DESIGN AND DEVELOPMENT OF A TWO-FAIL-OPERATE FLY-BY-WIRE FLIGHT CONTROL ROTOR ACTUATION SYSTEM UTILIZING INTEGRATED THREE-FUNCTION VALVES

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Abstract

Compared with conventional fixed-wing commercial aircraft, the task of designing helicopter flight control systems to avoid flight critical failure modes is considerably more challenging.

For typical fixed-wing commercial aircraft, flight control system redundancy can be provided through the application of multiple independently actuated surfaces. An example of this methodology is the use of two or three ailerons per wing. Configured in this manner, continued safe flight is achieved in the event of an aileron becoming uncontrollable or seized.

In helicopters and tiltrotors, application of multiple independently actuated rotors to provide flight control system redundancy is not a viable option. Typically in rotor systems, multiple flight control actuators are structurally or mechanically linked together to provide redundancy of actuation. This methodology provides for continued safe flight following the failure of a system or actuator, except for cases where a failed actuator cannot be freely back-driven (or bypassed) by the remaining actuators. For these failure modes, the result will be loss of rotor control. Therefore, it is a critical requirement for rotor control actuators that their designs incorporate devices that can reliably ensure that a failed actuator can be overridden. For hydraulic actuators, this implies ensuring a bypass condition.

This strict reliability design requirement, in conjunction with performance and weight considerations, resulted in development by Bell and Smiths of the integrated three-function valve (ITFV).

This paper is an overview of the design and development of the ITFV and its application in a dual configuration in the BA609 fly-by-wire collective actuator.

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Background

In conventional fly-by-wire (FBW) rotor control actuation, triple hydraulic redundancy is achieved by employing a dual tandem configuration (two rams end to end). A switching valve is used to connect two independent hydraulic sources to one of the tandem rams. This ram would be controlled by dual-redundant electrohydraulic valves and dual-redundant signals from a flight control computer (FCC). Typically, the tandem ram configuration is supported with spherical bearings or U-joints to minimize structural bending loads.

The original BA609 triplex collective actuator was a departure from this ram and system configuration, arranging three hydraulic rams side by side in a triangular pattern (Figure 1). Each ram is hydraulically powered and controlled from one of three independent manifolds, hydraulic systems, and FCCs. By using three rams instead of two, this configuration has the advantage of eliminating the need for hydraulic switching valves, control systems, and their associated failure modes. Degradation of actuator load/rate capacity following a single failure and the severity of transient motions from control failures are also improved by having two rams continuing to operate following a single failure instead of only one.

Each original BA609 collective actuator hydraulic manifold (see Figure 2) comprised an electrohydraulic servovalve (EHSV), a solenoid-valve-controlled bypass valve to disengage the cylinder in the event of a fault, a differential pressure sensor to allow force balancing across the triple active cylinders to minimize bending loads (a load control concept used in various configurations on other aircraft, including the RAH–66 Comanche), and a pressure relief valve to limit cylinder pressures during adverse failure conditions. For each system, four linear variable-displacement transducers (LVDT) were fitted for control and monitoring of the EHSV spool, the bypass valve spool, the ram piston, and the differential pressure sensor.

The delta pressure sensors, typical of other applications, consisted of spring centered pistons with one

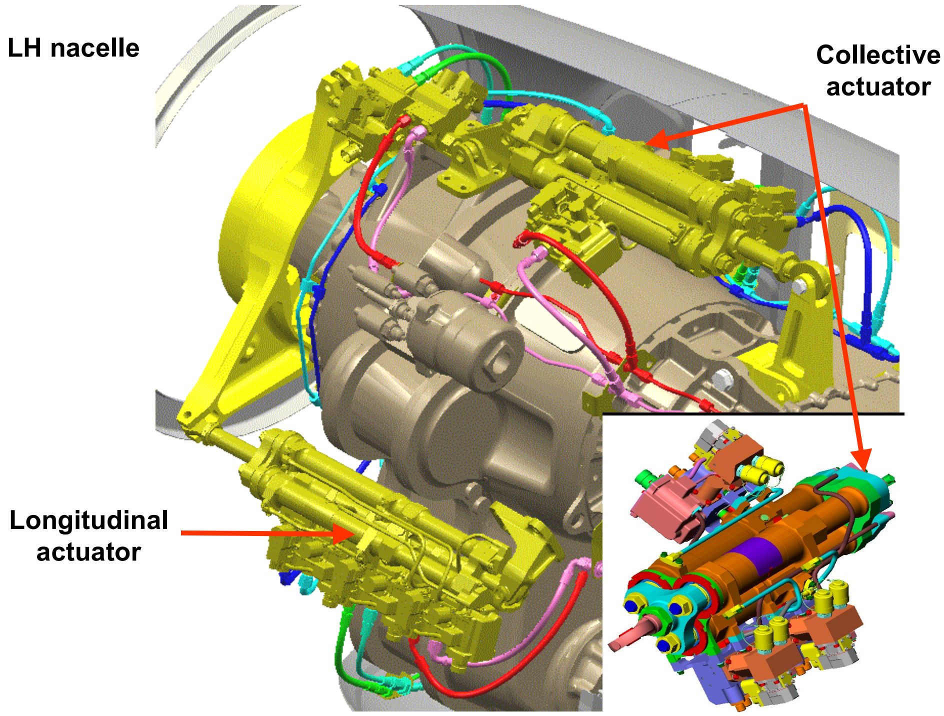

Fig. 1. Original triplex collective configuration.

