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THE IMPACT OF CIRCULATION CONTROL ON ROTARY
AIRCRAFT CONTROLS SYSTEMS

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Circulation technology for lift augmentation of airfoils has been around for many years. Application of circulation to rotary wing systems is a relative recent development. Substantial efforts to determine experimentally the near and far field flow patterns and to analytically predict those flow patterns have been underway in the fixed wing community for some years.

Rotary wing applications present a new set of challenges in circulation control technology. Rotary wing sections must accommodate substantial Mach number, free stream dynamic pressure and section angle of attack variations at each flight condition within the design envelope. They must also be capable of short term circulation blowing modulation to produce control moments and vibration alleviation in addition to a lift augmentation function. Control system design must provide this primary control moment, vibration alleviation and lift augmentation function. To accomplish this, one must simultaneously control the compressed air source and its distribution. The control law algorithm must therefore address the compressor as the air source, the plenum as the air pressure storage and the pneumatic flow gates or valves that distribute and meter the stored pressure to the rotating blades. Additionally, mechanical collective blade pitch, rotor shaft angle of attack and engine power control must be maintained by the control system.

CONTROL SYSTEM CHALLENGES

The control system design encompasses numerous support subsystem functions not conventionally addressed by control law implementation. These rotor subsystem impacts emanating from the circulation control rotor and its supporting hardware produce numerous challenges to control system design. Listed in Table I are those challenges that are considered to require attention to provide an acceptable control system design for rotary wing flight.

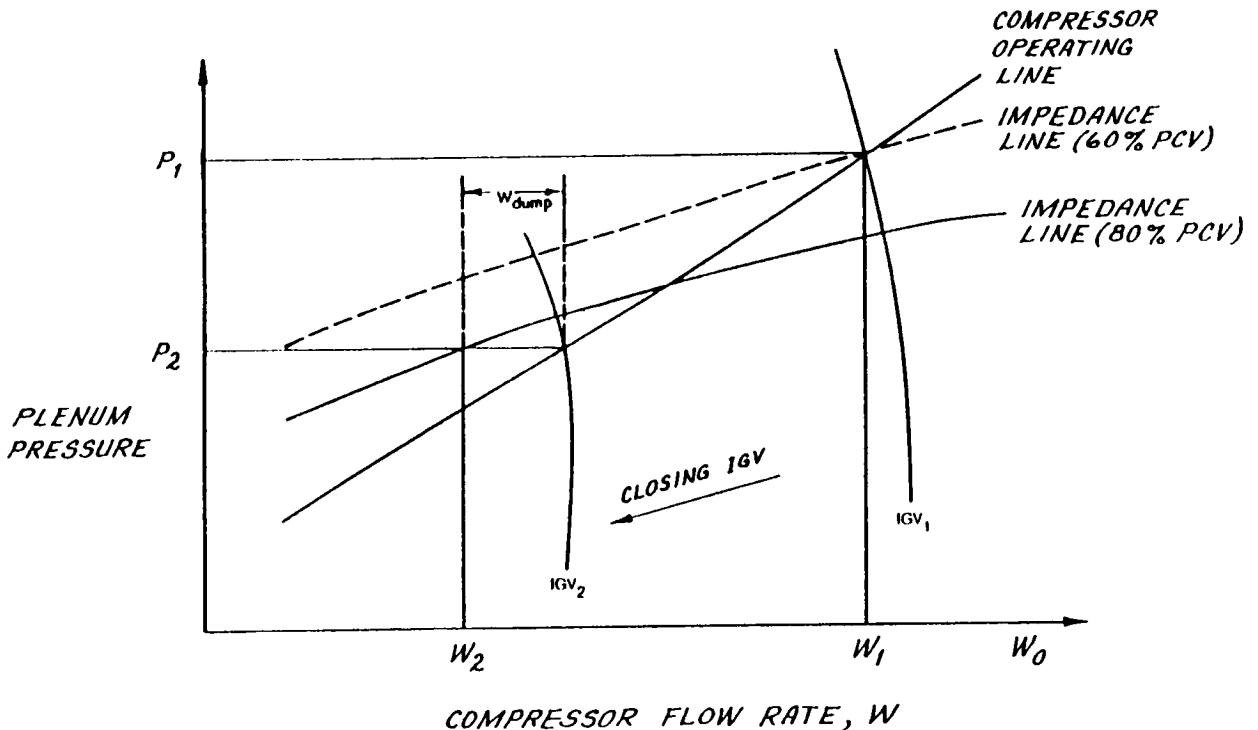
TABLE I. CONTROL SYSTEM DESIGN CHALLENGES

