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THE INFLUENCE OF SENSOR AND ACTUATOR CHARACTERISTICS ON OVERALL HELICOPTER AFCS DESIGN

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SUMMARY

The overall performance of a flight control system is dependent on the characteristics of:

i) sensors — type and performance

ii) control law computing and logic

iii) actuation — performance, configuration redundancy and authority.

The specifications in each of these areas must be considered in producing an integrated AFCS design which is compatible with the basic aircraft characteristics. The choice of sensors and the configuration and performance of the actuation are important decisions involving a high level of interdependence with the control law and system logic design.

1. INTRODUCTION

Historically the function of the AFCS was to ease pilot work load but it was not an essential flight requirement. The modern AFCS however forms an integral part of the overall aircraft system and may be a necessary facility in performing the mission tasks. The design of the AFCS will be greatly influenced by the basic aircraft stability which varies considerably with the type of rotor and the aerodynamic characteristics of the fuselage. Rigid rotors will generally exhibit greater divergence particularly in the pitch channel and will produce unsatisfactory stability in the roll channel if lags within the system are not kept to a minimum. These rotors can however provide higher maximum speeds and require less maintenance.

This paper looks therefore at the factors affecting the overall design of the AFCS in terms of the:

safety and mission requirements.

system configuration.

actuators and sensors.

The author is currently working for Louis Newmark Ltd. on new helicopter flight control systems in both the civil and military fields.

2 AUTOSTABILISER DESIGN

The AFCS can be considered in terms of the autostabiliser (inner loop control) which provides aircraft stabilisation and the autopilot (outer loop control) which provides longer term control to implement steering, height and speed control modes.

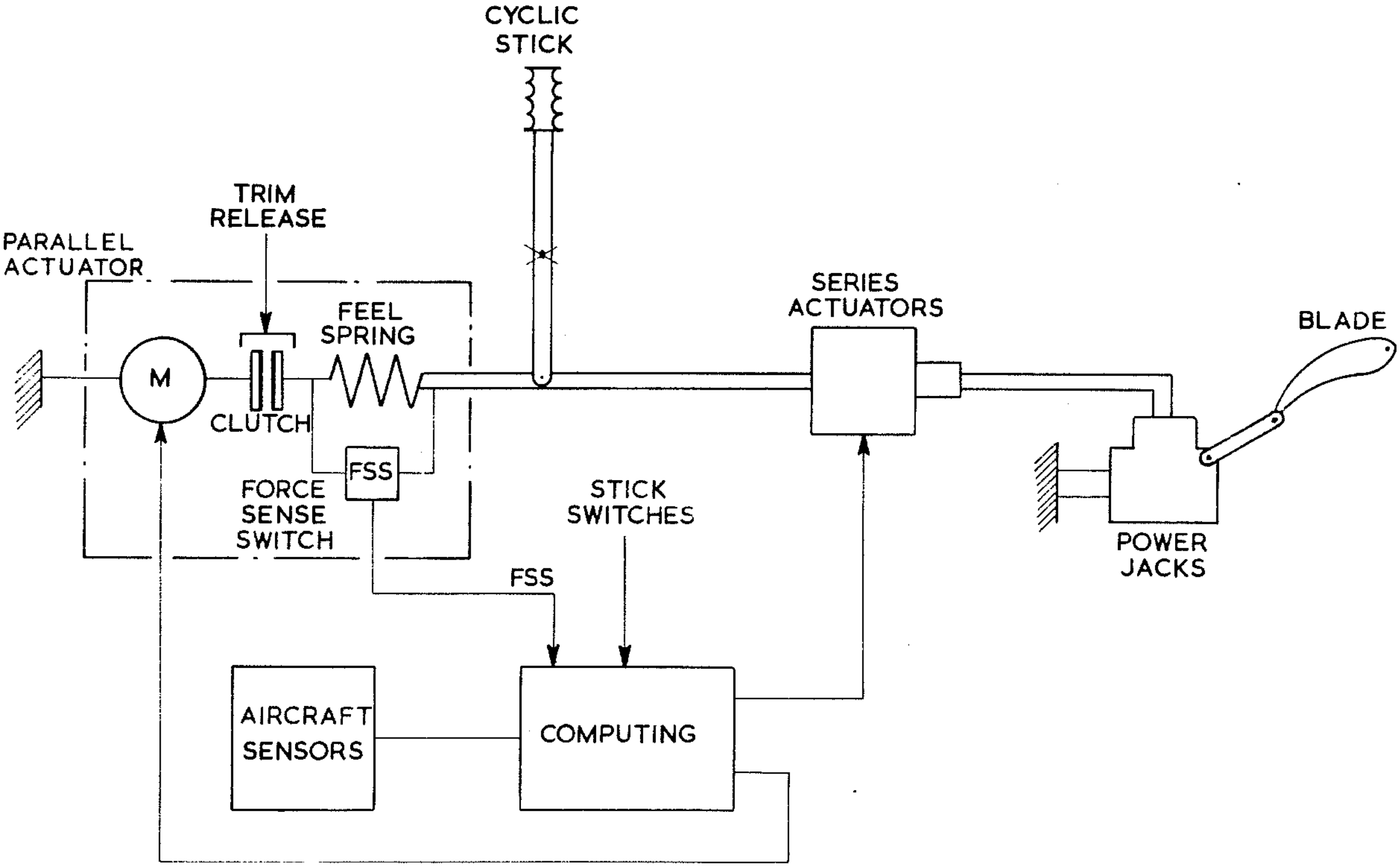
The autostabiliser equipment (ASE) must provide effective stabilisation and acceptable handling characteristics, over the complete flight envelope from the maximum speed down to the hover. Operation of the system should be as transparent as possible to the pilot and still provide adequate stabilisation during manoeuvres, it should also require the minimum of supervision under normal operation.

