Flight Control Systems for VTOL Transport Aircraft

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E-A A member of the Elliott-Automation Group

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/er the past few decades transport aeroplanes, military and civil, have been developed to ate with a very high degree of safety; in fact, probability of a fatal accident occurring is ıally less than one in a million per flight if /isiblity is good during the take-off, approach, landing stages.

is clear that the introduction of a new techni- such as VTOL to transport aircraft must not nade at the expense of an increased accident and the implementation of the new techniques : be to calculated high standards. This is equally of military as well as civil aeroplanes as the ıer may spend most, if not all, of its life operat- under peacetime conditions.

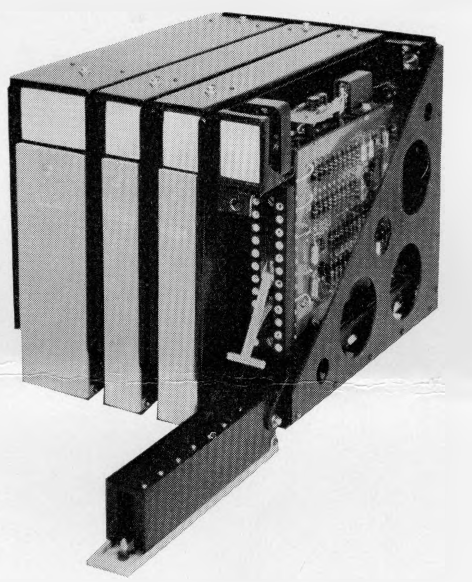
ıtt Brothers (London) Ltd. has investigated y of the problems involved in the control of i-engined V/STOL transport aircraft, parti- ry in the hover and transition modes. As a ; for one of these studies, the configuration of aircraft was assumed to be that of a medium ;e transport powered by two inboard vectored st engines such as the BS.53 or RB.168, and ımber of RB.162 lift engines in pods in each ; to give the additional lift required for vertical -off, landing and hover. It was also assumed the aircraft would have sufficient thrust, ıbly disposed, to survive any single engine ıre occurring in both the normal flight and ːr conditions.

'ith an arrangement of vectored thrust and ded lift engines an engine failure in the VTOL lition may cause a roll acceleration which is cult, if not impossible, for a pilot to compen- , and under normal operating conditions some ımatic assistance must certainly be given to the : to counteract such failures. As a minimum, such ;tance should ensure that the pilot's actions ıld not be required to be more precise, or more d or more complex, than comparable actions urrent transport aircraft. The automatic devices l must at least be fail safe and perhaps, for ain purposes, they may have a failure survival ıbility, but the latter should not be allowed to ıinate the aircraft system to the extent that two nore failures cause a catastrophe. In fact, the ·all automatic system should be so designed and grated into the aircraft that many reversionary ;ibilities are open, even to the limit of complete .ual control in an emergency in the VTOL mode. ; concept, that failures should cause only a 'ormance deterioration, and perhaps a reversion ı simpler mode of operation, has always been ɔrmal requirement in aircraft design. It applies ally well to automatic control devices although ıs rarely been employed in this context.

ı considering various concepts for automatic trol systems, Elliott has explored numerous gns aimed at meeting all the requirements with simple control system in each aircraft axis, ıparable to current aircraft installations. These mpts have not been successful. There are ample ;ons for this. A VTOL transport aeroplane of lift engine configuration requires additional fail control features for the VTOL modes, which not used in normal transport aircraft, such as ɔmatic engine failure compensation, and prob- ' automatic compensation of control character- ;s from "acceleration demand" to "rate demand." ; inevitable, therefore, that the systems will be ·e complicated but it is considered that if ade- te attention is given to the automatic system ıirements during the aircraft design stages an itable system design can be achieved.

It is clear from simulator studies that any automatic system employed for engine failure compensation in the hover must operate with a very high gain in terms of thrust change demanded against instantaneous thrust lost. This demands very high integrity thrust detection which can only be achieved by using pressure sensors operating from the engines themselves. The closest equivalent means of failure detection would be obtained with angular acceleration feedback, but this suffers from the severe disadvantage that high control loop gains cannot be achieved without meeting airframe flexibility difficulties, and therefore the possibility of using accelerometers only has been rejected.