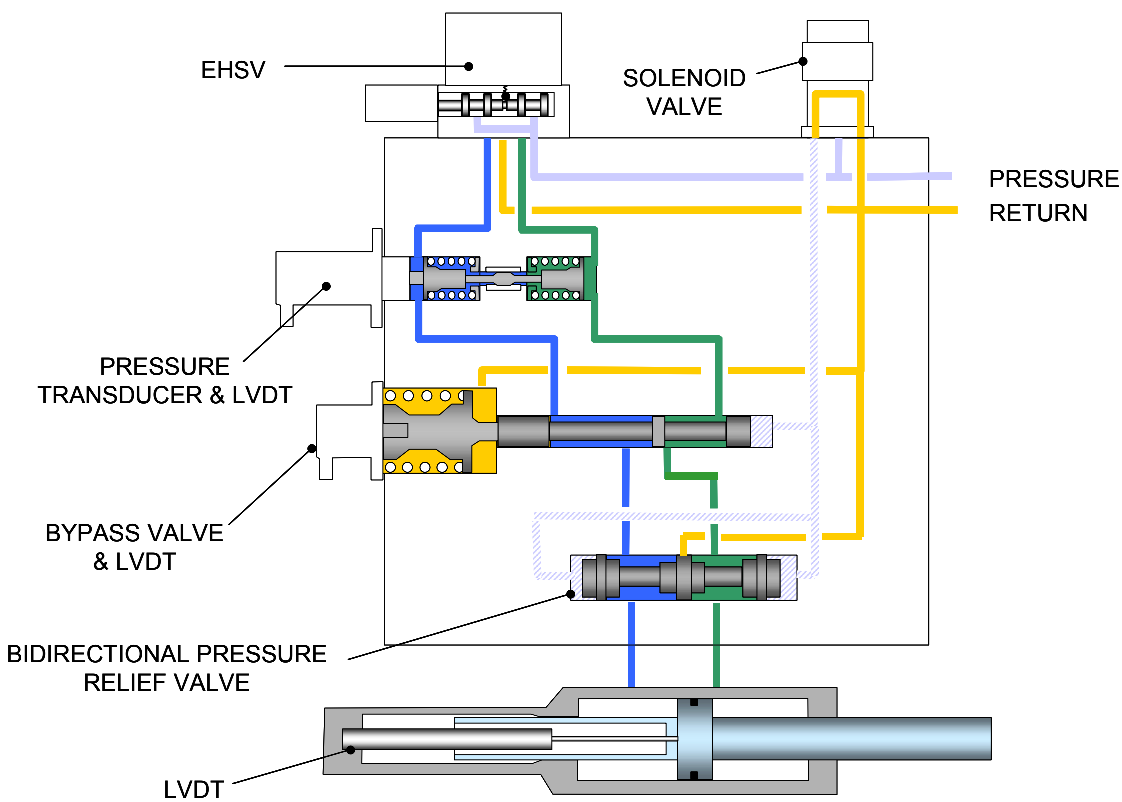

Fig. 2. Original triplex collective manifold.

side ported to extend pressure and the other to retract pressure. Sensor piston displacement (measured by an LVDT) was proportional to the delta pressure acting on the ram piston.

In principle, the system presented provides full triple redundancy, allowing continued operation after any two failures.

Reliability analysis of this system both during the design stage, and ending in a series of reliability reviews in September 2000, concluded that this system, using industry-accepted values for component failure rates, complied with the currently accepted reliability requirements. However, the critical function of the collective actuator in a tiltrotor aircraft, in conjunction with market perceptions of tiltrotor reliability, directed Bell management in September 2000 to set a higher standard for flight control actuator reliability. Bell imposed a flight-critical failure reliability requirement that “no combination of two electrical or hydraulic component failures, regardless of expected failure rate, should prevent an actuator from continued safe operation.”

Test experience and a design review indicated a number of possible double failure modes that would not comply with this revised definition. In addition, some electrical and hydraulic component failures may lie dormant in the actuator, if the component is not used during normal operation or is not capable of being periodically tested. Possible dormant failures, therefore, must be considered in combination with all other two-fail combinations. Such failure modes were

1. EHSV failure (hardover or at null position) in combination with failure to bypass the cylinder. The degradation in load rate capacity (resulting from the combination of driving flow across the relief valve on the failed cylinder and increased friction from bending) would not be acceptable.

2. An EHSV sticking at null position combined with the sticking of the pressure relief valve (PRV)—a dormant failure—could cause acceptable ram pressures to be exceeded. Although this condition would be overridden by the bypass valve, it was considered that the total time required between failure detection and achieving bypass was not adequate to protect the failed ram from a spike of overpressurization. This condition is a greater problem for the triplex ram than for the duplex ram, as the peak load can be three times the design stall (two active rams at stall plus air load) compared to twice the stall (one active ram at stall plus air load). Therefore, with the BA609 system operating pressure of 21.68 MPa (3,000 psi), this failure combination could generate a pressure spike of 62.05 MPa (9,000 psi). The failure on a triple ram system could therefore exceed normal design burst conditions of 1.71 MPa (7,500 psi) burst pressure required for 21.68 MPa (3000 psi) system actuators, unless excessive weight is added to accommodate the failure mode.

3. Loss of two hydraulic or two FCC systems combined with the dormant failure of a PRV. The ram controlled by the one remaining functioning system will be required to react all flight loads. If the ram on the remaining system contains a PRV that opens at pressures below system operating pressure, control of the actuator could be lost. A PFBIT can be incorporated into the FCCs to load each ram to stall in order to confirm that the PRVs do not open below system pressure. However, this subjects the actuator and structure to severe fatigue loads.

4. In the event of the loss of one ram due to FCC or hydraulic system failure, the two functioning rams should equally support actuator flight loads. However, if a failure mode of a delta pressure sensor results in a pressure indication opposite in direction of the actual ram load, a force fight between the remaining to actuators can result in the frequency response of the actuator becoming severely degraded. In addition to these double failure modes, a change of sensitivity of a differential pressure sensor would lead to increased fatigue due to the increased force fight between the triple actuators.

A number of design solutions were considered to resolve these issues, but most required additional components, adding significantly to the size, complexity, and weight of the collective actuators. They also degraded the mean time between repairs (MTBR) and unacceptably increased the number of interfaces between the actuator and the FCC. Examples of solutions considered were

1. Adding a redundant second EHSV to each manifold to counteract a failed EHSV.

2. Adding a second bypass valve (independently controlled by a second solenoid valve) to ensure bypass capability.

3. Adding a second pressure relief valve; however, this does not eliminate the possibility of malfunction due to problems of proving correct operation during preflight built-in testing (PFBIT).

4. Adding a redundant delta pressure sensor to each manifold, which allows cross-checking of accuracy.

It became apparent that when the strict critical failure reliability requirement ("no combination of two electrical or hydraulic component failures should prevent continued safe actuator operation") was applied to the original actuator design, major changes to the collective actuator would be required. Such changes to the actuator could not result in major changes to the FCCs, hydraulic system, and wiring configuration. These changes were prohibited due to the advanced state of the BA609 program.

