads during the retraction), the simplest approach to the actuation rate limitation is represented by an asymmetric valve arrangement in which the spool maximum stroke in the retraction mode is smaller than in the deployment mode. As a consequence, the pressure losses through the valve passages are higher during the retraction than the deployment; it acts as a sort of a simple flow limitation, counterbalancing the effects of the loads.

Flow limiter

A more sophisticated method, independent of the flap actuation orientation but acting on the flow rate and consequently on the flap actuation speed, is based on a flow limiter (Fig. 4) located on the supply pipe upstream of the control valve. This device is conceived and calibrated in order to produce a commanded pressure loss by a variable orifice: completely open when the flow rate is lower than a defined value, progressively closer and closer when the flow rate exceeds the defined value. As the flow rate is proportional to the actuation speed (excluding the effects of oil compressibility and leakage), the flow limiter acts as an actuation rate limiter.

Non-linear speed feedback

A similar behaviour may be obtained by means of a non linear speed loop, conceived in order to produce a control valve regulation following the flap actuation speed (measured by an angular tachometer): when it is lower than a defined value, the device has no influence on the system, when the speed exceeds the defined value, progressively reduces the control valve displacement.

Command ramp generator

The flap control system actuation speed limitation may be obtained by an appropriate selection of the command laws: any actuation demand is converted into a ramp command never exceeding both a defined slope and a defined position error.

The limitation to a defined slope prevents excessive speeds and flow rates in steady conditions, particularly with low or aiding loads; the limitation to a defined position error prevents excessive speeds and flow rates following a sudden decrease of high opposing loads.

Actuation system modelling

In order to compare the mentioned methods a mathematical model concerning the flap control system of Fig. 2 was considered. The schematic of such actuation

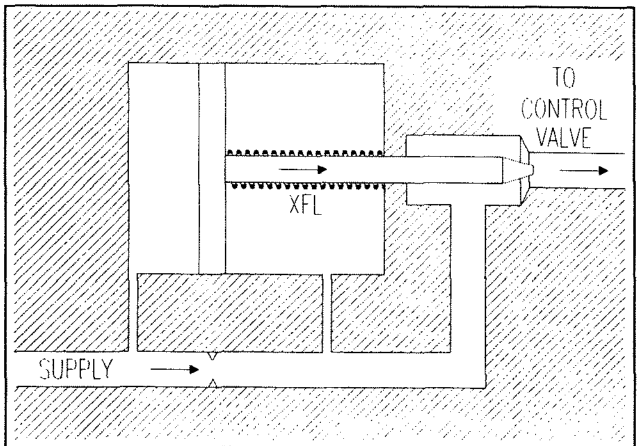

Fig. 4 - Flow limiter

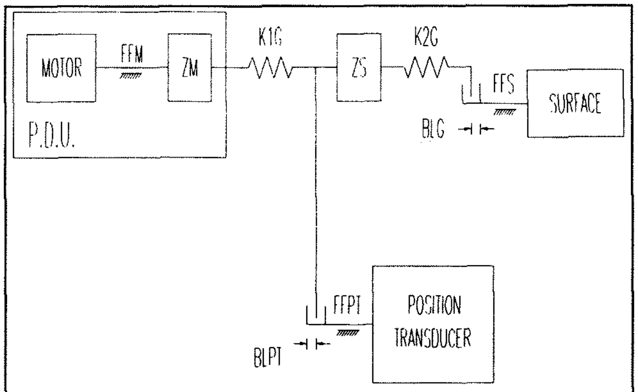

Fig. 5 - Actuation system mechanical model

system is shown in Fig. 5. The system consists of a Power Control and Drive Unit (PDU), a shaft system and ballscrew actuators (BS) driving the flaps. Each ballscrew actuator is an assembly containing a gear reducer (ZS) and a ballscrew. At the two outer ends of the shaft system are located the wingtip brakes (WTB), the position transducers (PT) and the speed sensors, if present.

The system control is performed by an Electronic Control Unit (ECU), not shown in Figg. 1, 2 and 3, which closes the position control loop. The position information provided by the transducers is also used by appropriate monitoring routines to detect possible asymmetries between right and left flap surfaces.

The PDU contains the hydraulic motors, the gear reducer (ZM), the solenoid, shutoff and control valves. The hydromechanical system considered for this work was assumed to also contain tachometers for a continuous actuation speed control.

