N76-31177

REDUNDANCY OF HYDRAULIC FLIGHT CONTROL ACTUATORS

C. C. Chenoweth and D. R. Ryder
Boeing Commercial Airplane Company

SUMMARY

The constraint of requiring airplanes to have inherent aerodynamic stability can be removed by using active control systems. The resulting airplane requires control system reliability approaching that of the basic airframe. Redundant control actuators can be used to achieve the required reliability, but create mechanization and operational problems. Of numerous candidate systems, two different approaches to solving the problems associated with redundant actuators appear the most likely to be used in advanced airplane control systems.

INTRODUCTION

Future civil aircraft will have to take advantage of all possible gains in aerodynamic efficiency and weight reduction to be economically viable. It has been shown in previous studies by Boeing and others that gains in aerodynamic efficiency and reduction in airplane weight can be achieved by placing the center of gravity aft of the longitudinal maneuver point. The resulting unstable airplane must be augmented through the flight control system to provide acceptable handling qualities. If the stability of the airplane is critical, such that loss of the augmentation would result in loss of the airplane, the control system reliability must approach that of the basic airframe. To meet this level of reliability, special consideration must be given to the control system design. Such considerations include design simplification, derating of components, elimination of electrical connectors, and physical isolation of electrical wiring and hydraulic power. Even then redundancy is usually required to obtain satisfactory reliability from the complex hydraulic actuators and electronic control systems used in airplane flight controls.

Use of redundancy to achieve reliability has always been an accepted engineering design technique. However, the advantages of redundancy are not easily realized in control systems because of signal channel interaction, failure effects, performance degradation after failures, null shift with channel switching and failure detection problems. If force voted multiple hydraulic actuators are used to drive a single load, actuator load sharing also becomes a concern. Methods of insuring proper load sharing can reduce load reaction stiffness, cause poor resolution, and may lead to dynamic instability if not properly designed and built. Monitoring used to effect the orderly shutdown of failed elements may cause inadvertent shutdown of good elements. All of these problem areas with respect to redundant control systems and actuators require careful consideration in control system design and mechanization.

REDUNDANCY REQUIREMENTS

Redundancy requirements for flight control actuation systems can be divided into two areas, the requirement for flutter free control surfaces and the maintenance of critical control surface operation.

The need to minimize airplane weight reduces the permissible use of control surface mass balance as a means of preventing control surface flutter. If mass balance is not used, the surface must be restrained by the surface control system. The Federal Aviation Regulations, Volume III, Part 25, paragraph 25.629, "Flutter, deformation, and fail-safe criteria," requires that an airplane be free from flutter after any single failure in the flight control system, plus any other "reasonably probable" single failure or malfunction affecting flutter. Hydraulic system failures are classified as "reasonably probable" by the FAA. Therefore, when airplane design dictates that control surfaces be restrained by the surface power actuators to avoid the mass balance weight penalty, these requirements dictate a need for at least two surface power actuators and three hydraulic systems for each surface.

Independent of considerations for suppression of surface flutter, surface power actuator redundancy is also influenced by the need to maintain control of the airplane flight path. The Federal Aviation Regulations, Volume III, Part 25, paragraph 25.671, requires, in part, that the airplane must be capable of safe flight and landing after any single failure, excluding jamming, in combination with any probable hydraulic or electrical system failure.

One form of redundancy to assure continuance of control function would be to use multiple aerodynamic surface segments, independently controlled, in each airplane axis. If actuator redundancy were not required for prevention of flutter, each surface could be controlled by a single actuator. Degraded, but safe, operation would be possible if one or more surface segments became inoperable. This feature is used in some current airplanes. However, if the airplane design is such that a limited number of flight control surfaces are available or if all control surfaces in an axis are needed for flight path control, each surface must remain controllable after certain dual control system failures.

Advanced supersonic airplanes will probably be limited in use of control surface redundancy, particularly in the longitudinal axis, because of the need to attain maximum aerodynamic efficiency. The need for minimum weight in an advanced supersonic transport airplane will also limit the consideration of mass balance for flutter prevention. These two factors are sufficient to set the minimum redundancy level for surface power actuators and show the need for redundancy in flight control actuation systems.

ACTUATOR REDUNDANCY MECHANIZATION

There are two distinct categories of mechanization applied to redundant actuator channels used in aircraft control systems. One type is the parallel active configuration, and the other type is the active/standby configuration. The principle differences between the two types are as follows:

a. Since the parallel active technique implies that the control channels are working together at some point in the control system, the failure of one of the control channels can cause an output performance change. For an active/standby system, the control elements operate independently and failures of the active control element causes transfer to a correctly operating standby channel with no performance degradation.

b. With a parallel active system all of the control channels are working at the same time and the failure of one channel is compensated for by the remaining correctly operating channels (to varying degrees). It is not necessary to rapidly switch the failed channel off. With an active/standby mechanization, rapid transfer between control elements is essential (with the actual required transfer time being determined by the particular application).