Based on the conclusions of the reliability and failure mode analysis conducted on the original BA609 collective actuator, the following requirements for the new actuator design were defined:

a. Bypass valve function must be redundant and independent.

b. Confirmation of redundant bypass valve operation must possible during PFBIT as a minimum. Continuous health monitoring is preferred.

c. PRV function must be redundant and independent.

d. Confirmation PRV operation must possible during PFBIT as a minimum. Continuous health monitoring is preferred.

e. Redundant delta pressure sensors must be provided to permit continuous cross checking of accuracy.

f. Delta pressure sensors must be robust and free from common mode changes in accuracy.

g. Additional actuator redundancy must not require any additional wiring or changes to existing FCC interfaces.

The strict reliability design requirement in conjunction with performance, cost, and weight considerations, resulted in the development by Bell and Smiths of the integrated three-function valve (ITFV).

Concept Definition

The breakthrough in meeting these difficult requirements was achieved by Bell and Smiths through the design of the ITFV. ITFVs utilize two hydraulic spools to combine the functions of bypass valve, pressure relief valve, and delta pressure transducer into a simple and compact assembly (see Figure 3). When used as a matched pair in the BA609 collective actuator, the ITFVs provide redundant bypass valve, pressure relief valve and delta pressure transducer functionality. This allows all the required redundancy and monitoring requirements to be met with fewer springs, hydraulic spools, and pistons than the original actuator design.

Figure 4 depicts the configuration for the new BA609 collective actuators. Each ram has been redesigned to create unequal extend and retract areas to better match predicted flight loads and reduce transient effects (flight loads are predominantly in tension). In order to minimize ram bending and associated frictional effects, the three collective rams, positioned in a plane side-by side, are now interconnected by a rigid bracket on the control surface via spherical bearings on each ram. This change in ram position arrangement and structural attachment permitted the larger dual ITFV manifolds to fit within the available aircraft space envelope.

Figures 5 through 10 schematically illustrate the operation of new BA609 collective manifold incorporating a dual ITFVs. Although other porting arrangements through the spool are possible, the concept shown was selected as providing the most compact form for the BA609 application. The dual ITFV manifold contains an EHSV with an LVDT to monitor spool position as with the original design. Each ITFV is comprised of a pilot spool, a primary spool, an LVDT that senses primary spool position, and two primary spool springs. Because the original manifold design utilized one LVDT to measure delta pressure and a second LVDT to monitor bypass function, no wiring or FCC interface changes were required.

Two solenoid valves are utilized to control the bypass function for the ITFV pair, one deenergized "off" solenoid valve to drive the primary spool engaged position, and a second deenergized "on" solenoid valve

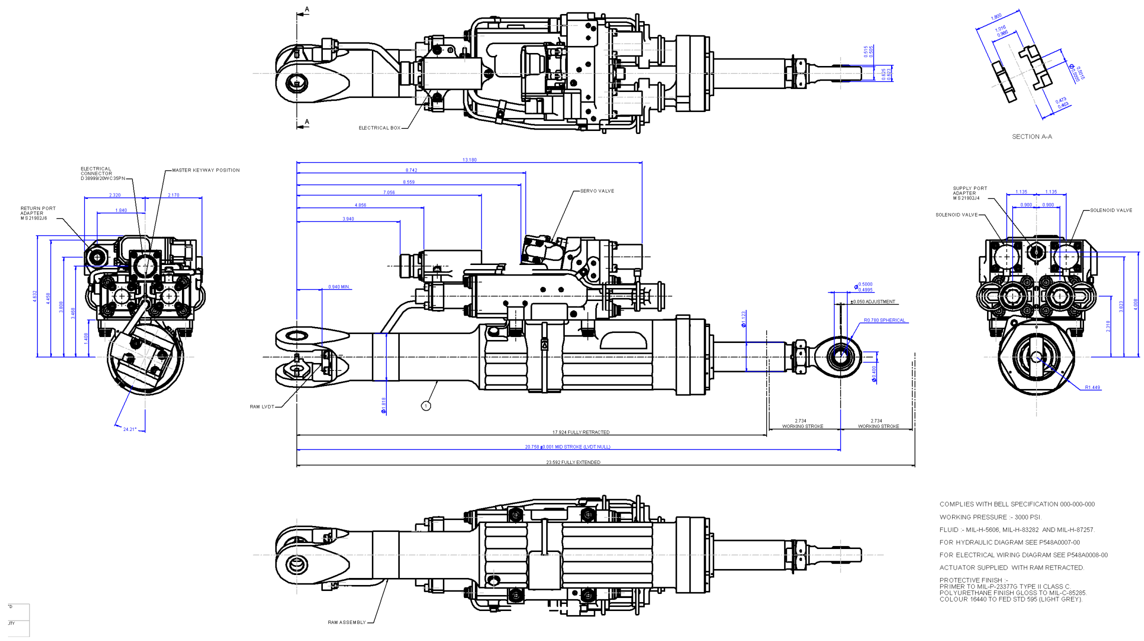

Fig. 3. ITFV collective actuator.

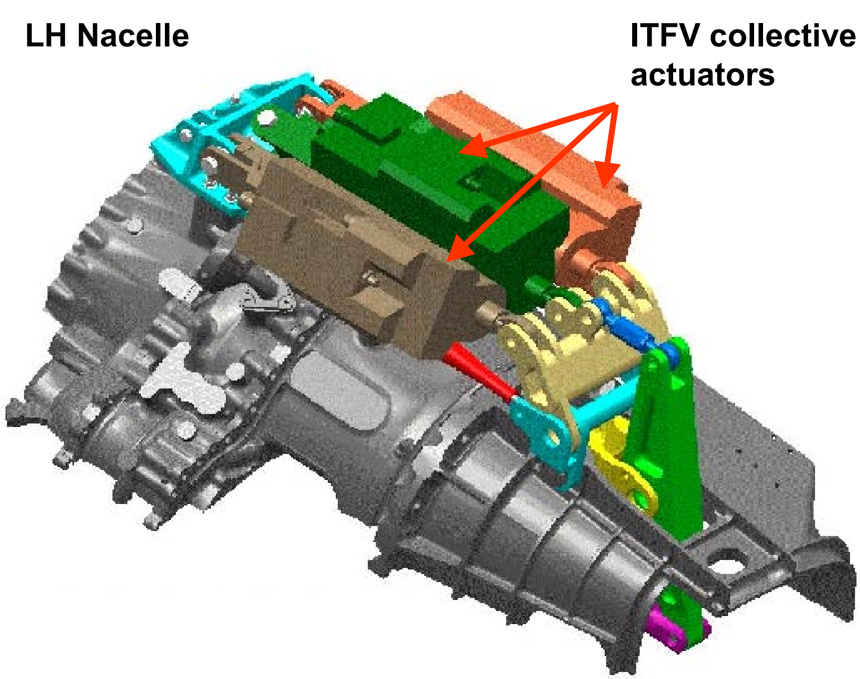

Fig. 4. New ITFV collective configuration.

to control chip shear pressure. As each of the new solenoid valve coils has twice the impedance of the original and is wired in parallel, no FCC or wiring changes are required. The solenoid valves are configured this way to achieve a high chip shear capability (to bypass) when no failures exist while ensuring that bypass can be achieved should either solenoid valve fail to deenergize.