In a Force & Moment Control System (proposed by Elliott), a direct measurement is made of the thrust of each nozzle being used for lift or control and these are resolved into their components in a suitable system of axes and these components are combined to give the forces and moments acting on the aircraft. These can be compared with the demanded forces and moments and the error signals may be used to control the aircraft via conventional servo actuators.



The Elliott force and moment computer. Both the autostabiliser and force and moment computer are modular units, rack mounted, and have the same dimensions (10″ × 8″ × 7½″). A particular feature is the electroluminescent panel at the top of each unit. The face of the panel is divided into a matrix of small squares, all of which are illuminated when the unit is fully serviceable. Faults which do not significantly affect performance are indicated by the extinction of one or more squares so that the remaining "life" of the unit can be estimated at a glance.

The problem of automatic engine failure compensation revolves around the task of designing a system which is adequately safe so that, due to its own failure, it cannot produce more than a small fraction of the effect of an engine failure, i. e. the performance and authority of the automatic system must be sufficient to offset engine failures and yet must not be open to dangerous application. It is considered that such a system should be as independent as is possible of other aircraft automatic controls such as the autostabilisation system and the autopilot system, but in the interests of economy on initial cost and weight, if safety criteria can be met, some integration is desirable.

In conjunction with the force and moment control system it is proposed to instal engine pneumatic group thrust compensators in each wing. A group thrust compensator (GTC) is a combined detector/actuator which is fed from appropriate pressure tappings on each engine of the group it serves, and its action is automatically to adjust the RB.162 group throttle demands only, in order to keep constant the total achieved thrust of the podded RB.162's and the BS.53's, in the event of any single engine failure.

The object of GTC is not to maintain the perfect balance of thrusts and moments required for the hover, but rather to provide a simple coarse control which continuously decreases the trimming effort required by the pilot. In particular it significantly reduces the rolling moment due to an engine failure so that the time available to the pilot for manual correction is adequate. The aim in the design of such a system is that the pilot's correcting actions following an engine failure should not be required to be more rapid or more difficult than those involved in correcting an engine failure during takeoff on a conventional multi-engined aircraft.

The group thrust compensator is specified as a pneumatic device for simplicity and for reliability which is dependent only upon the presence of engine thrust, and not upon ancillary electrical or hydraulic supplies.

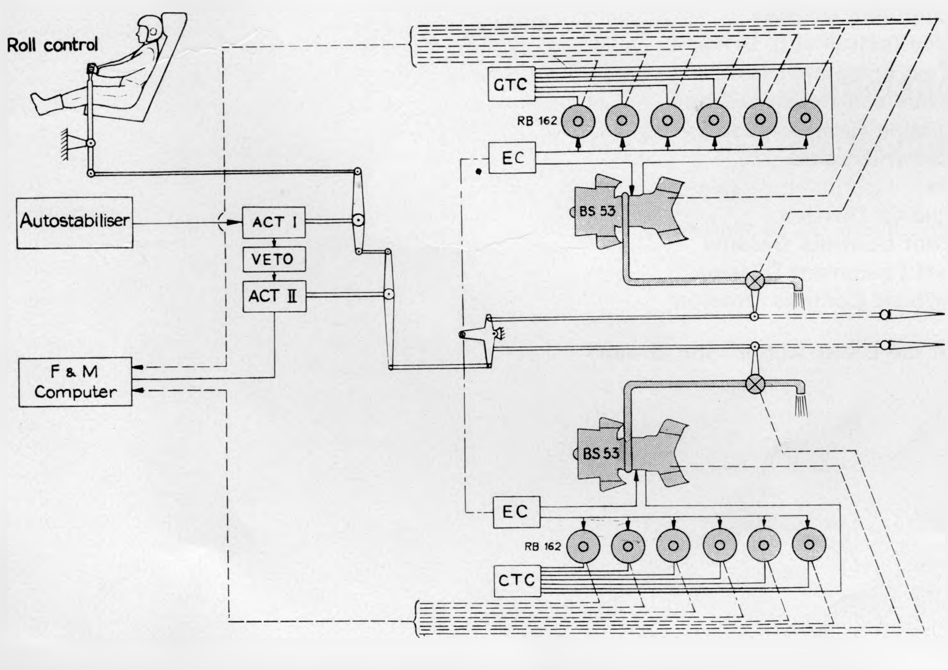
Examination of a number of flight control system layouts has led to the conclusion that the most effective scheme is a system offering full authority force and moment control with autostabiliser veto. This is effected by using the limited authority autostabiliser as a "gating" or comparison control (or in the case of a failure of the force and moment computer as a veto) on the operation of the force and moment control system. In practical operation, the autostabiliser in this system positions its associated actuator in accordance with aircraft angular rate, and is used to apply a physical restraint to movement of the force and moment control actuator, via its hydraulic connections, if the latter attempts to move in the opposite sense to the autostabiliser actuator. This condition can normally arise only from a failure of one or other of the two systems. The addition of group thrust compensation would render an aircraft with this type of system capable of meeting very high safety requirements comparable with those for civil transport operations. Such a system combining full authority force and moment control, autostabiliser veto, and group thrust compensators, would enable an aircraft to be employed in the VTOL mode following any single failure in the GTCs or force and moment control system, and probably following a failure in the autostabilisation system.