Fig. 5 shows the mechanical model of the actuation system. The model takes into account the hydraulic and mechanical characteristics of all system components, including their friction, stiffnes and backlash. In particular, the model takes into account the following:

- Coulomb friction in the PDU (FFM), in the actuators (FFS) and in the position transducers (FFPT),
- stiffness (K1G) and backlash of the torsion bar of the right and left shaft systems,
- errors and temperature effects in the position transducers and backlash (BLPT) within the position transducers drive,
- errors in the position transducers electronics and in the A/D conversion,
- stiffness (K2G), backlash (BLG) and lead errors of the ballscrew actuators,
- second order electromechanical dynamic model of the servovalve with position and speed limitations and complete fluid-dynamic model [8],
- dynamic and fluid-dynamic hydraulic motor and high speed gear reducer model taking into account, beside the above mentioned Coulomb friction, viscous friction and internal leakage.

It must be pointed out that the stiffness K1G and the backlash BLPT are within the system servoloop; the stiffness K2G and the backlash BLG are parameters of a system branch off the servoloop.

System mathematical modelling and simulation results

The above described model of the actuation system has been used to build a mathematical model of the whole system and a dedicated computer code written in Fortran 77 has been prepared. The computer code allows the introduction of aerodynamic loads formed by a term proportional to the flap deflection and a constant one and has options for the system equipped with the four above mentioned techniques employed in the flap control system actuation speed limitation and without any device; the purpose is the evaluation of their effectiveness in keeping almost constant the actuation times in different conditions.

A similar computer code has been prepared by using the Matlab-Simulink code for validation purposes.

By the mentioned Fortran 77 computer code four simulations have been run for a system without any speed