Although Louis Newmark have produced successful rate stabilisers all recent systems have provided attitude stabilisation in the pitch and roll channels. A block schematic is given in Fig. 1 of a typical cyclic channel. Vertical gyroscopes are generally used to provide attitude information from which rate is derived within the computing to produce the necessary damping terms.

The computing provides the necessary control laws within the stabiliser and also any monitoring facilities required to check performance of the computing, actuators and sensors. Attitude hold datums will be provided within the pitch and roll channels along with the necessary control logic required to select the appropriate mode. Transparency is provided through the force sensing associated with the cyclic stick. On detection of a pilot input, attitude stabilisation is removed, leaving the system stabilised in rate only, thereby minimising opposition to the manoeuvre. A four way beep trim switch provides facilities for updating the attitude datums.

These attitude hold systems have been successful in producing good helicopter handling qualities and reducing pilot work load and fatigue.

The yaw channel is usually rate stabilised, with additional lateral acceleration control at high speeds if required.



SCHEMATIC OF CYCLIC STABILISER CHANNEL

FIG. 1

Redundancy

The level of redundancy for any particular system will depend mainly on the type of mission, and the safety aspects. Redundancy also provides two basic facilities, a reversionary capability in the event of failure and a method of monitoring performance by a comparison of different outputs.

Types of mission will vary considerably between operators, from flights involving mainly high altitude cruise modes to flights requiring prolonged time periods in low level flight such as ASW and SAR roles. Long mission times in conjunction with poor basic aircraft characteristics will cause considerable pilot fatigue if stabilisation is lost at any significant distance from base. The mission success rate may be a determining factor in ASW modes, where long duration hover conditions and transition modes are required. In some specialised civil applications such as oil rig work a capacity to be able to take off with a failed ASE lane may be desirable.

Redundancy will reduce the severity of aircraft disturbances in the event of a failure within the AFCS, thereby improving safety. The greater the level of redundancy the smaller the effect that any single failure will have.

The time taken after a disturbance for the aircraft to reach a condition where the pilot must intervene is designated the intervention time. Intervention times will vary dependent on the mission requirement and the flight phase under consideration. For civil applications, hands off flight phases such as cruise, descent and approach will require intervention times between 3½ and 5 seconds. Such intervention times might be achieveable over the majority of the flight envelope with relatively simple systems, but for the extremes of the flight envelope more complex solutions may be required. In these circumstances trade off studies will have to be made against the cost of the system and the economics to the operator of restricting the flight envelope. These restrictions in the certification of the aircraft will usually take the form of maximum speeds and maximum aft C.G.s. If they infringe significantly on the flight envelope this method of certification is unlikely to be acceptable to operators.

In military applications intervention times will depend on the role of the aircraft, the number of pilots and the degree to which a pilot might be expected to carry out mission tasks not related to flight management. The ability to use the complete flight envelope will usually take precedence in a military machine, although some alleviation of intervention times may sometimes be acceptable.

Runaways

The worst case failures are those failures which will cause series actuator hard overs. If the actuators are allowed to operate significantly away from the null position then the potential runaway becomes more severe. This can be alleviated by the use of auto trim, where the cyclic parallel actuators are driven to maintain the series actuators operating about their central position.