Figure 5 shows the actuator in the bypass mode (solenoid valves off). In bypass mode with the hydraulic system at operating pressure, system flow is ported to the pilot solenoid valve, through the ITFV solenoid valve to the left side of the primary spools, and to the EHSV. The primary and pilot spools, with the solenoid valves deenergized, are held in bypass position by the springs. The primary spool is also held in bypass position by system pressure. The LVDTs attached to the primary spools provide confirmation to the FCC of bypass mode.

Flow from the “retract” EHSV control port to the retract side of the actuator cylinder is blocked by the upper ITFV primary spool. Flow from the “extend” EHSV control port to the extend side of the actuator cylinder is blocked by the lower ITFV primary spool. This configuration isolates the EHSV from the cylinder in bypass mode, but permits the EHSV to be cycled for PFBIT and independent performance checks.

In bypass mode, the primary spools connect both extend and retract cylinder ports to return and (indirectly) to each other. This allows the actuator to be moved freely by other actuators in bypass mode. Because the new collective uses an unequal-area piston, makeup flow from return prevents cavitation.

Figure 6 shows the actuator with the EHSV at null (center) position and in the engaged mode (solenoid valves on). With the EHSV at null, system flow to the ram ports is blocked by the EHSV. In the engaged mode with the pilot solenoid valve energized, system flow is ported from the pilot solenoid valve to the right side of the pilot spools, driving them left to their engaged position. Engagement of the ITFV solenoid valve replaces system pressure with return pressure on the left side of the primary spools. This allows the primary spools to be centered by the equal preload forces of the springs. The LVDTs attached to the primary spools provide confirmation to the FCC that the engaged mode has been achieved.

In engaged mode, flow from the retract EHSV control port is connected through the upper primary spool left side differential area chamber to the retract side of the actuator cylinder. The upper primary spool left side differential area chamber is also ported to the lower primary spool right side differential area chamber.

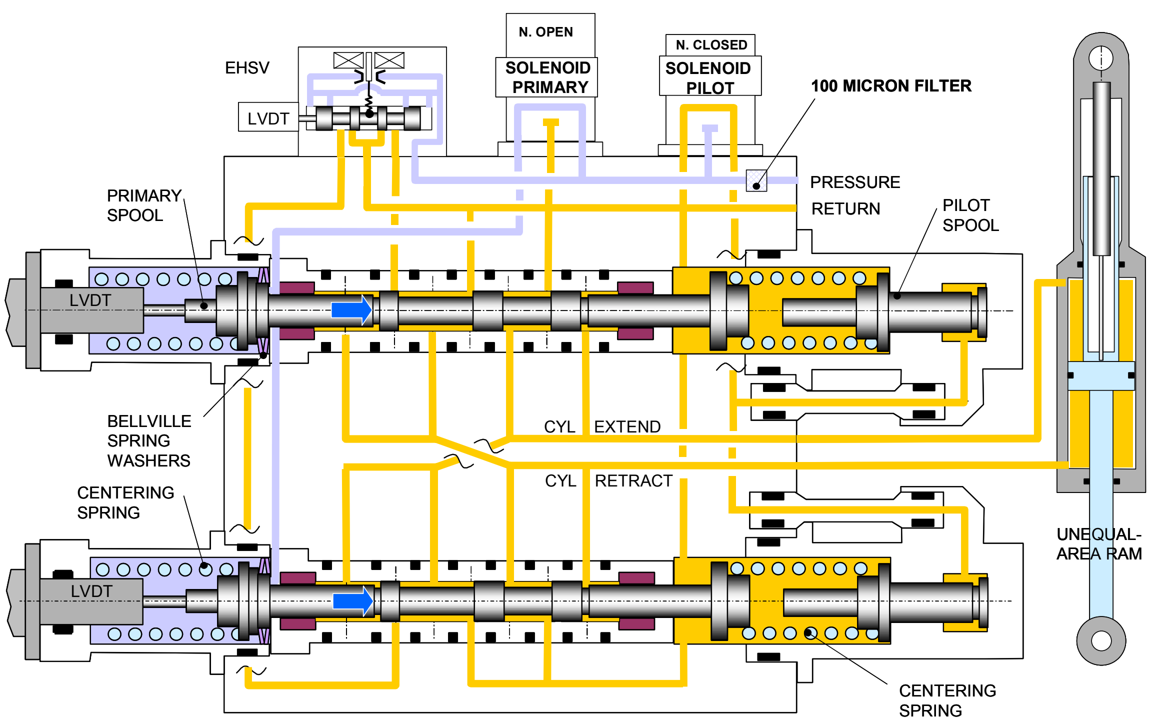

Fig. 5. Actuator in bypass mode.