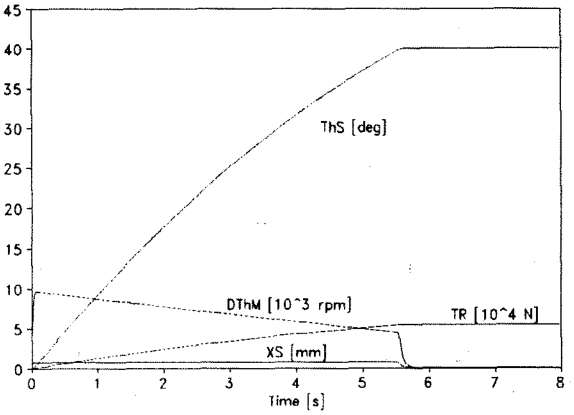

Fig. 6 - No limiting device - Deployment low load

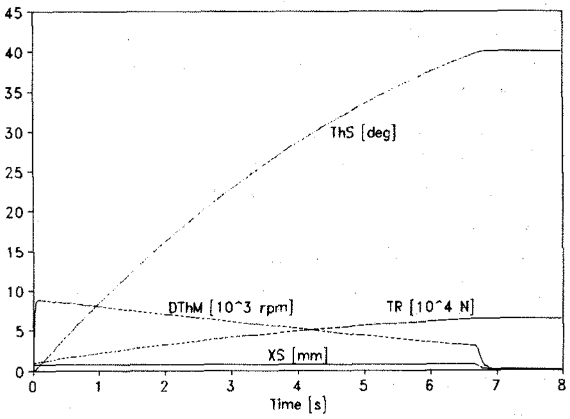

Fig. 7 - No limiting device - Deployment high load

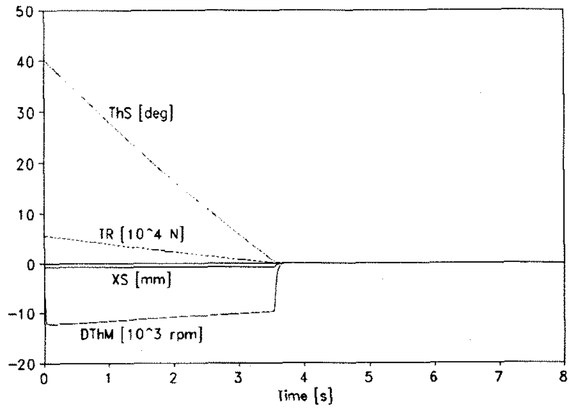

Fig. 8 - No limiting device - Retraction low load

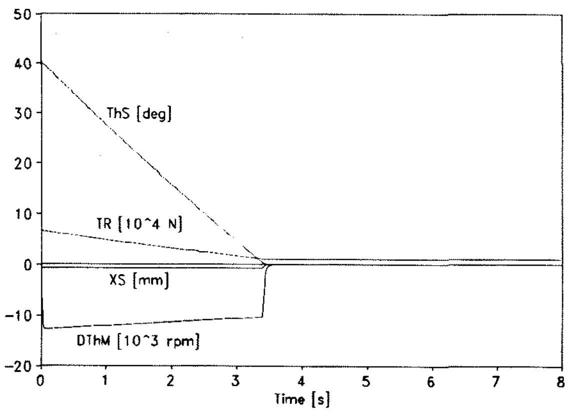

Fig. 9 - No limiting device - Retraction high load

limiting device and for systems equipped with each type of speed limiter: deployment and retraction without and with constant loads (the loads proportional to the flap deflection are always present).

The figures 6-7-8-9 show respectively the deployment and the retraction without and with constant load for a system without any device limiting the actuation speed.

In figures 6-7-8-9, as in the following ones, the system behaviour is represented by the trend of the quantities:

- flap displacement ThS,
- motor angular rate DThM,
- valve spool displacement XS,
- total aerodynamic load acting on the flap surfaces TR.

It must be noted that the actuation times in case of aiding loads are markedly shorter than in case of opposing loads (approx. half); furtherly, mainly in case of opposing loads, the actuation time is highly sensitive to the average load.

The figures 10-11-12-13 show respectively the deployment and the retraction without and with constant load for a system characterized by a reduced valve spool maximum stroke in the retraction mode (asymmetric valve).