Runaways in the pitch channel at high forward speeds will generally produce the most severe runaways. Since at high speed collective blade changes will also affect pitch attitude, collective acceleration control (CAC) may be provided to alleviate the effects of pitch runaways.

In a duplex system the two outputs will generally be monitored and if they disagree by more than a predetermined threshold a warning will be given. The warning will identify the channel in which the fault has occurred thereby indicating in which axis the corrective action is to be taken.

Assuming there is no other information available in the duplex system the only other way in which the monitoring information could be used would be to automatically disengage both lanes in the event of a disagreement. This might produce initially milder aircraft divergence but would leave no information on which lane was at fault. This would make the provision of a reversionary capability more complicated in terms of pilot operation.

In triplicated systems intervention on detection of the first failure can be automatic, thereby providing a failure survival capability. Three signals are compared and any lane discrepancy can be identified and disengaged. On disengagement a warning will be given to indicate that the system is now operating in duplex in that channel and to show the cause of any aircraft disturbance which might be felt as a result of disengagement.

If parts of a system cannot be fully triplicated modelled elements may be used to derive the third lane information. In a system where triplicated actuators are not practical the third actuator may be provided by an electrical model. These elements do not contribute to the closed loop control of the aircraft and therefore do not provide any backing off of defective lanes. They provide runaway protection by allowing identification and disengagement of the defective lane. Other runaway protection systems are feasible using alternative sensors to identify failures. In these systems additional computing will be used to compensate for differences in sensor characteristics.

Second Failures

If in order to meet the safety/mission success requirements redundancy has been employed, this redundancy will be used to retain stabilisation after the first failure. If duplicated series actuators have been used the potential second failure will be more severe than the first, since there is no second actuator to back off the runaway. As a result greater pilot attentiveness may be required and/or a restricted flight envelope maintained. Methods of easing these restrictions are currently under investigation which involve the use of parallel actuators driven to oppose the runaway and thereby increase intervention times on second failures.

3. ACTUATION

Performance

The combined performance must be considered for the actuation system from the autostabiliser demand through to the blade angle movement. This will therefore include the series actuators, their drive systems and the power jacks.

The performance requirements may be split into two main areas.

(i) Large amplitude or linear performance necessary to provide adequate stability with good aircraft response characteristics.

(ii) Maximum effect of non-linearity which can be tolerated within the system.

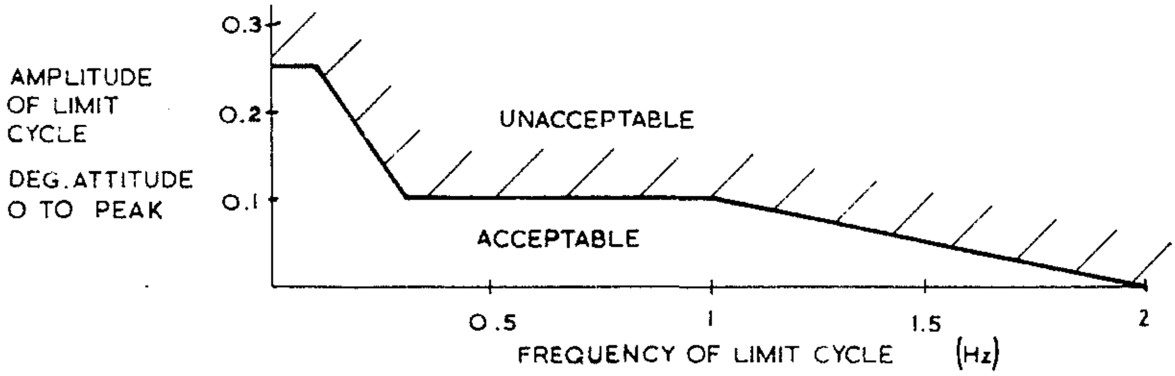
Large Amplitude

For large amplitude performance the actuator system may be represented by one or more first order lags. As the velocity of the actuator system is reduced the phase and gain margins will reduce, resulting in degradation in the aircraft handling. This will be seen in the form of overshoots in response to step inputs.

A further limitation will be a restriction on the selection of control law parameters. For each flight case there will be an optimum control law. Selection of a control law to cover the complete flight envelope may not be possible if lags within the actuator system become significant.