There are three options available in mechanization of parallel active systems. The control channels can be brought together and the actuator outputs summed in the following ways:

a. Force voting
b. Velocity summing
c. Position summing

Force voting is the most common technique used in mechanizing parallel active systems. By force voting several actuators on a common output, an output representing the mid value of all input commands can be achieved. Many examples of this type of system exist. The Boeing 747 pitch and roll autopilot actuators (autoland option), and the GE 680J F-4 roll and yaw secondary actuators are typical. One problem with this type of system that does not exist with other types is the force fight that can occur between actuator channels when channels differ in input command or actuator characteristics.

Velocity summing is an alternate parallel active mechanization which does not incur the force fight problems of the force voted systems. Probably the best example of this method is the electromechanical secondary actuator developed by LTV for the 680J F-4 pitch axis. This mechanization uses servo motors summed through differential gear boxes. Net output velocity is the sum of the individual motor velocities and the force output is the sum of the individual force outputs of the servo motors.

Position summing systems have no actuator force fight. However, since the individual actuators are summed by differential linkage, a channel failure or actuator shutdown will reduce total output stroke capability. Each individual actuator must have a larger stroke than the minimum allowable output stroke to accommodate channel failures. This characteristic restricts the application of the position summing technique to systems that require only small output displacement. It has been used in dual systems for series actuation. Examples are the Boeing 737 dual yaw damper and the dual channel series actuators on the Grumman F-14. Mechanization becomes difficult when more than two actuators are summed because of linkage complexity.

ACTUATOR REDUNDANCY IMPLEMENTATION FACTORS

There are several factors that must be considered when redundant actuators are used. The most significant are those that affect normal operation, operation after failures, and cause interface problems. These are outlined below.

Failure Insensitivity

Failure insensitivity is the ability of a redundant control system to experience failures and automatically continue operation with an acceptable transient. If the system performs a critical function, operation must be maintained in the presence of one or more failures; i.e., be fail operational. However, a fail operational system does not insure minimum control system transients. The criticality of transients has an impact on the detail design of the system. All four methods of redundancy mechanization can be fail operational. However, the number of channels required and failure characterisitcs vary as discussed below:

a. Fail-operational capability can be achieved in parallel active systems by majority voting or averaging three or more active actuators. With three active channels operation continues after the first failure. With four channels operation continues after two failures. In voting systems the first failed channel must be disconnected before the second channel fails for the system to remain operational. In the force voted systems the failed channel is automatically overpowered by the remaining channels and the magnitude of the failure transient can be insignificant. Displacement and velocity summing provide an averaged output but have inherent failure transients and steady state null offset after failure. The magnitude of the transients is dependent upon the system closed loop response.

b. With active/standby systems a failure detection device must assess that the active channel has failed, automatically disconnect it, and switch to a good channel. The failure transient is dependent upon the failure detection level, the switching time and the tracking of the standby channel.

Failure Detection

Detection and indication of failures during operation must be provided so that failed channels or actuators can be disengaged to preserve the integrity of the system. The failure detection system must be designed to detect all types of failures; hardover, passive, and oscillatory and slowovers or ramps which could produce an unsafe situation.

The ability of the failure detection system to sort out legitimate failures from apparent failures which might occur due to adverse tolerances has an equivalence in reliability. If the failure detection system trips a channel off inadvertently due to an apparent failure, the equivalent mean-time-between-failure (MTBF) for the system may be significantly affected.

Failures in parallel active systems may be sensed by in-line monitoring of actuator characteristics or by cross channel monitoring between active actuators. A method of reducing the number of redundant actuators is to add a model of a working channel and use it for cross channel monitoring. While this extends the system fail operational capability with one less working channel, its effectiveness depends on how well the model matches the actual hardware. In certain applications, where actuators are large and where weight is critical, the model approach may provide a way to minimize the overall weight.

In active/standby systems each channel must be individually monitored for failure detection. Each control channel is usually duplicated or modeled to provide the comparison required to detect failure of the active channel.

Load Sharing

Load sharing is a measure of the ability of multiple actuators with identical inputs to work together in positioning a common output. Load sharing is a problem peculiar to force voted actuators since, obviously, there is no force fighting in an active/standby system when only one system controls at a time, or in position summed and rate summed systems where forces of individual actuators are additive.