AIR VEHICLE SYSTEM	CHALLENGE DESCRIPTION
Compressor	. Avoid surge and stall
Rotor	. Hub moment feedback trade-offs
Pneumatics	. Valve flow non-linearities . Notable lags
Control	. Limited available range . Angle of attack non-linearities . Higher harmonic control

COMPRESSOR STALL/FLOW RATE/PRESSURE INTERACTIONS

The control system must provide plenum and blade pressure and mass flow required while maintaining the compressor on or below its operating line to avoid compressor stall. To accomplish this the control system employs feed-forward and feedback paths to simultaneously adjust inlet guide vanes, pneumatic control valves and the modulating dump valve to provide the system impedance required to maintain operation on or below the compressor operating line and thus avoid compressor stall. The pressure control loop restricts maximum PCV setting to 80 percent leaving 20 percent margin for high frequency flow demands. Plenum pressure control by IGV setting accommodates low frequency blowing demands. Where 80 percent PCV setting will not provide a low enough impedance to maintain the compressor on its operating line, a modulating dump valve is used to reduce impedance. This occurs any time that the flow demand is less than that produced by the compressor with closed IGV's. These characteristics are apparent in the conceptual compressor map shown in Figure 1.

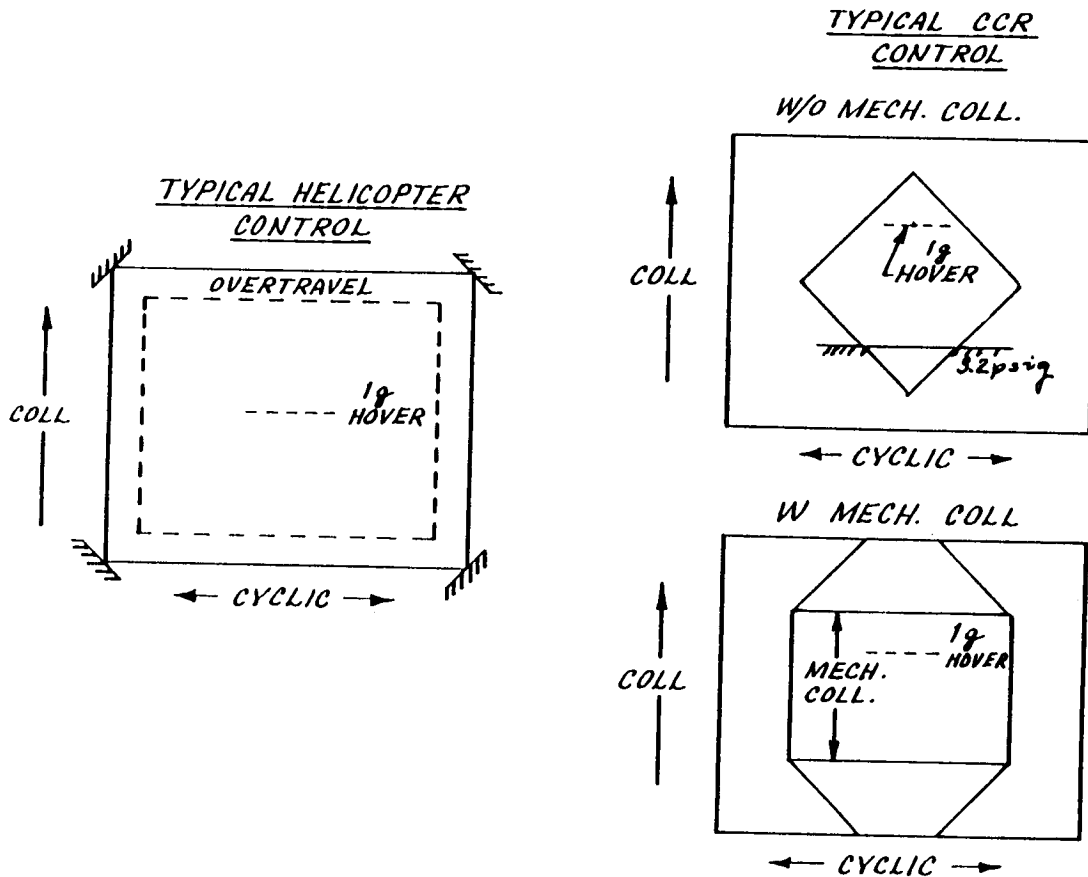
FIGURE 1
COMPRESSOR STALL /FLOW RATE/PRESSURE INTERACTION



CIRCULATION CONTROL SYSTEM LACKS COLL/CYC "OVERTRAVEL"

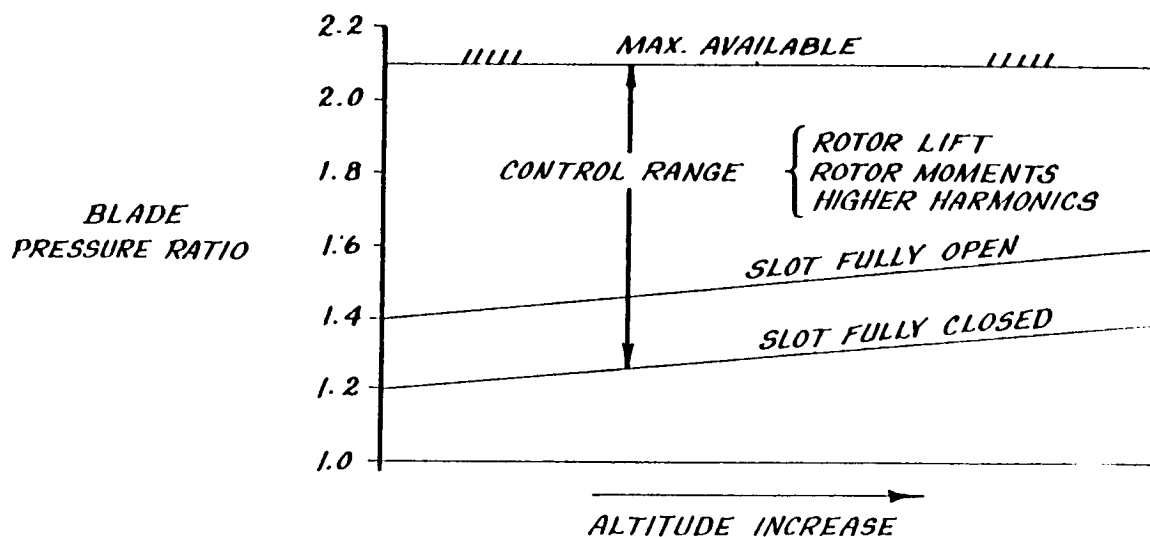
Vehicle control with the CCR must be provided with substantially less collective/cyclic range than conventional helicopters enjoy. Modern Helicopters are also provided with "overtravel" to allow full travel of each control independent of the other control setting and provide inner loop stability and outer loop autopilot inputs without infringing on primary flight control travel as shown on the left in Figure 2. The CCR system, shown on the right in the figure without mechanical collective has a very restricted collective/cyclic range. Pneumatic collective settings substantially influence pressure ratio available for cyclic moment control. By addition of mechanical collective control to the CCR system, the nominal center pneumatic collective can be used for lift leaving the full cyclic blowing range for moment control. Rationing the limited pressure ratio range between lift and moment control represents a considerable challenge to the control design.