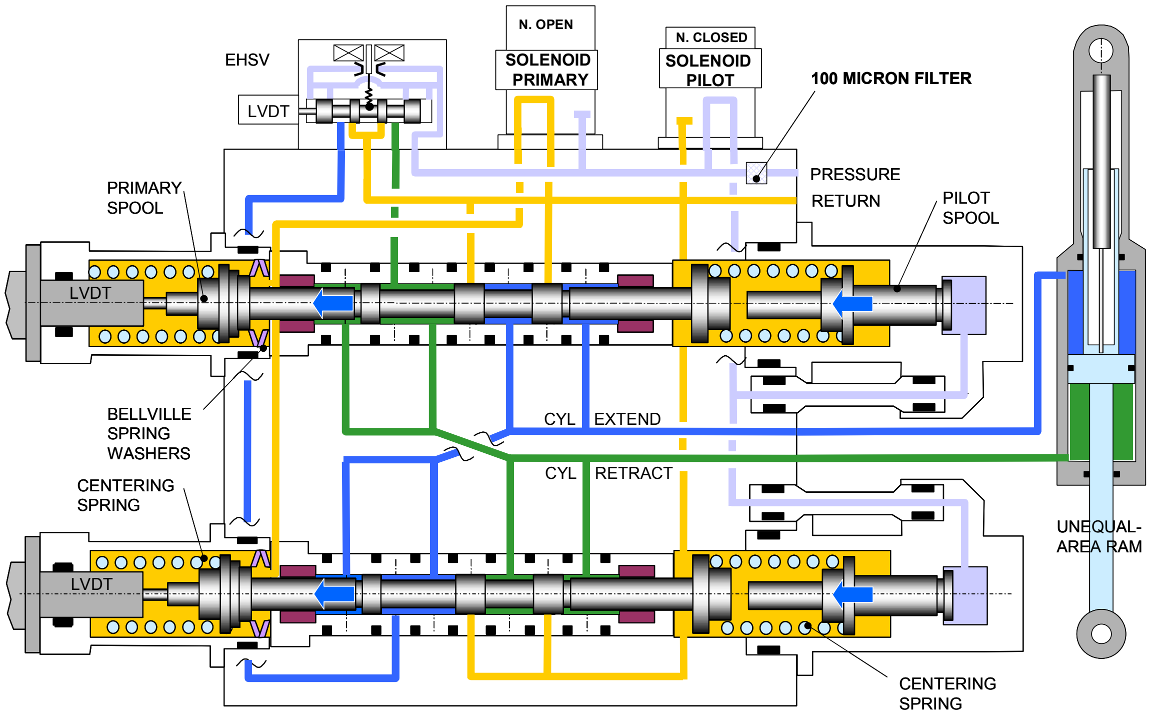

Fig. 6. Engaged EHSV at null (center) position.

Symmetrically, flow from the extend EHSV control port is connected through the lower primary spool left side differential area chamber to the extend side of the actuator cylinder. The lower primary spool left side differential area chamber is also ported to the upper primary spool right side differential area chamber.

Differential area chambers on the left and right sides of the primary spools are created by the difference in diameter between the three center lands and the smaller end lands of the primary spool. The smaller end lands of the primary spool are equal in diameter. Therefore the differential areas on the left and right sides of the primary spool are equal. When the EHSV is at null, pressures at the left and right differential area chambers are equal. Hydraulic forces on the primary spools are therefore balanced and the spool remains at the spring centered position. This primary spool LVDT position is interpreted by the FCC as zero differential pressure between extend and retract sides of the actuator cylinder.

Figure 7 shows the actuator engaged with the solenoid valves energized and with the EHSV responding to an extend computer command. The EHSV directs system flow to the extend side of the cylinder and connects the retract side of the cylinder to return. Pressure generated at the extend side of the cylinder will be proportional to any load-restricting actuator movement. Increasing extend side pressure in the lower primary spool's left side differential area chamber and return pressure in the lower spool's right chamber results in a net force that displaces the spool to the right. Because the spool is centered by fixed-rate identical springs, spool displacement is proportional to the differential pressure between extend and retract sides of the cylinder. Displacement of the primary spool LVDT resulting from increased extend pressure provides an indication to the FCC of the compression load acting on the actuator.

Under increasing extend side pressure, the upper primary spool reacts identical to the lower with the exception of direction of displacement. Because the upper spool's right side differential area chamber is ported to extend pressure and the left chamber is connected to return pressure, the upper spool displaces to the left with increasing differential pressure between the extend and retract. Because when acting as delta pressure sensors the pair of ITFVs operate in opposite directions, the possibility of a common mode failure affecting both sensors accuracy equally is extremely remote.

Except for a reversal of the direction of spool displacement and indicated load resulting from differential pressure between retract and extend, response of the upper and lower primary spools with increasing retract

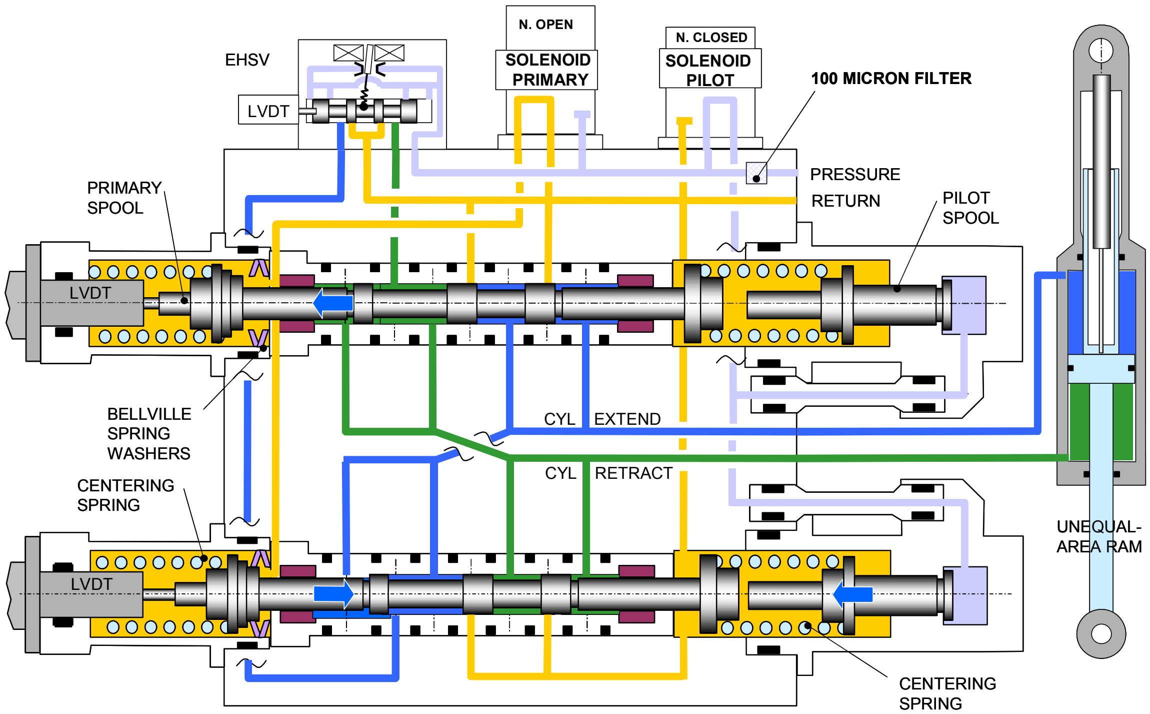

Fig. 7. Engaged EHSV commanded to extend.

side cylinder pressure is the same as described for increasing extend pressure.