The operation of the flight system is best described by considering the arrangement of the major elements. The manual controls for the pitch axis comprise a control column coupled to an artificial feel unit which operates each of two elevator surfaces via tandem hydraulic power controls. A gearbox coupling unit, which may or may not be variable, connects the elevator control runs to the nozzle controls of the two rear downward facing jets. The heart of the autocontrol system is the multiple electrohydraulic actuator which is placed in the control runs near to the surfaces and rear nozzles. The actuator assembly comprises three separate actuators and their associated pickoffs, together with connecting linkage. The autopilot actuator may be clutched via a spring box to operate the main control runs in parallel. The autostabiliser actuator

Stabilisation System Performance Comparison

System	Effect of failure	Approximate probability of dangerous situation in 2 minute hover	Remarks
1. 3-Axis Autostabiliser: Single Channel Limited Authority	Pilot takeover of stabilisation in one axis	9×10^{-10}	Effective Mean Time Between Failures and Failure Probability in 2 min: Autostabiliser, 10,000 hr. 3×10^{-6} GTC, 10,000 hr. 3×10^{-6} Engine, 5,000 hr. 6×10^{-6} F & M Control, 10,000 hr. 3×10^{-6}
Group Thrust Compensators on RB-162 Pods	Passive failure: significant only if combined with engine failure	5×10^{-10}	
	Engine failure: mainly compensated by Group Thrust Compensators but requires pilot takeover. Pilot workload high.	8×10^{-7} Total: 8×10^{-7}	Failure Probability for Pilot takeover: 10^{-2} to 10^{-4}, depending on circumstances. All failure probabilities derived from mean times between failures must be multiplied by 60 to cover scheduled vertical landing after 2 hr. flight. Using generous assumptions, not satisfactory by civil safety standards. High pilot workload, no margin for initial unserviceability.
2. 3-Axis Autostabiliser: Single Channel, Limited Authority	As for System 1	9×10^{-10}	Both Group Thrust Compensators and Force and Moment Control are essential to this result. No margin for initial unserviceability.
Group Thrust Compensators on RB-162 Pods	As for System 1	5×10^{-10}	
* Force & Moment Control: Limited Authority	Similar to Autostabiliser failure, but may affect all axes.	3×10^{-9}	
	Engine failure: Completely compensated by Group Thrust Compensators and Force and Moment Control combined.	Less than above Total: 4.4×10^{-9}	
3. 3-Axis Autostabiliser: Single Channel Limited Authority	As for System 1, plus loss of Force and Moment Control or reversion to limited authority (in one axis)	9×10^{-10}	Installation only slightly different from System 2 but significant improvement in reversionary facilities permits scheduled vertical landing to civil safety standards. *But* see note below.
Group Thrust Compensators on RB-162 Pods	Passive failure: required only as reversionary facility for Force and Moment Control	Negligible	
Force and Moment Control: * Full Authority * Vetoed by Autostabiliser	As for System 2	3×10^{-9}	
	Engine failure: Completely compensated. Loss of Group Thrust Compensators is immaterial. Loss of Autostabiliser or Force and Moment Control gives reversion to System 1 or 2	Negligible Total: 3.9×10^{-9}	
		Probability of system failure in a 2 hour flight	
4. 3-Axis Autostabiliser: * Duplicated, Limited Authority	No pilot takeover necessary. Failure disturbance eliminated	10^{-7}	Further developments give advantages of System 3 without reversion and permit takeoff with partly unserviceable systems. *Note:* To permit scheduled vertical landing, two engine failures must not be catastrophic.
Group Thrust Compensators on RB-162 Pods	As for System 3. Could be eliminated.	—	
Force and Moment Control: * Duplicated Full Authority Vetoed by Autostabiliser	As for autostabiliser.	3.2×10^{-8}	
	Engine failure: completely compensated. Any system failure gives reversion to System 3 or better.	1.3×10^{-7} (Two BS-53 failures: RB-162 not running during flight)	