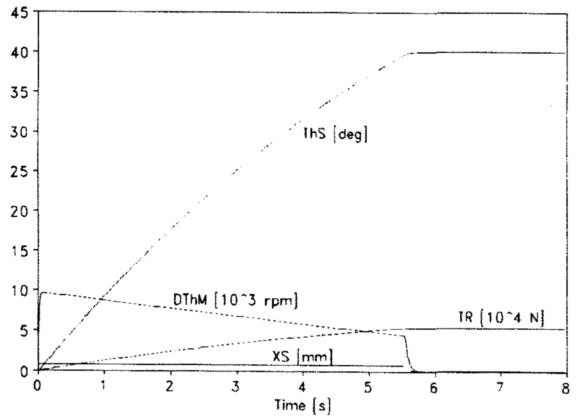

Fig. 10 - Asymmetric valve - Deployment low load

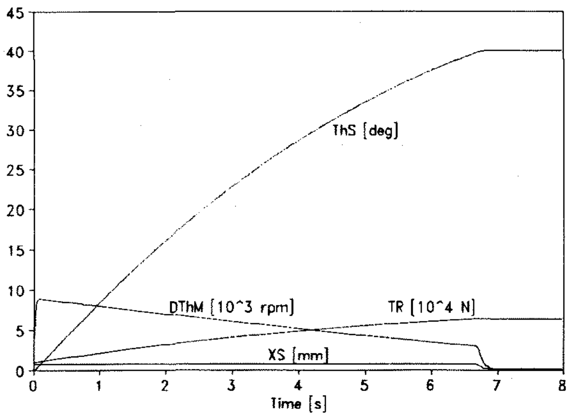

Fig 11 - Asymmetric valve - Deployment high load

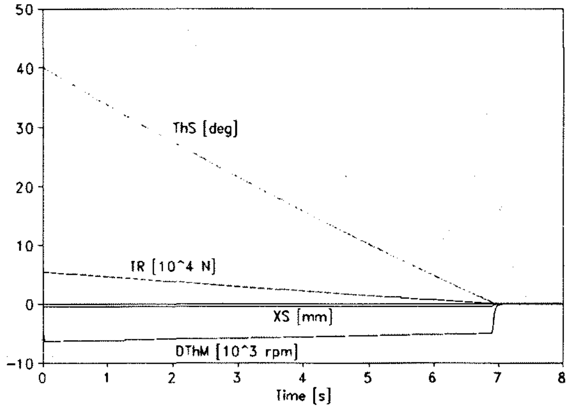

Fig. 12 - Asymmetric valve - Retraction low load

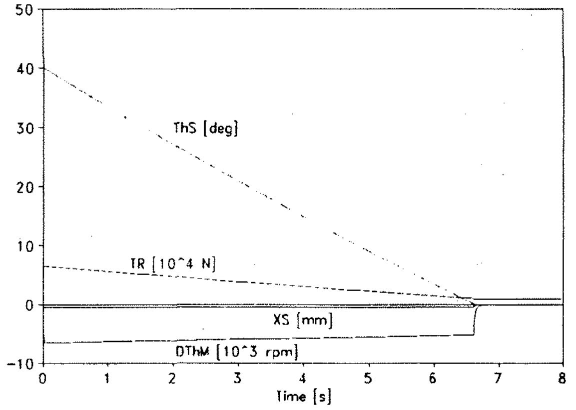

Fig. 13 - Asymmetric valve - Retraction high load

In case of deployment the behaviour is the same as for the system without any speed limiting device, as shown by the comparison between the figures 10-11 and the figures 6-7.

The arrangement effectiveness is pointed out in figures 12-13, showing the retraction case; the actuation time is very close to the deployment actuation time. It must be noted that the effectiveness of this type of arrangement is strongly dependent on the aerodynamic loads: the different spool strokes allow to equalize the actuation time in deployment and retraction for a defined average value of the aerodynamic loads, while for other load conditions the actuation times may be different, even greater in retraction than in deployment.

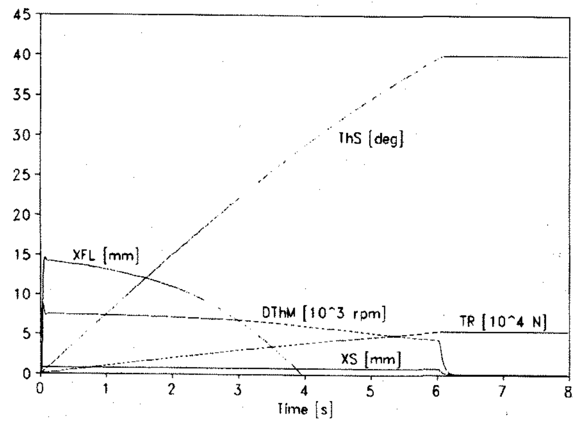

Fig. 14 - Flow limiter - Deployment low load

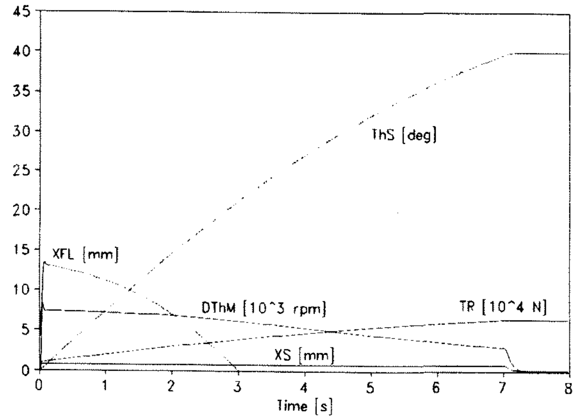

Fig. 15 - Flow limiter - Deployment high load

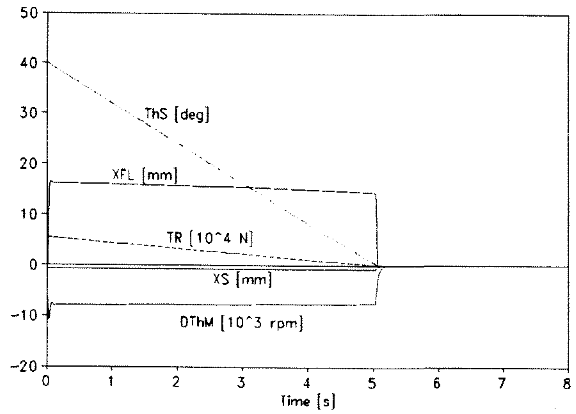

Fig. 16 - Flow limiter - Retraction low load

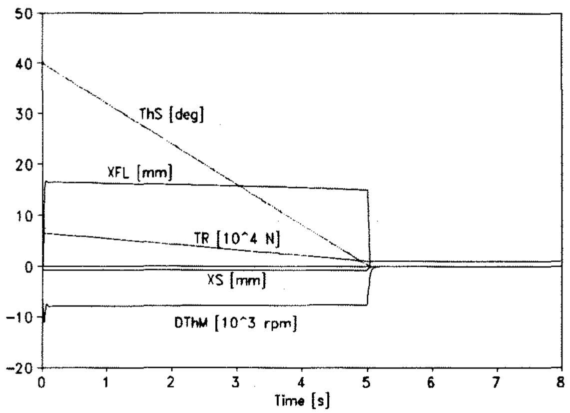

Fig. 17 - Flow limiter - Retraction high load

The figures 14-15-16-17 show respectively the deployment and the retraction without and with constant load for a system equipped with a flow limiter: the piston position XFL of the flow limiter (fig. 4) gives rise to the progressive shutting of the variable orifice.