In the event of the actuator being subjected to external loads exceeding its acceptable structural limit, the primary spools function as relief valves to vent excessive extend or retract cylinder pressure to return. Figure 8 shows the actuator engaged with the solenoid valves energized and with the EHSV in the null position blocking extend and retract ports from return or system pressure. When the actuator is subjected to excessive external compressive load, pressure generated at the extend side of the cylinder exceeds the relief valve function opening pressure of 27.58 MPa (4,000 psi). At 27.58 MPa (4,000 psi) extend side pressure, the lower primary spool's left side differential area chamber generates a net force that displaces the spool sufficiently to the right to uncover ports and vent excessive pressure to return. The upper primary spool reacts identically to the lower, with the exception of the direction of displacement.

Response of the upper and lower primary spools with 27.58 MPa (4,000 psi) retract side cylinder pressure is the same as described for 27.58 MPa (4,000 psi) extend pressure, except for a reversal of the direction of spool displacement resulting from differential pressure between retract and extend.

Cavitation protection during pressure relief is provided when paired ITFVs are incorporated on unequal-area cylinders. The primary spools, venting excessive cylinder pressure in the same direction as the normal bypass function, connect both cylinder ports to return to prevent cavitation.

Because the same centering springs and hydraulic components that support the delta pressure measurement function are also used to provide relief of excessive pressure, the integrity of the ITFV relief valve function is continuously monitored in flight.

When changing from the engaged to the bypass mode (Figures 6 and 5, respectively), the pilot and ITFV solenoid valves are deenergized. This causes preload in both the ITFVs' centering springs to return their pilot spools to their disengaged stops. Concurrently, the ITFV solenoid valve feeds system pressure (if available) to the left end of both the primary spools. System pressure acting on the primary spool end area generates an 890 N (200 lb) force to move the spool to the right. This force works in combination with preloaded springs to provide primary spool chip shear capability when bypass is commanded.

For the failure mode where one of the primary spools sticks and fails to move into bypass position, the

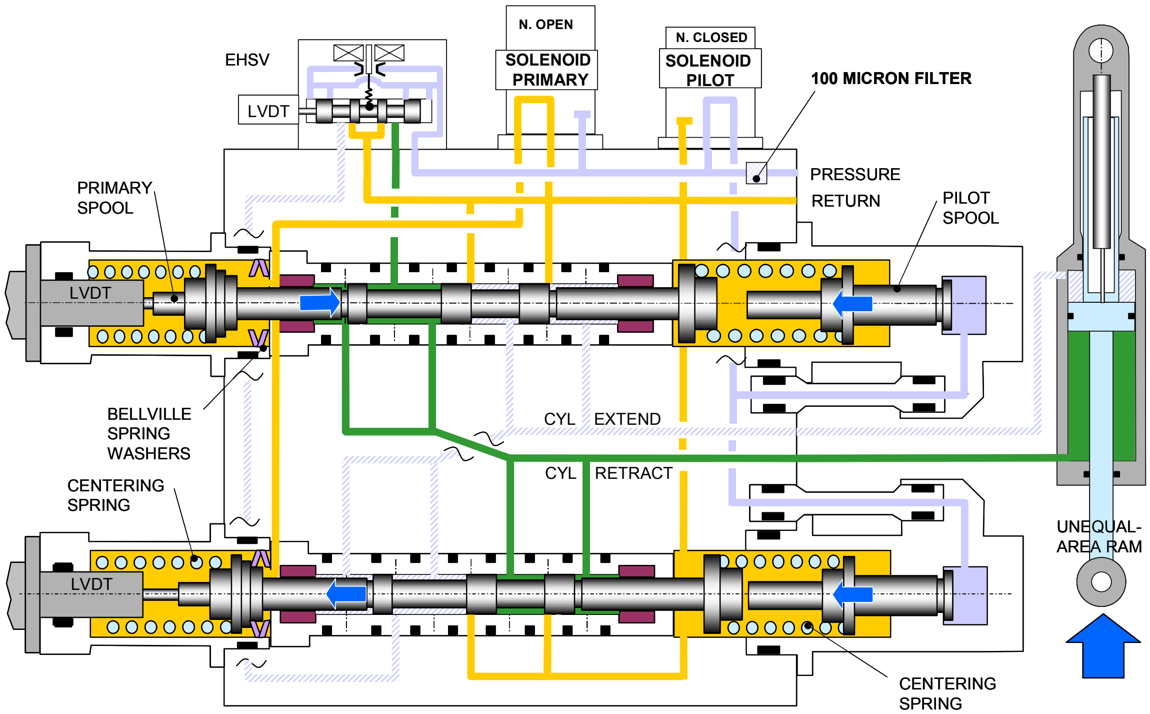

Fig. 8. Actuator in compression pressure relief at 27.58 MPa (4,000 psi).

second ITFV spool provides the conditions for bypass. In the event that the primary solenoid valve fails to port system pressure to the primary spools, the centering springs preload is sufficient to move the primary spools into bypass position. For the failure modes where the pilot solenoid valve fails open or a pilot spool sticks in the engaged position, the 890 N (200 lb) force from system pressure acting on the left side of the primary spools is sufficient to compress the centering springs and move them into the bypass position.

Because the same centering springs and hydraulic components supporting the delta pressure measurement function are also used to provide bypass, the integrity of the ITFV bypass function is continuously monitored in flight, with the exception of the solenoid valves.

Since deenergizing either the primary or the pilot spool solenoid valves will cause both ITFVs to enter bypass mode, failure of one of these solenoid valves could lay dormant. To permit the PFBIT to identify if either the primary or pilot solenoid valves has failed, the ITFV assembly is designed to stop the primary spool just short of the normal bypass position if either solenoid valve has failed. The correspondingly incorrect LVDT output, for the bypass position, provides the FCC with indication of solenoid valve failure.

Implementation of this feature is as follows:

1. In the case where a pilot solenoid valve has failed, the pilot spools will remain in the engaged position. To halt the primary spool just short of the full bypass position, the primary contacts a stop on the pilot spool. System pressure acting on the left of the primary spool is sufficient to compress the springs but not enough to move the pilot spools (Figure 9).

2. In the case where a primary solenoid valve has failed, the pilot spools will move to their disengaged position. To halt the primary spool just short of the full bypass position, Bellville spring washers are employed on the primary spool bypass position stop. The spring rate of the washers is sufficient to halt the primary spool from achieving a normal bypass position unless system pressure is supplied through the primary solenoid valve to the primary spools (Figure 10).