FIGURE 2
CURRENT SYSTEM LACKS COLL/CYC "OVERTRAVEL"



The pressure ratio at which a blade slot will open, increases with pressure altitude as shown in Figure 3. The internal duct pressure for which the slot hold-down spring is set represents higher pressure ratios as the outside ambient pressure gets lower. The limited CCR collective/cycle control range is therefore further reduced as altitude increases. These altitude impacts can be reduced or eliminated completely by providing positive slot control. Both passive and active concepts for slot control are practical and achievable attributes for next and future generation CCR systems.

FIGURE 3
CCR CONTROL RANGE IS LIMITED AT ALTITUDE

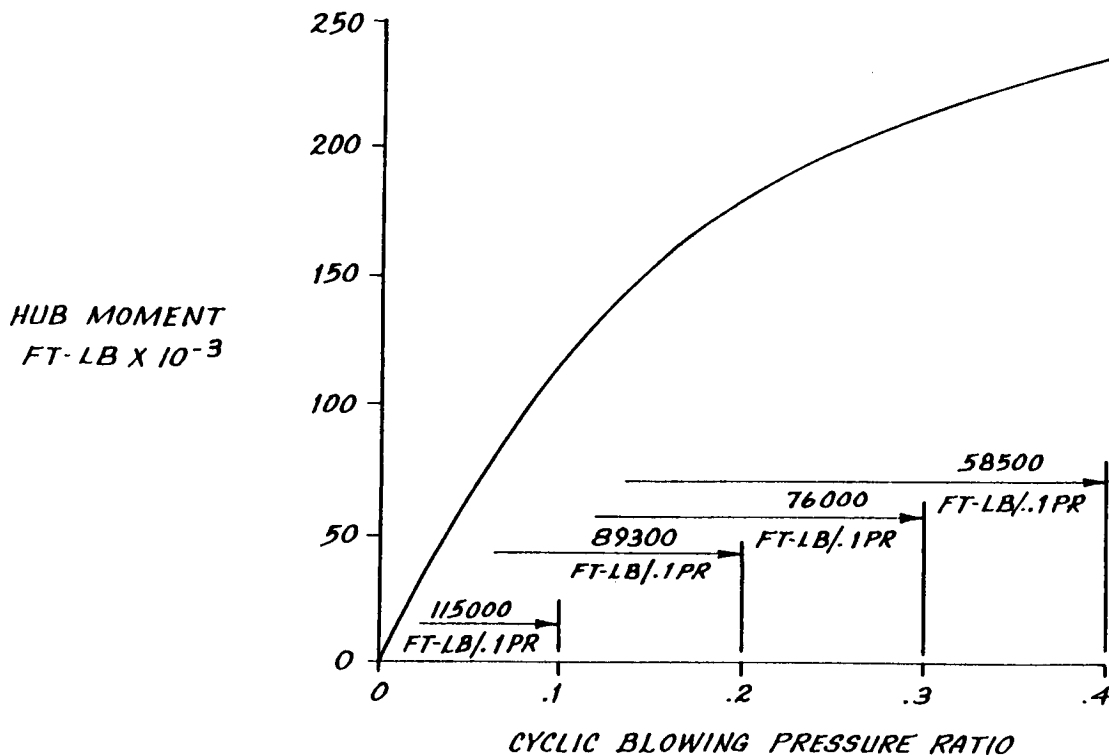


PNEUMATIC MOMENT CONTROL IS NON-LINEAR

Control system design for CCR systems must accommodate the inherent non-linear characteristics of circulation rotors. Conventional aerodynamic rotor systems have a moment producing capability proportional to feathering input magnitude

up to stall encounter. CCR systems do not enjoy this characteristic. The mean control power in foot-pounds per tenth of a pressure ratio reduces rather substantially with the magnitude of the cyclic input as shown in Figure 4. At hover for example, a control power of 115,000 ft-lb per .1 PR cyclic exists if only .1 PR cyclic is applied. If .4 PR cyclic input is applied, however, the control power per .1 PR has a mean value of only 58,500 or essentially one half of that for small cyclic inputs. This non-linear control power characteristic exists to varying degrees over the rotary wing flight envelope. Extreme care must accompany linearization techniques to support linear analyses.