In the deployment (figures 14-15) at the beginning the variable orifice is partially closed because of the low value of the opposing load; when the load grows, the variable orifice progressively opens. In this way the actuation speed is more strictly controlled with respect to the system without any speed limiting device (see figures 6-7).

In the retraction the aiding load gives rise to a marked

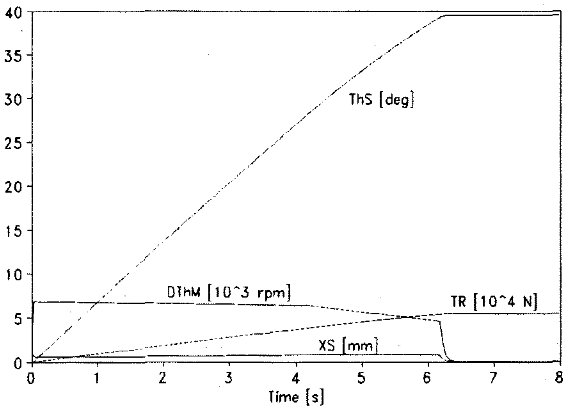

Fig. 18 - Speed feedback - Deployment low load

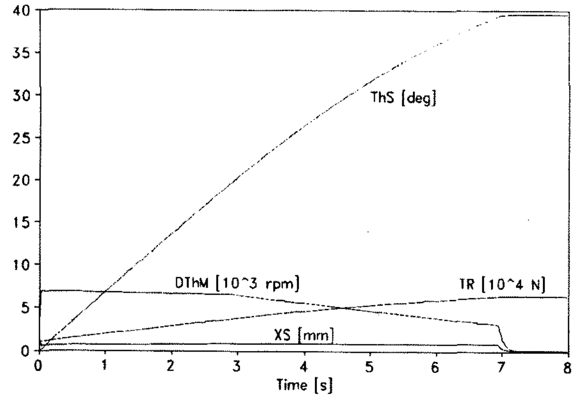

Fig. 19 - Speed feedback - Deployment high load

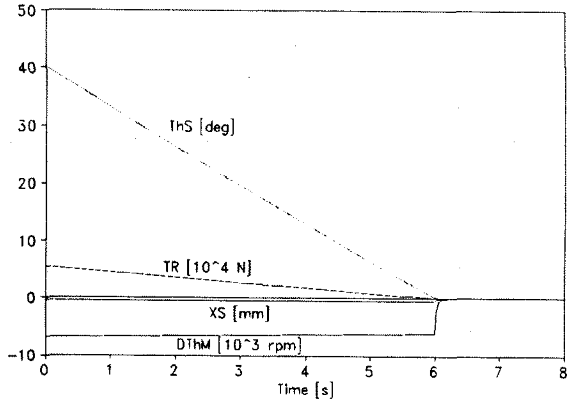

Fig. 20 - Speed feedback - Retraction low load

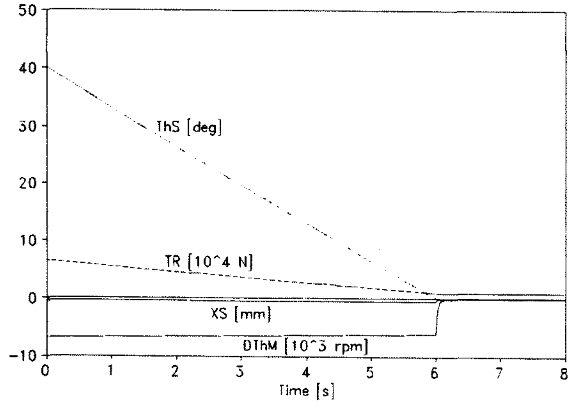

Fig. 21 - Speed feedback - Retraction high load

shutting of the variable orifice, which leads to an actuation time closer to the one in deployment.