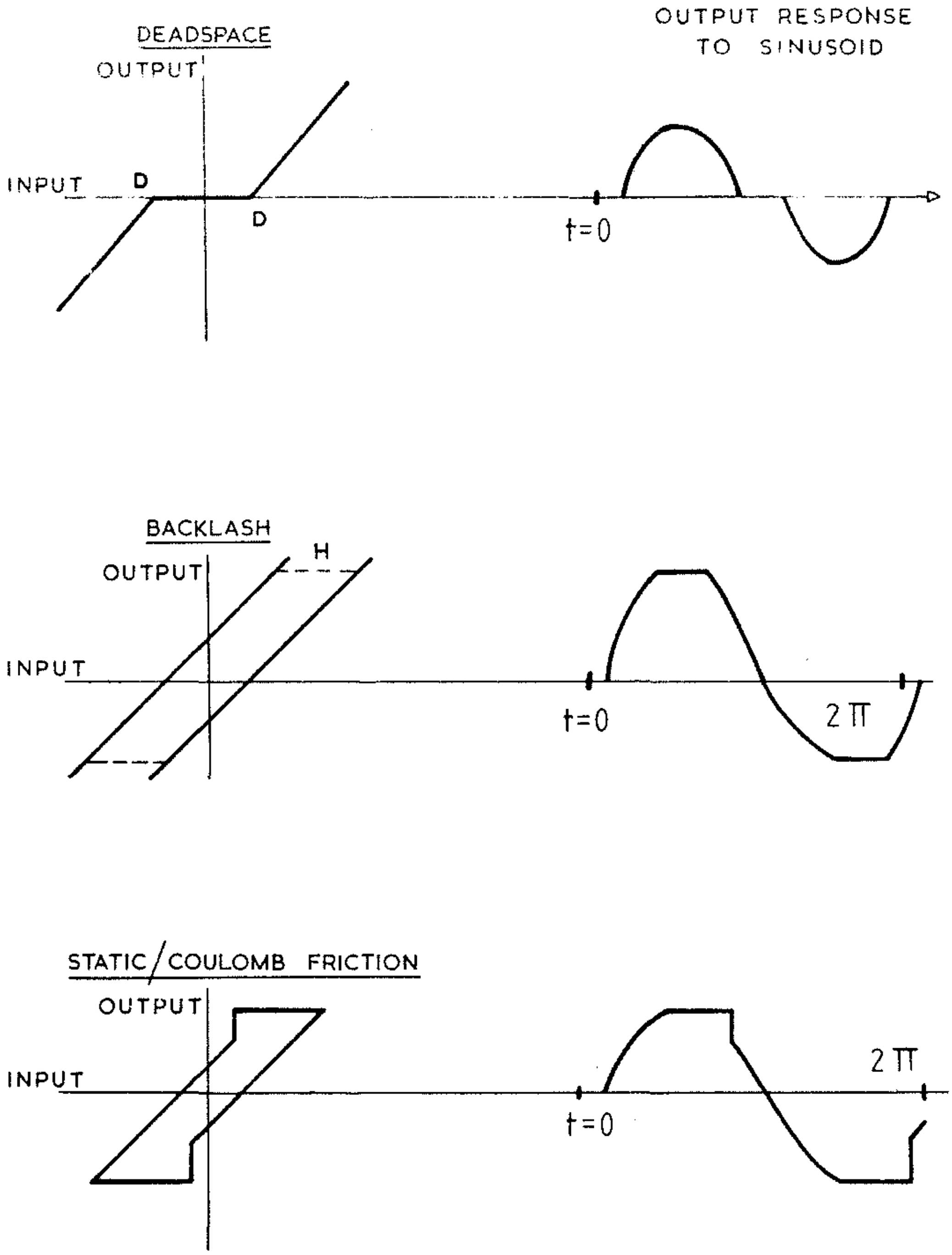
Small Amplitude

The small amplitude performance must be considered in relation to the maximum limit cycles which can be accepted as a result of nonlinearities. What is acceptable in terms of limit cycles will depend on the amplitude and frequency of the oscillations. Fig. 2 gives suggested limits of acceptability where oscillations are not perceptible to the pilot.



SUGGESTED ACCEPTABILITY OF LIMIT CYCLES

FIG. 2



TYPES OF NON-LINEARITY

FIG. 3

The non-linearities to be considered are:—

(i) Dead space.
(ii) Backlash.
(iii) Static and coulomb friction.

The responses of these types of non-linearities are given in Fig. 3.

Using Nichol's plots of the linear transfer function of the aircraft, actuator system and control law for various flight cases, and plotting the inverse describing functions of the various types of non-linearities it is possible to predict the frequencies at which limit cycles will appear. The maximum amplitude which is acceptable at these frequencies may then be used to determine the maximum allowable non-linearity.