FIGURE 4
PNEUMATIC MOMENT CONTROL IS NON-LINEAR

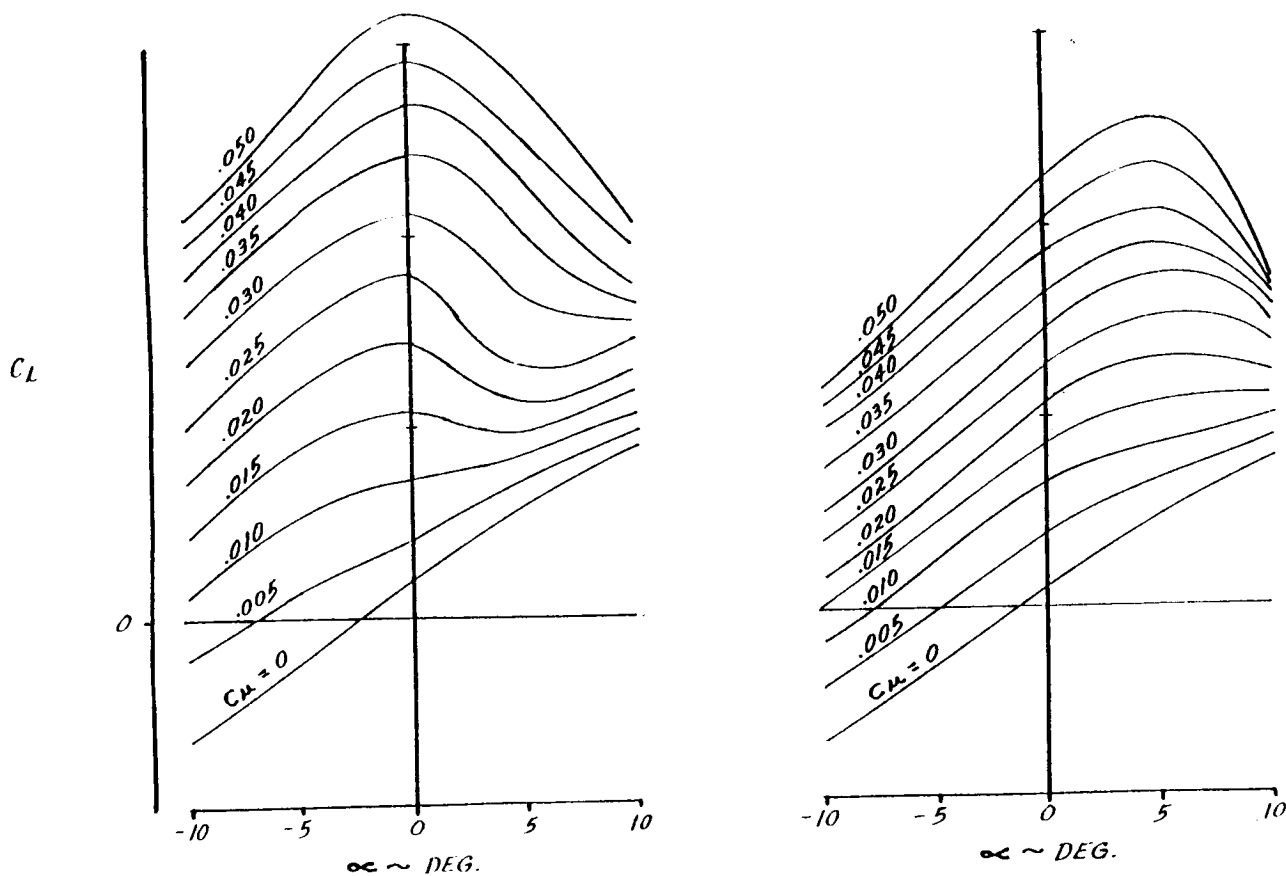


CCR SECTION STALL CHARACTERISTICS ARE UNCONVENTIONAL

Lift coefficient against angle of attack characteristics are presented in Figure 5 for two representative sets of circulation sections. The section on the left is a thick inboard type of airfoil with a slot height to chord ratio of .0013. The section on the right is a relatively thin outboard type section with a slot height to chord ratio of .0020. The inboard type section has a