The figures 18-19-20-21 show respectively the deployment and the retraction without and with constant load for a system equipped with a non linear speed feedback device. The actuation time, both in deployment and in retraction, is quite similar in the case without constant load (figures 18 and 20) and in the case with constant load (figures 19 and 21): that confirms the device effectiveness.

It must be noted that the device limits the actuation speed even during the deployment, all the more as the opposing load is higher (see the almost constant part of the DThM curve in figures 18 and 19).

The figures 22-23-24-25 show respectively the deployment and the retraction without and with constant load for a system provided with a command ramp generator: the position demand (Dem) computed by the command ramp generator is the true input in the flap control system, while in the previous cases the input is the pilot command directly.

In the deployment (figures 22-23) at the beginning the maximum slope of the position demand limits the actuation rate because of the low value of the opposing load; when the load grows, the maximum allowed position error limits in turn the actuation speed. In this way the actuation speed is more strictly controlled with

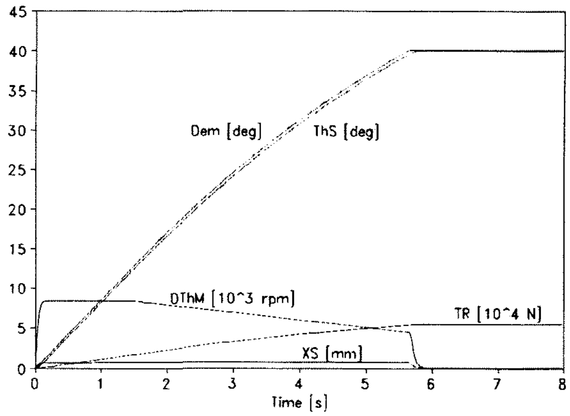

Fig. 22 - Ramp generator - Deployment low load

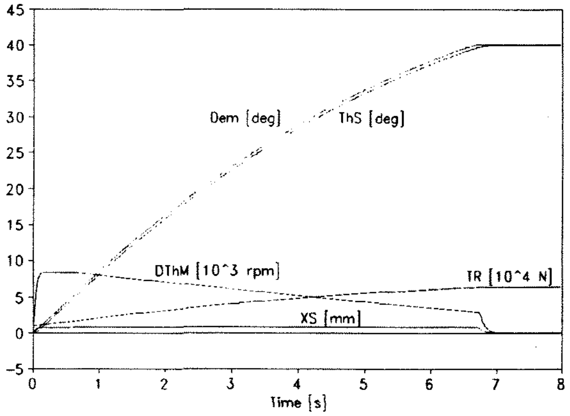

Fig. 23 - Ramp generator - Deployment high load

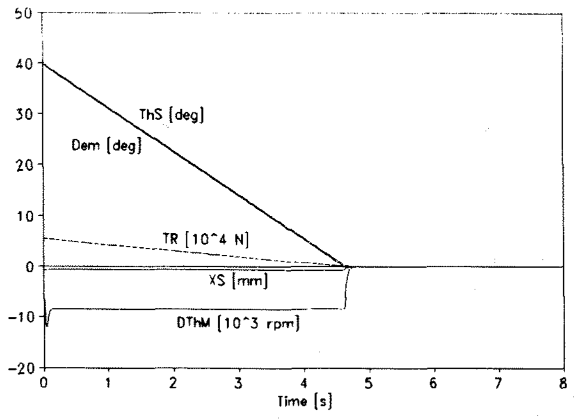

Fig. 24 - Ramp generator - Retraction low load

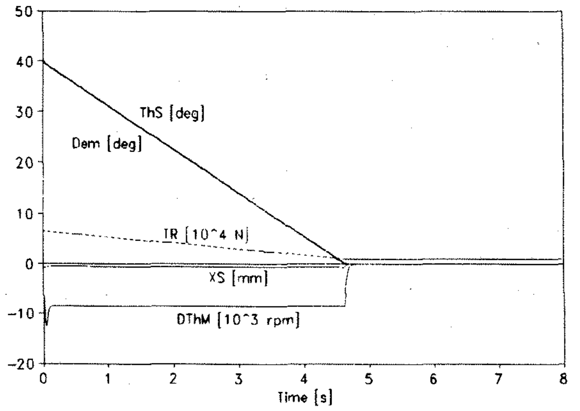

Fig. 25 - Ramp generator - Retraction high load

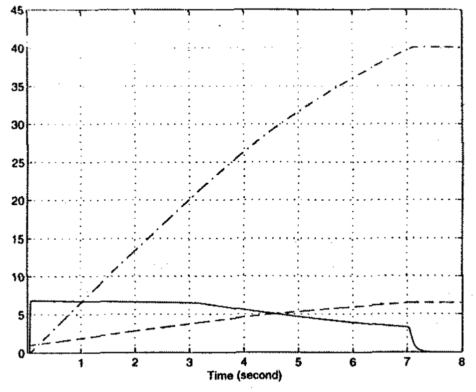

Fig. 26 - Speed feedback - Deployment high load

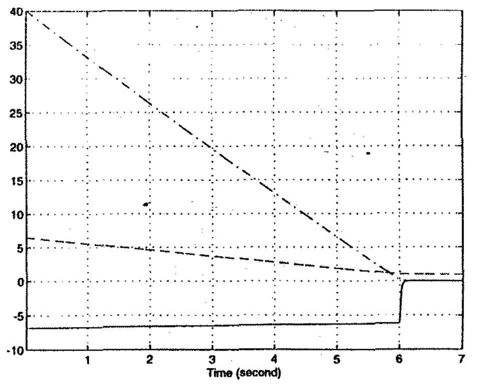

Fig. 27 - Speed Feedback - Retraction high load

respect to the system without any speed limiting device (see figures 6-7).

In the retraction (figures 24-25) the arrangement gives rise to a limitation merely imposed by the maximum slope of the position demand, which leads to an actuation time closer to the one in deployment.

By means of the mentioned Matlab-Simulink code the figures 26 and 27 have been obtained, showing respectively the deployment and the retraction with high load of a flap control system equipped with a nonlinear speed feedback device.

The results are quite similar to the ones shown in the figures 19 and 21.

Conclusions

The results emphasize the different dynamic behaviour of the control system employing each considered method for the actuation speed limitation.