Ideally, it is desirable that the load be divided equally among redundant actuators to eliminate any force fighting. However, tracking errors arise due to tolerance buildup in each actuator servo loop and actuator installation that tend to make each actuator seek a unique position even though the input commands are identical. With the actuators tied to a common output all position commands cannot be satisfied and force fight occurs between actuators.

To minimize the force fighting in force voted actuator configurations and assure acceptable sharing of the load, four methods are commonly used:

a. Accurate tolerance control of the feedback loop of the actuator. A mechanical actuator can be mechanized with good tolerance control because of the manufacturing accuracies that are possible and the unchanging nature of the mechanical linkages.

An electrically controlled actuator has command path elements such as summing amplifiers, demodulators, and feedback transducers which can change characteristics with time, temperature, and power. It is generally accepted that the tolerances associated with an electronically controlled actuator are significantly greater than for a mechanically controlled actuator.

b. Compliance between channels. In some applications the structural compliance between actuators allows sufficient individual actuator position difference to reduce force fight through the normal position feedback loop.

c. Low force gain actuators. Low pressure gain servovalves can be used to reduce the force fight resulting from expected valve command differences to an acceptable level. In some applications a feedback path consisting of deflections of the actuators' reaction structure has been sufficient to provide the actuator force gain reduction, and reduced force fight. Another way to reduce actuator force gain is to use actuator pressure as a feedback command. However, there is a limit to the amount of compliance that can be tolerated without reducing the overall actuator stiffness below the minimum allowable level. Reducing actuator force gain (stiffness) has been used successfully where the inputs are reasonably matched, such as a set of surface power actuators signalled by a common mechanical command, or in secondary actuators where the output load is small.

d. Equalization to average load. For cases where the actuators are required to operate into large aerodynamic loads and have uncontrolled input mismatch, any pressure feedback system requires modification to be useful. The individual actuator load must be compared to the average load. Computation of the average load and the individual difference from average requires cross channel comparison. This method does not degrade actuator stiffness but adds complexity and introduces the possibility of cross channel failures.

Input Mismatch

Differences in commands (input mismatch) due to tolerances in an electrical control system, from sensor to actuator, can be quite high, as much as a quarter of full scale command, unless some design precautions are taken to prevent such buildup. It should be noted that differences in commands generated by actuator loop tolerances are an order of magnitude less than those generated by computational elements in the upstream portions of the system. The various methods of redundant actuator mechanization deal with the input mismatch problem as itemized below.

a. Force Voting Systems. In force voted systems the output is the mid value of all input commands. The force fight that occurs due to input command mismatch can be reduced by the same methods used to insure load sharing. In some applications the only possible means of controlling command differences may be the use of electronic signal conditioning to reduce the input mismatch.

b. Velocity Summing Systems. Velocity summed actuators allow the individual channels to cancel command differences by differentially summing rates.

c. Position Summing Systems. Position summed actuators give a single output which is the average of the input commands.

d. Active/Standby Systems. Usually the active actuator is commanded by a single electronic channel and mismatch is of no concern during operation. Mismatches between the commands of the active and the standby channel are of concern, however, and must be minimized to avoid large surface transients upon switching from active to standby actuators.

SECONDARY ACTUATORS

Surface actuator input signals can be either electrical or mechanical. A dual load path mechanical signal to three power actuators can satisfy all reliability requirements. However, the control signals for critical stability augmentation or fly-by-wire systems will be electrical.

The power associated with the electronic signals for fly-by-wire command, autopilot, and stability augmentation systems must be kept at low levels as a matter of good design. These low level signals are required to command surface actuators that operate at high power levels. To transform the electrical commands to surface displacements controlled by large hydraulic power actuators requires several stages of amplification. Review of current redundant flight control actuation systems shows an almost universal use of small electrically signaled hydraulic actuators as one of the stages of amplification. These small actuators are termed secondary actuators.

It is advantageous to treat the command path and computation and power actuation errors independently by inserting a synchronizing stage between the two functions. The synchronizing stage provides a single valued command and may be an electronic voter or a mechanical output of a secondary actuator arrangement. Some of the advantages of synchronizing are:

a. When surface power actuators are isolated from the upstream command differences, the task of providing adequate power actuator load sharing becomes easier, permitting a simpler and more reliable mechanization.

b. When secondary actuators are used to provide the synchronizing stage they do not eliminate the problems of redundant actuators but the magnitude of the problems are less severe because the secondary actuators operate at significantly lower force levels than the surface power actuators.

SYSTEM SELECTION

Four types of actuator redundancy have been discussed. It has also been shown that prevailing control system designs use secondary actuators as a stage of signal amplification and as a means of command path synchronization. Surface power actuators are usually force voted mechanical input actuators. The system differences are in the redundancy mechanization of the secondary actuators. Active/standby and force voted systems predominate by a large margin with force voted systems the most common.