Actuator Configuration

The configuration of the series actuators will influence the run-away characteristics of the system. The method of combining the actuator outputs will involve many detailed design considerations and may be different for different levels of redundancy and for different types of prime mover.

The two basic methods of combining actuators in redundant systems are:

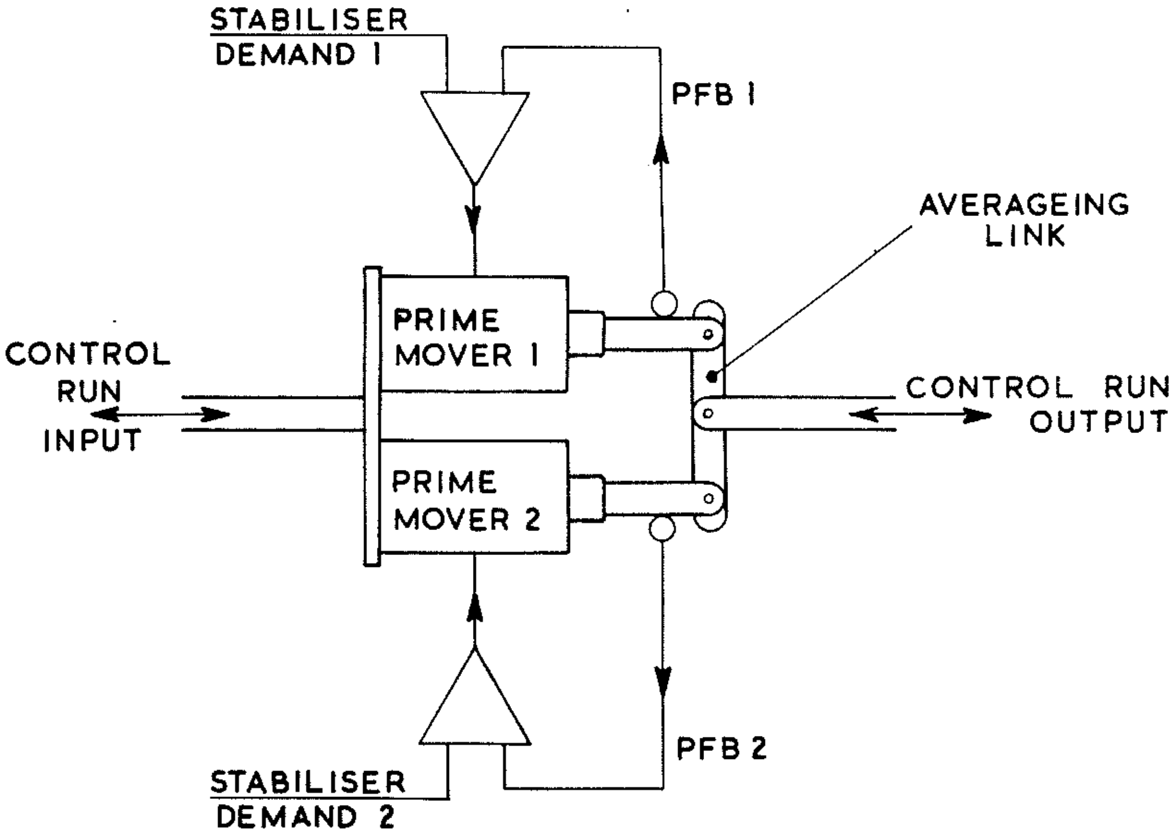
(i) The displacement summed or averaged system.
(ii) The force summed system.

The schematic representation of these is shown in Figs. 4 and 5 for duplex configurations.