A system equipped with a reduced valve spool maximum stroke in the retraction mode (asymmetric valve) is characterized by an effectiveness strongly dependent on the aerodynamic loads, which may be different following the several flight conditions. Therefore it must be designed for an average load condition: for different loads the actuation time may sensitively change, even greater in retraction then in deployment. This method does not involve any change in cost, reliability and maintainability.

On the contrary, the flow limiter is effective in a wider range of aerodynamic loads, but it is difficult to make its dynamics so quick to avoid the motor speed overshoot at the start-up. The increase in cost and the decrease in reliability and maintainability are not negligible.

An almost similar effectiveness in a wide range of aerodynamic loads is attainable by a system equipped with a speed feedback, characterized by negligible motor speed overshoot at the start-up. However, in order to avoid the speed loop instability, it is necessary to limit the speed loop gain and the consequent effectiveness of the method. The same difficulty is also present in a system equipped with a flow limiter, even in a lower extent, because the servovalve dynamics is out of the speed control operated by the device. The increase in cost and the decrease in reliability and maintainability are lower than in the previous case.

The command ramp generator allows to obtain the desired effectiveness in the actuation speed limitation, but only by extending the retraction time. However the motor speed overshoot at the start-up, essentially caused by the Coulomb friction, is greater then in the previous cases. This method involves almost negligible change in cost, reliability and maintainability.

Therefore the selection of the most suitable method depends on the specific dynamic characteristics of the flap actuation and control system and on the design performance, reliability, maintainability and cost requirements.

List of symbols

BLG	Ballscrew actuator backlash
BLPT	Position transducer backlash
BS	Ballscrew actuator
BSN	Ballscrew actuator with built-in irreversibility brake
Dem	Flap control system position demand
DThM	Motor speed
FFM	Motor Coulomb friction torque
FFPT	Position transducer Coulomb friction torque
FFS	Surface Coulomb friction torque
KG1	Torque tube stiffness
KG2	Ballscrew actuator stiffness
PDU	Power Drive Unit
PT	Position transducer
ThS	Flap position
TT	Torque tube
WTB	Wingtip brake
XFL	Flow limiter piston position
XS	PDU servovalve spool position
ZM	Motor gear reducer ratio
ZS	Ballscrew actuator gear reducer ratio

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