Although the use of velocity summing solves the problem of force fight there are disadvantages which make this type of system a questionable candidate for future use in critical flight control applications on civil aircraft. The complex gearing could make it difficult to prove that jam-type failures would be extremely remote, as required by FAA regulations. Also, for the same output force the electromechanical actuator is larger and heavier than an equivalent electrohydraulic actuator. One advantage would be the availability of four independent actuator signals in an airplane with only three hydraulic signals. Another advantage for military aircraft is the reduced vulnerability to loss of hydraulic systems.

Position summed systems are difficult to mechanize for more than two redundant channels because of the complex linkage required. In addition the loss of rate and travel capability after failure and the inherent output position transient that occurs with failure are also disadvantages.

The active/standby and the force voted systems have advantages and disadvantages that must be considered in conjunction with the specific airplane and control system application. The most significant differences between the two types of systems are:

Normal Performance

The single channel operation of the active/standby system can give optimum performance. In the force voted system residual actuator force fight can affect output resolution and reduce actuator stiffness.

Failure Transients

Force voted systems can be mechanized to give very small failure transients. The active/standby system must trade failure detection levels and nuisance trips against the allowable failure transient.

Performance After Failure

The active standby systems preserve normal performance in the failure sequence from the active channel to the standby channel and on to the second standby channel. The force voted system may suffer a performance degradation as it fails down. This degradation can be exhibited as reduced resolution capability and force output.

Failure Detection

The active/standby concept requires immediate failure detection to be safe following failures. The force voted concept does not require immediate detection of a failure to be safe. Failure detection is only required to enable a failed channel to be shut down before another failure occurs.

Switching

Each standby channel must be continually monitored to assure that it is capable of control if the active channel fails. Further, somewhere in the system a device like a switch or blocking valve is required to operate without prior knowledge of its condition to provide a successful transfer to a standby channel. Force voted systems are comprised of only active channels continually monitoring each other and require no immediate switching to be safe.

CONCLUDING REMARKS

Advanced technology airplanes will require redundant flight control actuators to achieve reliability because operational stability augmentation system will be essential for safe flight and acceptable airplane handling qualities.

Surface restraint to meet the fail safe requirements for flutter prevention and minimum safe controllability requirements will dictate the minimum redundancy levels for control surface power actuators. Airplanes with redundant flight control surfaces may have dual surface power actuators if a third hydraulic system is provided. Control surfaces that are critical for control functions will require at least three actuators per surface in order to meet FAA requirements and provide an adequate level of safety.

Reliability requirements for control systems that amplify autopilot, stability augmentation, and pilot commands and provide inputs to the control surface power actuators are determined by the need to remain operational in spite of control channel malfunctions. Actuation systems with fault corrective capability that will meet the system reliability requirements and satisfy FAA regulations require at least four active channels or three monitored channels. Surface power actuators could be mechanized with this level of redundancy but it has been found to be more efficient to utilize small secondary actuators to provide a reliable single valued mechanical input to three surface power actuators of reduced complexity.

Based on a review and examination of current redundant actuation systems, two concepts were found to be representative of secondary actuator mechanization which meet advanced civil airplane flight control system requirements. The two actuator configurations are a four channel force voted system and a three channel active/standby system. Both of these systems should be considered since they reflect different design philosophies.

Redundant control systems have operating and failure characteristics that are affected by overall control system and airplane design. Redundant actuators should be studied in conjunction with pilot and airplane to understand pilot reaction and airplane response to variations in control system characteristics and failures.

Acknowledgment is given to NASA-ARC who are presently funding investigations in the area of redundant control systems and control system-airplane-pilot interaction. The material in this paper is drawn in part from studies accomplished under NASA Contract NAS2-7653 and reported on in reference 1.

REFERENCES

1. NASA Report, NASA CR-114730, D. R. Ryder, "Redundant Actuator Development Study," December 1973

2. Federal Aviation Regulations, Volume III, Part 25 with Amendments through 25-34 dated 31 December 1972

3. W. T. Kehrer, "The Performance Benefits Derived for the Supersonic Transport Through a New Approach to Stability Augmentation," AIAA paper No. 71-785, presented at Third Aircraft Design and Operations Meeting, July 12-14, 1971

4. USAF Report AFFDL-TR-71-20, D. S. Hooker, R. L. Kisstinger, et al, "Survivable Flight Control System Interim Report Number 1, Studies Analysis and Approach," May 1971

5. SAE A-6 Committee Paper, D. A. Wiggins, Hydraulic Research and Manufacturing Company, "Redundant Actuators for the NASA Digital Fly-by-Wire Aircraft," presented at Miami Beach, Florida, April 1972