Displacement Systems

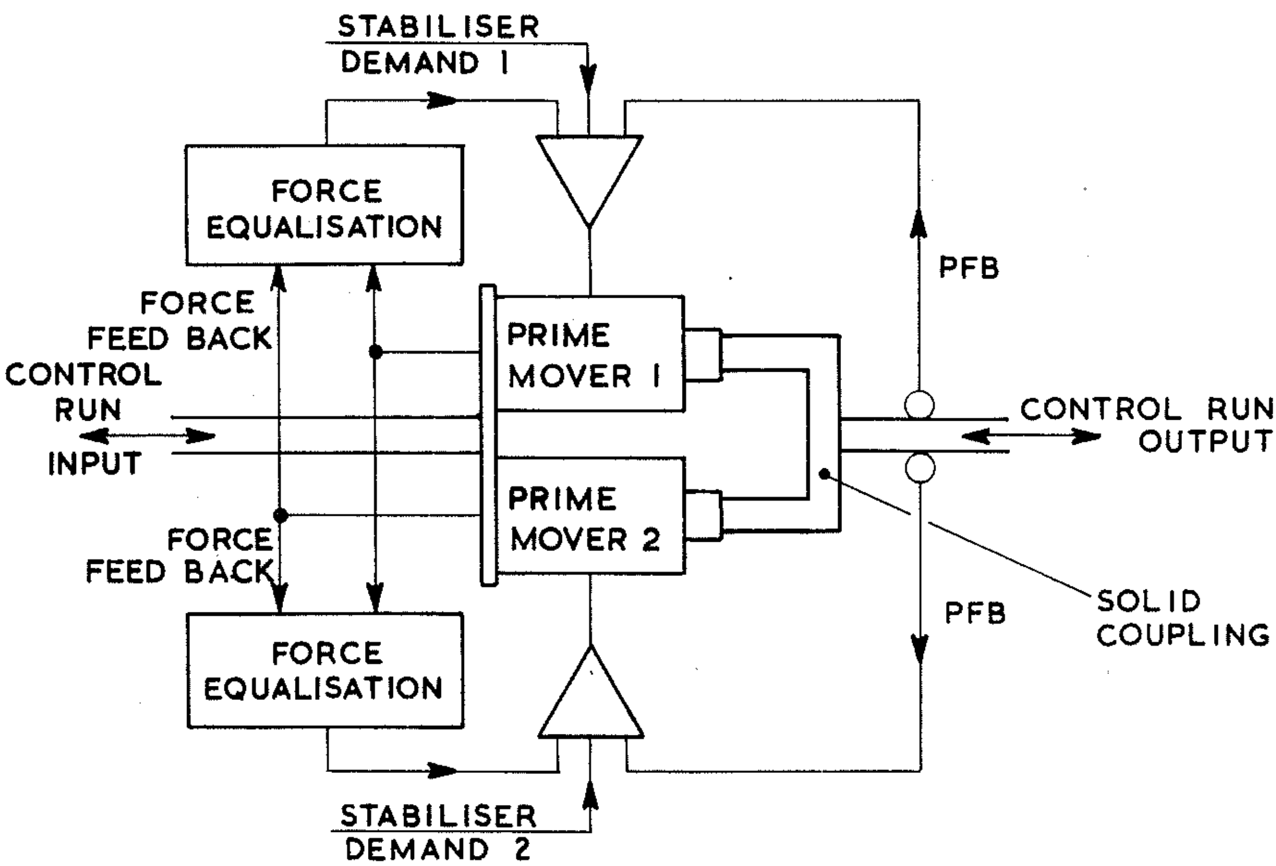
In the displacement systems each actuator will take up a position where its position feedback equals the stabiliser demand. The outputs are then either summed or averaged (an averaging link system has been shown in Fig. 4). Each actuator then produces 50% of the total series actuator authority.

In the event of a runaway of one actuator to its end stop, assuming a runaway from the nulled position, 50% of the total series authority will be applied to the blade and the aircraft will move from the trimmed condition. As this happens the second actuator will move in a direction to oppose the runaway due to aerodynamic feedback. When the second actuator reaches the limit of its authority stabilisation is lost. The second actuator therefore increases the intervention time but does not correct for the divergence from the intended flight path.



SCHEMATIC DUPLEX DISPLACEMENT
AVERAGED SYSTEM

FIG. 4



SCHEMATIC DUPLEX FORCE
SUMMED SYSTEM

FIG. 5

Once the defective actuator has been disengaged stabilisation is provided by the remaining actuator with half authority and gain. The gain will be restored within the autostabiliser. The halved authority of the remaining actuator may be a disadvantage in terms of stabiliser performance but is an advantage in the event of a second actuator runaway.

Implementation of displacement systems is relatively simple in duplex configurations. In hydraulic systems the actuators are incorporated with the power jacks and a simple averaging link is used to connect the series actuator to the power jacks. In electrical systems two extending link actuators mounted back to back in the control run will form a displacement summed system. Triplicated systems can be implemented in displacement systems but the connecting linkages will become complicated and the cost and weight will reflect this.

Force Summed Systems

In forced summed systems the actuator outputs are fixed to a common output shaft. The actuator positions must therefore be equal. Each actuator will still attempt to move to a position where its position feedback signal equals the stabiliser demand. However due to the high loop gains small differences in tolerances will result in the actuator forces opposing each other. Due to this characteristic it is necessary to provide some method of equalising the forces between the two actuators. The equalisation will have limited authority dependent on the tolerances within the system. It may be implemented either mechanically or electrically, dependent on the type of prime mover.