Development

The concept of combining the functions of bypass valve, delta pressure transducer, and PRV raised many practical concerns at Bell and Smiths. The principal concern was that by combining these three

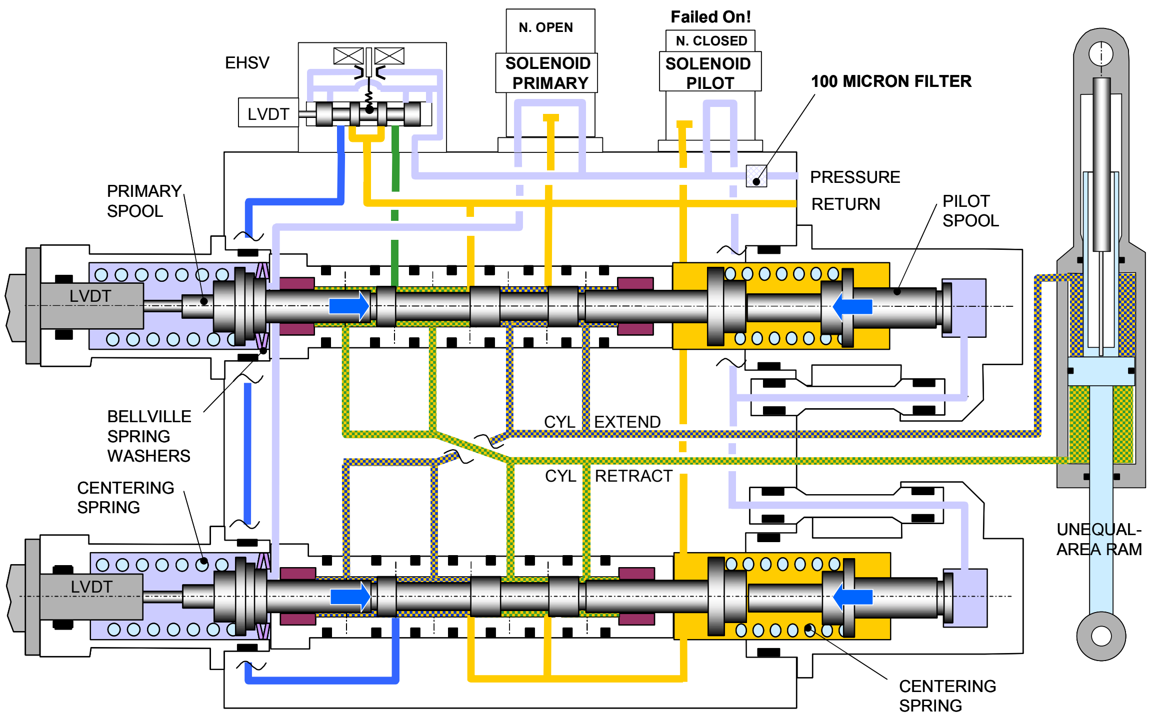

Fig. 9. Pilot solenoid valve "failed on."

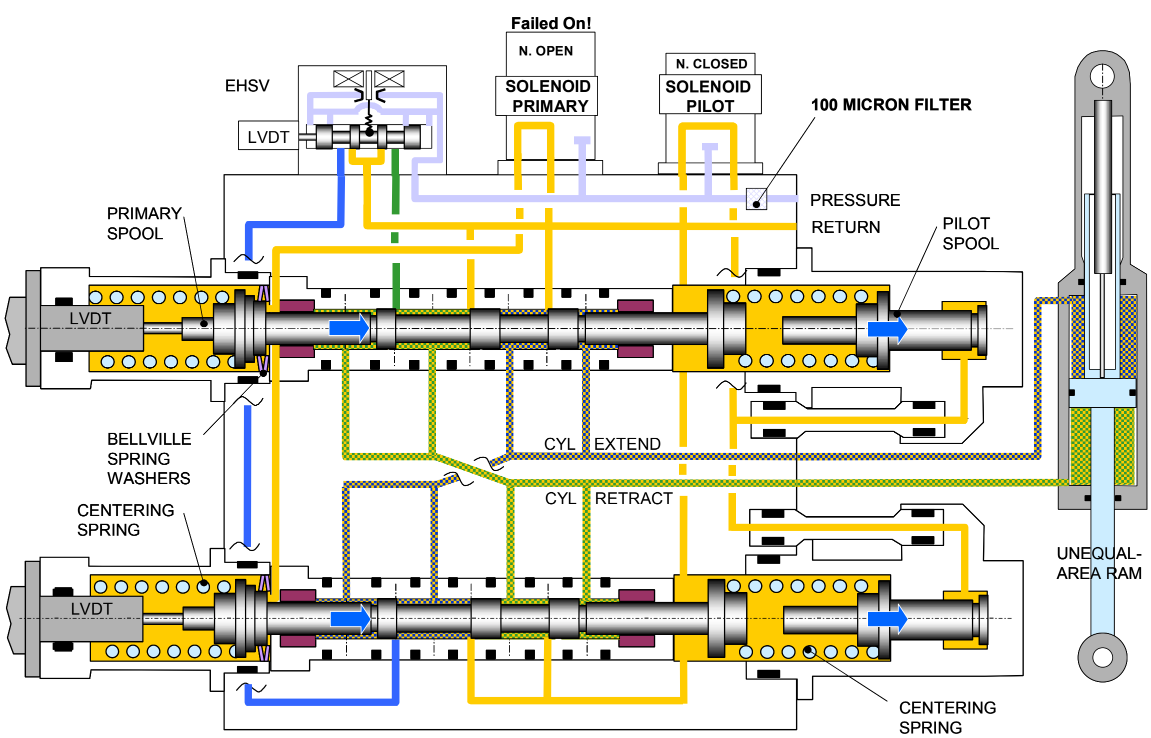

Fig. 10. ITFV solenoid valve "failed on."

separate functions into a single valve assembly, the flexibility to refine components to meet specific performance requirements would be lost.

In order to meet internal leakage requirements valve spool fits with very close tolerance would be required. However, in order to achieve required delta pressure sensor accuracy, a loose spool fit would minimize frictional effects. Both leakage and friction could be reduced by decreasing the ITFV spool diameter. However, the requirement to have a minimum chip shear force of 890 N (200 lb) during bypass engagement required a relatively large spool diameter.

Because this was a novel design for both Bell and Smiths, it was determined that construction of a development article in parallel with computer simulations of predicted performance would be required prior to proceeding with a production design. A photo the of the dual ITFV development test article is shown in Figure 11. The development test article varied in design from the final production configuration, primarily in the configuration of the pilot spool. It was the ITFV spool, however, that was the critical component of interest in the development testing.