good circulation lift augmentation ability but stalls at zero angle of attack with any significant blowing applied. The outboard type section provides somewhat less circulation lift augmentation and a somewhat higher stall angle of attack (5 deg). The single most significant characteristic that stands out is the low angle of attack stall of the sections. Control law impact particularly at higher speeds is substantial. Attempts to save pneumatic power by using mechanical collective for roll control must be approached with extreme caution since potential for control reversal is rather apparent. In addition, vehicle angle of attack non-linearities are most probable. Control laws must therefore use combinations of angle of attack and normal load factor feedback algorithms to assure rotor operation be maintained to the maximum extent possible on the positive values of lift curve slope. New airfoil developments underway at Sikorsky and David Taylor NSRDC show promise of substantial extension of stall to higher section angles of attack.

FIGURE 5
CCR SECTION STALL CHARACTERISTICS ARE UNCONVENTIONAL

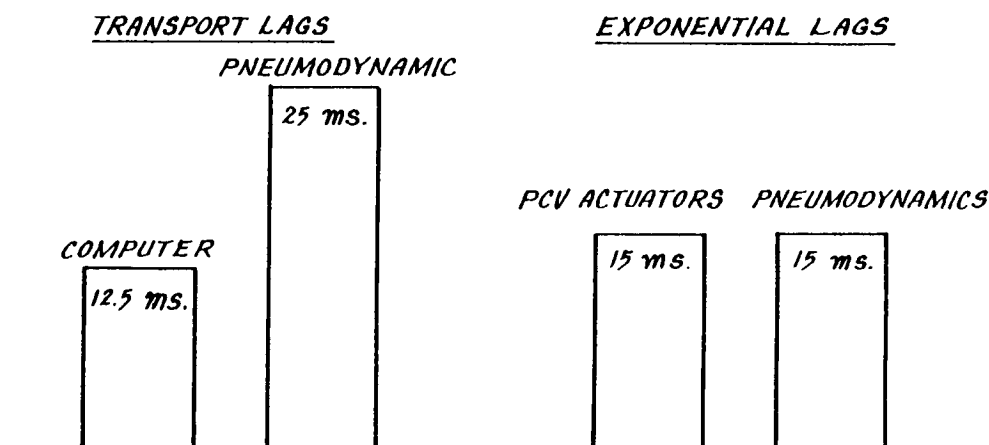


SYSTEM LAGS ADD SERIALLY

Control system design for CCR system applications must be capable of accommodating notable transport and exponential lags. The magnitude of these system lags unique to CCR are shown in Figure 6. Fly-by-wire control through a quad-redundant digital computer together with redundancy management software allows rotor system updates at an 80 Hz rate. Thus the flight control computer represents a 12.5 ms transport lag from input to output. Adding to that is a 25 ms transport lag caused by the sonic pressure wave propagation from the pneumatic control valves (PCV's) to full span slot flow on the blades. Therefore an open loop transport lag of 37.5 ms must be compensated for by the control system design. In addition, two substantial exponential lags exist in the current technology CCR system. The first of these occurs between plenum pressure demand and plenum pressure response as a function of change in the compressor inlet guide vanes. The second exponential lag is associated with the PCV actuators and is also 15 ms. As a result, the control system must accommodate a 30 ms time constant in addition to the 37.5 ms transport lag. This lag compensation must be accomplished by the control algorithms while retaining adequate systems phase margins.