In the event of a runaway both actuators will move to a position dependent on the authority of the equalisation. At this point the good actuator will oppose the runaway. Since the forces from the actuators will be equal and opposite no further movement will occur and stabilisation will be lost. The intervention time is therefore increased if the equalisation authority can be kept small. Once the defective actuator has been disengaged stabilisation is restored with full gain and authority. The intervention times for single lane operation will therefore be severely reduced unless some other method is employed to protect against second actuator runaways.

Force summed systems are mechanically simpler than displacement systems. A single mechanical assembly may incorporate several drive mechanisms on a single shaft and the cost and weight will therefore not increase in proportion to the redundancy.

However, the complexity of the force equalisation will increase as additional drives are added and the mechanical configuration must be kept simple if the simplex nature of it is to provide adequate integrity.

Actuator Technology

Historically, both hydraulic and electro-mechanical series and parallel actuators have been used. A typical hydraulic series actuator requires less than 0.1 watt electrical input, while the small amplitude frequency response may extend to 60 Hz or more. Therefore the effect of the actuator in limiting the overall closed-loop performance of the AFCS is negligible.

However, for practical reasons, the hydraulic series actuator is usually made as an integral part of the main powered flying control actuator, and due to the need for at least duplex main servos, complex equalising linkages are necessary. There are also environmental problems as the powered flying control actuators are necessarily mounted on the transmission and rotor head assembly, where temperature and vibration levels are high, therefore the reliability of the actuator, and in particular the associated electro-mechanical components tends to be reduced. It is also often difficult to provide good access for maintenance purposes.

Electro-mechanical series actuators have in the past had a very restricted bandwith (typically 3 Hz) due to the use of AC servomotors. These motors have been preferred to DC due to reduced maintenance requirement because of the absence of brushes.

A number of actuators are available based on DC motors driving ACME or similar lead screws, via reduction gearing. These may be satisfactory in terms of life and performance in stable types of aircraft, but in the case of a more unstable aircraft such actuators may be found to be inadequate. The available bandwidth will encroach upon the AFCS stability margins, and the relatively fast actuator movements required will cause brush wear problems.

A solution is offered by the use of DC torque motors mounted directly on the actuator leadscrew. Such actuators can provide a bandwidth of 10 or 20 Hz, which is adequate. Developments in brushless motors will in the near future allow "on-condition" maintenance with a typical life of 20,000 hours. The electronics associated with the brushless motor may be incorporated in the actuator, in hybrid form, to minimise external wiring.

The present trend in parallel actuators is towards incorporating the feel springs, trim release clutch and any other required mechanism in one unit, with DC motor drive, which due to the low operating duty cycle is adequately reliable.

A possible development is the use of stepping motors as the prime movers in series or parallel actuators. It is easier to produce "fail-passive" drives for stepping motors than for AC or DC servo motors and the stepping motor is appropriate for use in conjunction with an all-digital AFCS. The performance of a stepping motor driven series actuator can be made adequate in terms of speed and resolution, but will become more attractive when rare-earth magnet motors become available.

4. INNER LOOP SENSORS

The objectives in the selection of the inner loop sensor configuration is to provide adequate performance and the integrity necessary to meet the safety and mission requirements in terms of redundancy and axis isolation.

The inner loop sensors generally used to provide stabilisation and attitude hold are:–

Pitch – vertical gyroscope

Roll – vertical gyroscope

Yaw – rate gyroscope
lateral accelerometer

Collective – vertical accelerometer

The pitch and roll channels will be stabilised in attitude together with additional rate damping terms. Vertical gyroscopes are generally used to provide attitude information from which rate is derived within the computing. Each gyro will provide pitch and roll information and therefore there is a common failure between these axes. This is generally acceptable even in less stable aircraft since any simultaneous disturbances can be corrected by pilot intervention using the cyclic stick to control both axes.

The vertical gyro does not produce any significant lags in the attitude information and therefore is quite suitable in the roll channel which is usually the most sensitive axis to lags. The derivation of rate is generally adequate with the gains involved in the cyclic channels.

The yaw channel is rate stabilised generally using rate gyros. To provide the necessary stability relatively high gain signals may be required through the system. These sensors will provide the necessary good quality rate signals to implement the high gains. In cases of poor directional stability additional lateral acceleration signals may be switched in at high speeds.

If implemented to alleviate pitch runaways, the collective acceleration control will use body axis vertical accelerometers. Body axis sensors are generally adequate over the attitude ranges of helicopters.

All the above sensors may be aircraft mounted and therefore can be provided with the required degree of redundancy and axis isolation.