*) denotes item or feature additional to the previous system.



operates in series and is locked central whe
use; it has limited authority and may be a
unit if a duplicated autostabiliser is requi
force and moment control actuator is also
actuator with a centring lock, but has full a
it is vetoed by a selective shut off valve in
sure lines which is operated mechanically
autostabiliser actuator.

The arrangement of the various elemen
roll control system is similar in principle
of the pitch control except that two roll
assemblies are required. Additional aircraf
features that have been included are a pair
tip nozzles taking H. P. air from the BS
fast response requirements, and a water
injection arrangement to satisfy short-te
lift requirements. The latter is automatic
vided when large aileron angles are dema
is expected that these additional control
will be part of the basic aircraft contro
outside the automatic control loops.

The force and moment computer receives
inputs from thrust sensors on both tail no
all engine nozzles (RB-162's and BS-53's)
modified according to particular nozzle an
will demand differential thrust to compe
mediately for any engine failures. The gro
compensators will also provide partial com
for an engine failure.

An engine vertical control system is also
in the proposed design. This consists of
which can be coupled, one to the two BS
the other to the collective input to the sets c
RB-162's. The purpose of this automati
system is to provide the force and mom
puter with a means of adjusting the to
of the engine complex to compensate for
failure, and also to provide a means for
rate of descent stabilisation. It is prob
major short-term thrust stabilisation will b
via the high response RB-162's but both
accept inputs from the force and mom
puters.

The table on this page details four syste
have been examined by Elliott. These are
native but a graduated range of different
System 1 gives only coarse compensatio
engine failure and is consequently a "pilo
device only. Failure of a GTC would prol
vent safe operation in the VTOL mode.
is almost certainly capable of full autom
pensation of an engine failure, but a sing
in a GTC or the force and moment co
negate this capability although the latt
merely indicate a reversion to System 1.
can be employed in the VTOL mode foll
single failure in the GTC's or force anc
control system, or probably following a
the autostabilisation system. The last and
solution, System 4, is merely System 3
autostabiliser and force and moment con
cated. This can be regarded as the ulti
permits operation at a safety level no w
that of System 3 if it is neccessary to tak
a system partly inoperative, for instance o
flight. The ultimate limitation on Syster
by the probability of a double engine fail
no further development would be justifiec
problem is met.

*This simplified diagram illustrates the basic elements of the
system. Thrust sensors on the RB.162s and the BS.53s fe
force and moment computer, pressure tappings on the engin
the group thrust compensator. In the event of engine failure
designed to reduce the effects to a manageable level while t
moment control will demand differential thrust to compen
failure. In operation, the pilot or autostabiliser demands are
the force and moment computer from a pick-off near the ser
The autostabiliser positions its associated actuator in acco
aircraft angular rate and acts as a veto on the force and n
puter if the latter attempts to move in the opposite sense.
authority autostabiliser can be regarded as the fine cont
force and moment control to provide engine failure comp*

E-A Flight Automation Limited

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