FIGURE 6
SYSTEM LAGS ADD SERIALLY

INDIVIDUAL LAGS:



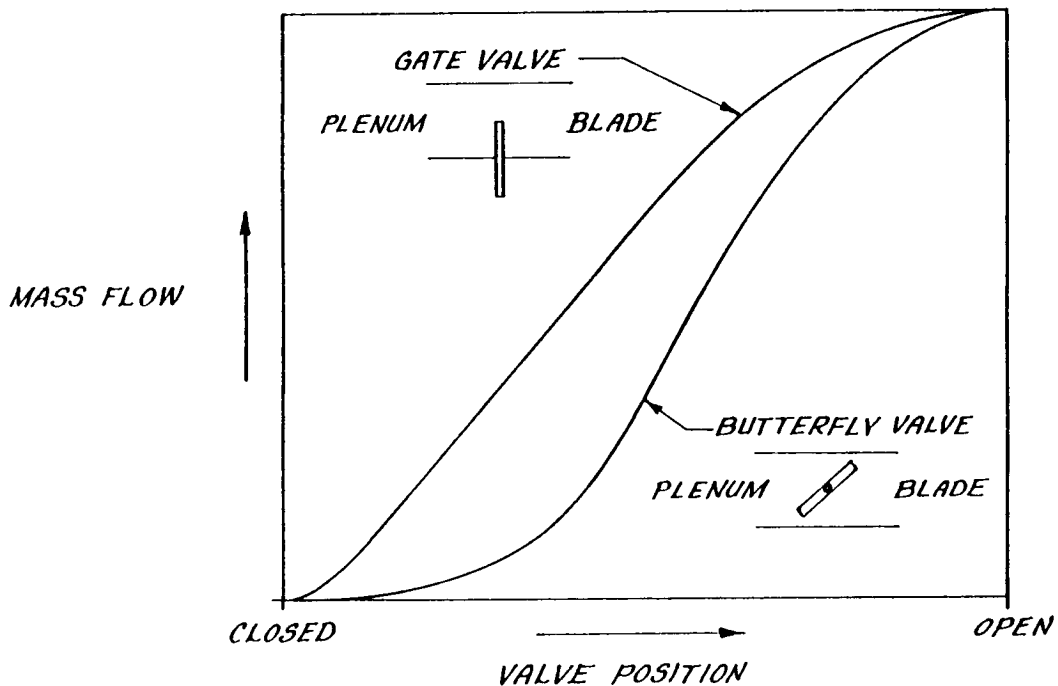
NET OPEN LOOP LAGS:

37.5 ms TRANSPORT
30.0 ms EXPONENTIAL

VALVE POSITION TO MASS FLOW NON-LINEARITIES

Two common types of flow valves have been applied to CCR systems. The two types are gate valves and butterfly valves. There are attributes and deficiencies associated with each type. Flow characteristics as a function of valve position are shown in Figure 7. Gate valves demonstrate the least non-linear flow versus position characteristics but represent a weight and performance penalty solution. Rotor head designs to accommodate vertical travel of trailing edge and leading edge gate valves are rather large and heavy and create excess drag. Design approaches are practical that could make gate valves a future viable solution. Butterfly valves on the other hand package in the rotor head very efficiently providing weight and performance benefits. Some additional demand is placed on the control system design to compensate for the substantial non-linear flow versus rotation characteristics of butterfly type valves. Flow characteristics are of a form that basically conforms to a $[1-\cos(\text{angle})]$ relation. Pneumatic control valve logic developed for control laws application is effective in compensating for the non-linear characteristic of the butterfly valve system.