Platforms in the form of attitude heading reference systems (AHRS) may be available and are another source of attitude information. However, unlike the vertical gyro the platform uses servo drives to position the gimbals which must produce some lags for large amplitude inputs, and non-linearities for small amplitudes. The use of a platform as part of the inner loop sensor configuration must therefore be treated with caution.

The pitch and roll rates may be obtained directly from rate sensors which provide better rate signals. Systems using this principle may provide attitude hold facilities as autopilot functions. The handling characteristics of such systems will be different as a result of the rates being measured with reference to aircraft body axes.

With the cheap computing power made available by microprocessors and the introduction of high quality rate sensors in the form of tuned rotor and laser gyroscopes other sensor configurations are possible which may provide more reliable attitude systems in the future. Such systems resolve body axis pitch, roll and yaw rates to produce earth axis rates which must then be integrated to obtain attitude. The integration process will require some form of long term update after initial erection to prevent drift. This is similar to the slow erection forces in the vertical gyro where gravitation is used to prevent long term drift.

Strapdown systems in general do offer considerable advantages in terms of reliability and in terms of the information that can be obtained from a particular sensor set. However, if all the information is to be used this will inevitably lead to inter-axis dependence on sensors unless additional sensors are provided over and above the normal redundancy requirement.

5. OUTER LOOP SENSORS

The integrity requirements of the autopilot functions are not necessarily the same as for the autostabiliser. The autopilot demands operate through the autostabiliser and therefore will be controlling the flight path through a stable system. Safety standards can generally be met by the restriction of the demands in both amplitude and rate. In the more specialised ASW and SAR modes requiring automatic hovers and transitions to and from the hover some degree of axis isolation will be required to provide adequate intervention time in the event of failure. In general it is acceptable to combine the cyclic channels, since intervention using the cyclic stick will control both axes.

Steering

At cruising speeds steering may be implemented either through the roll or yaw channels. However if a steering mode can only operate through the roll channel it cannot provide control in the low speed range.

The heading hold mode will use either a gyro compass or an attitude heading reference system. These produce no particular integrity problems unless the AHRS is providing information in other axes. In this case, where heading hold is required to operate with other modes dependent on the AHRS the failure effects must be considered.

Navigation and approach modes involve the use of various navigation sensors and radio approach aids. The approach aids may control through more than one channel to provide a coupled approach in heading, height and possibly speed. The safety requirements in these modes are currently provided by restrictions in the minimum height and speed for the approach. An aim for future systems is to provide sufficient integrity such that these restrictions may be reduced, thereby increasing the utilisation of the low speed range unique to helicopters.

Speed

Fore and aft speed is controlled through the pitch channel. An airspeed hold mode may be required if the attitude hold facilities do not hold speed adequately for a particular aircraft. If provided the mode will operate down to about 50 kts this being the lower limit to which current airspeed sensors are effective.

In the hover hold and transition modes speed is controlled in both fore/aft and lateral axes through the pitch and roll channels respectively. Doppler radar signals are used to provide the ground speed information. These signals are combined with acceleration terms such that the short term quality of the acceleration sensors may be used for control while being updated by the long term accuracy of the doppler information. This will protect against intermittent reception of the doppler signals. Earth axis acceleration will be required and if this is derived from body axis sensors there will be inter-axis dependence on them since they will also be used in the height channel during transition and hover modes. Some level of redundancy will generally be required in these sensors where strapdown systems are used.

Height

At cruising speeds height control may be implemented through the pitch or collective channels. However if implemented through the the pitch channel height modes cannot be operated simultaneously with speed modes and will not provide control in the low speed range.

The height hold modes normally provided are barometric height hold and radio height hold. Barometric height is generally used in higher altitude cruising flight due to limitation in the accuracy of the air pressure measurement. The radio altimeter however will be accurate to within a few feet, but will have some maximum height range dependent on the resolution. The signal will be combined with earth axis acceleration terms in the same manner as the doppler signals to provide a complementary signal suitable for height control.

Radio altitude is used in the hover hold mode and transition modes and since these modes are associated with SAR and ASW roles the complementary filter is tailored to attenuate sea wave motion for these applications.

6. CONCLUDING REMARKS

This paper has attempted to show the interdependence between the functional elements within the AFCS and the effects of the aircraft characteristics and mission on the overall design of the AFCS.

The aim in the development of future systems is to provide at acceptable cost greater aircraft utilisation while maintaining or improving safety standards. Development in new technologies will provide higher reliabilities while enabling sophisticated solutions to be implemented economically.

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