Testing on refinements of the ITFV development unit is still proceeding. However, sufficient testing was completed in February of 2002 to confirm the viability of the ITFV concept. Prototype testing also provided valuable empirical leakage and friction values to correct and validate analysis.

The following analysis of bypass valve response time and delta pressure transducer accuracy has been substantiated by development testing.

Effective Time to Achieve Ram Bypass

The severity of failure transient actuator motions is directly related to the speed in which an actuator can be placed into bypass. This issue raised considerable concern over the viability of the ITFV meeting the original actuator bypass requirement of 30 milliseconds. Intuitively, the large size of the ITFV spool should make it slower to respond than the original smaller dedicated bypass valve spool. However, because the ITFV spools are also functioning as a delta pressure sensors and relief valves, force fight loads induced by EHSV or other failures effectively preposition one of the ITFV spools closer to the bypass pass position. In addition, full bypass position is not required to disengage the failed ram. Since the pressure relief ports are uncovered as the ITFV spool moves to the bypass position, any ram force fight is significantly reduced at that valve position. In the final analysis, the speed in which the dual ITFV configuration can achieve effective bypass of a failed ram under force fight conditions is as fast as, if not faster than, the original design. See Table 1.

Fig. 11. Prototype development ITFV.

The following calculated times are given for the shown operating temperatures. They are all inclusive of solenoid valve valve switching time. See Table 2.

Accuracy – Differential Pressure Sensor

Accuracy of differential pressure setting is determined by dimensional variations resulting from a combination of manufacturing tolerances (LVDT sensitivity, spring rate, spool and sleeve diameters) and differential thermal expansion.

Table 1. ITFV component parameters for bypass time.

SOV piston area (nominal	0.62064 cm^2	0.0962 in^2
Spring force at bypass	10.43 kg	23.0 lb
Spring force at null position	27.28 kg	60.16 lb
Maximum spring force – normal operation	41.73 kg	92.0 lb
Spring rate	378.96 N/cm (each)	216.39 lb/in ± 10.0 lb /in (each)
Valve flow – normally closed solenoid valve	14.748 cm^3/s at 20.68 MPa	0.9 in^3/s at 3000 psid
Valve flow – normally open solenoid valve	16.387 cm^3/s at 20.68 MPa	1.0 in^3/s at 3000 psid
Switching time – solenoid valve (both types)	<0.02 s at –6.67°C	<0.02 s at 20°F

Because the ITFV LVDT is also used to indicate the primary spools bypass position, only 60% of the LVDT stroke is used to measure delta pressure. This made it difficult to meet the original sensor absolute accuracy requirement of 2,068 kPa (±300 psi; worst case 4,137 kPa [600 psi] between two sensors).

In the original design, thermal effects influencing delta pressure accuracy were considered as absolute values. However, the purpose of the delta pressure sensors is to balance ram pressures relative to each other. Therefore, it is acceptable to allow greater deviation in the absolute accuracy of the sensors as long as their accuracy relative to each other is maintained. From Bell thermal analysis of the hydraulic systems, it was determined that without failures, the worst case maximum difference between the three return system temperatures should never exceed 10°C (50°F).

Table 2. Calculated time to bypass.

Primary spool position	Time at temperature –6.67°C (+20°F)	48.8°C (+120°F	Required
Null to pressure relief	42.5 ms	42.5 ms	≤43
Null to bypass	55 ms	55 ms	≤55
Hardover to pressure relief	24.5 ms	24.5 ms	≤30
Hardover to bypass	37 ms	37 ms	≤37

Therefore, between actuators, the difference in ITFV delta pressure readings when subjected to fluid temperatures within 10°C (50°F) is not allowed to exceed 4,137 kPa (600 psi) up to 20.68 MPa (±3,000 psi). See Table 3.

This accuracy between lanes falls within the specified requirement of 4,137 kPa (600 psi), even given an adverse buildup of tolerances.

Allowing for sensitivity variations between LVDTs and manufacturing tolerances, ITFV lane-to-lane matching within a manifold should be possible to within 13 % of reading.

Conclusion

The integrated three-function valve as an assembly is less complex and more reliable than separately housed pressure transducers, bypass valves, and pressure relief valves.

When used as a matched pair in a hydraulic actuator, the ITFVs provide redundant bypass valve, pressure relief valve, and delta pressure transducer functionality. This added redundancy is achieved with no additional LVDTs or wiring over conventional arrangements. This redundancy allows a control linkage or aerodynamic surface driven by multiple actuators to continue to operate safely following most common dual failures.

Table 3. Calculated delta pressure sensor accuracy.

		SI units	(Conventional units)
Thermal null shift for ΔT = 10°C (50°F), Xth	=	1.66×10^{-5}cm/°C	(1.178×10^{-5} in/°F)
	=	1.5×10^{-3} cm	(5.89×10^{-4} in)
Using nominal spring rate	=	758.3 N/cm	(432.8 lb/in)
Nominal control area	=	0.07310 cm^2	(0.01133 in^2)
Thermal null shift for 50°F ΔT	=	0.15 MPa	(22.5 psi)
Spool friction (per lane) = 2.2 N max^m (0.5 lb)	=	0.30 MPa (assumed value)	(44.13 psi)
Dimensional tolerance (per lane) error	=	±4.90 % of reading	
	=	1.06 MPa at 21.68 MPa	(147 psi at 3,000 psi)
LVDT error (per lane)	=	±2% half range (27.58 MPa):	[4,000 psi]
	=	0.41 MPa at 21.68 MPa	(60 psi at 3,000 psi)
LVDT error over ΔT range of 10°C (50°F)	=	1% half range pre 10°C	(1% half range per 50°F)
	=	0.21 MPa at 21.68 MPa	(30 psi at 3,000 psi)
Total ΔP sensor error between actuators	**=**	**4.14 MPa at 21.68 MPa**	**(555 psi at ±3,000 psi)**

Currently, the dual ITFV collective actuator is planned for installation into the BA609 Ship 1 for envelope expansion flights that are scheduled in 2003.

At this writing, a Smiths design study is in progress to evaluate the benefits of modifying the BA609 triplex longitudinal actuator to incorporate dual ITFV manifolds. Studies are also planned to investigate the benefits of employing a single ITFV assembly in less critical actuator applications to replace separate bypass valve, PRV, and delta pressure sensors.