FIGURE 7
VALVE POSITION/MASS FLOW NON-LINEARITIES

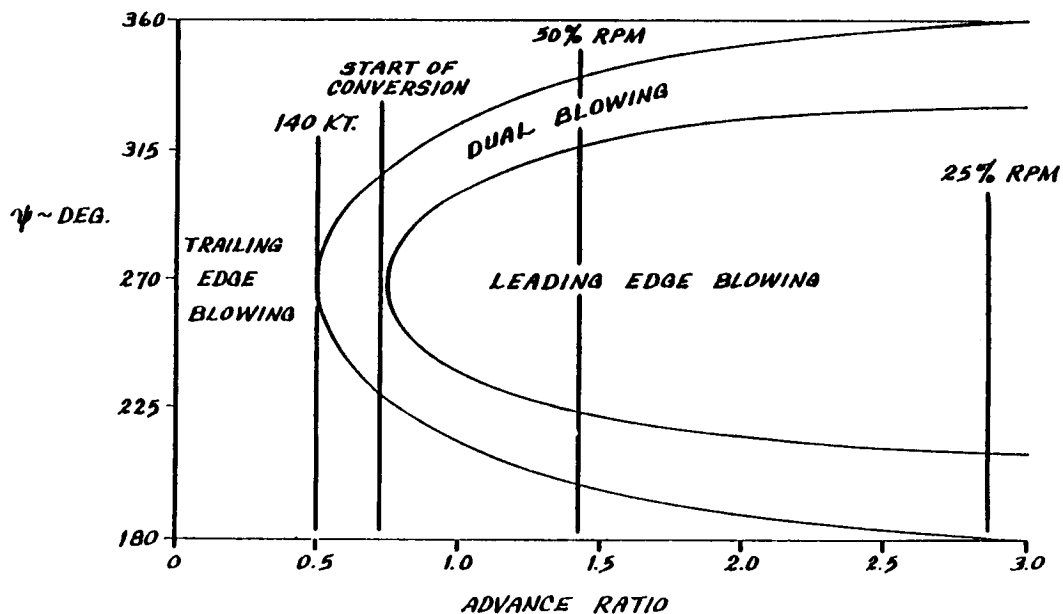


LEADING EDGE BLOWING SCHEDULE

Current technology in slot design requires blowing over the full span or no blowing over the full span of the blades. In addition the slots are spring loaded closed until internal duct pressure of 3.2 psig is present at which

point the slot commences to open. At 5.9 psig the slot is fully open against an internal stop. This is a relatively low risk approach for first generation flight hardware. Possible production variance will only impact blade to blade performance in the elastic slot range between 3.2 and 5.9 psig duct pressure. At higher advance ratios, leading edge blowing is required on the retreating side of the rotor to compensate for the onset of reverse flow. Without the ability to radially adjust slots, a schedule was developed for control of high advance ratio leading edge blowing to maximize lift at these flight conditions. The schedule for high advance ratio dual and leading edge blowing is shown in Figure 8. Dual blowing, trailing edge plus leading edge commences at the 270 degree azimuth location at .5 advance ratio which occurs at 140 KT. Transition to single leading edge blowing occurs at .75 advance ratio. Each of these occurrences spread fore and aft on the retreating side of the disc as advance ratio increases and finally goes to infinity when the rotor stops. At the stopped rotor condition with blades at 225 and 315 degrees azimuth, the valves concerned have only leading edge blowing in accordance with the schedule shown. Leading edge blowing on the retreating side is in fact trailing edge blowing relative to the blade flow.

FIGURE 8
LEADING EDGE BLOWING CONTROL SCHEDULE



CONCLUSIONS

Current circulation control rotor technology forces some control system design compromises and some control system design challenges. The control system design must accommodate more subsystem functions than encountered in conventional systems. These include:

1. Compressor stall avoidance
2. Pneumatic control valve algorithm
3. Impacts on primary control by HHC blowing
4. Engine power response to rotor and compressor power requirements
5. Adequate lift, moment and vibration control from a limited pneumatic control range
6. Substantial cyclic blowing to control moment nonlinearities
7. Moment trim with pneumatic cyclic when moments are produced by pneumatics plus aerodynamics
8. Substantial non-conventional section stall characteristics
9. Leading edge blowing at higher advance ratios without radial slot control
10. Notable transport and exponential lags not previously encountered in rotary wing control system design
11. Mechanical collective pitch scheduling to enhance system control range characteristics

Circulation control rotor design improvements are under study that will reduce or eliminate many of the above control system design challenges and compromises. Reasonable success in a number of areas can provide substantial performance, maneuverability, stability and handling qualities improvements in next generation rotor designs.