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HELICOPTER ENGINE CONTROL - THE PAST 20 YEARS AND THE NEXT

BY EDWARD A. SIMONIS & MALCOLM P. PERKS

Controls & Accessories Design Dept.,
Rolls-Royce (1971) Limited,
Small Engine Division,
Leavesden, Watford, England.

SUMMARY

The paper broadly surveys the first 20 years of gas turbine application to helicopters and the progressive evolution of their associated fully automatic engine control systems. It is only recently that the dominant performance and safety requirements of the control have emerged with sufficient clarity to allow them to be viewed by an overall systems engineering approach instead of as piecemeal needs. When this is done, the paper shows that considerable simplifications are possible.

A system is outlined which offers substantial reductions in size and weight over current systems without any sacrifice in performance or safety and with marked improvement in integrity. The utilisation of digital control techniques leads to simple handling from the cockpit with self monitoring facilities and unambiguous reversionary control modes. Such a system is seen as setting a pattern for control of helicopter engines of the future.

INTRODUCTION

During the past 20 years or so, the gas turbine has almost completely taken over from the piston engine as the power plant for helicopters. In this period it has evolved from an adaptation of the fixed shaft turbo-propeller engine into a breed of free turbine engine with quite distinct characteristics of its own.

The engine's control arrangements have also been developing on lines especial to the helicopter and markedly different from the controls of other aero gas turbines. Starting off by copying the piston engine's manual twist grip throttle interlinked with the helicopter's collective pitch mechanism, the control has evolved via a partial authority speed control trim into a fully automatic rotor speed governing system with total authority in the flight mode.

As the helicopter has developed, the engine control system has had progressively to take on additional tasks. These have called up new functional requirements, but as with any evolving science, there are inevitably time lags between the recognition of a functional need, the design of hardware to meet that need, the manufacture of the hardware and its development to a standard suitable for introduction into service. Further time elapses before the operators can have determined the advantages of the new equipment to the extent of registering the function in specific numerical terms as a firm demand for the future.

The same goes for safety. Each new advance in control concept introduces its own peculiar failure modes and these need to be countered if the helicopter is to remain a safe means of transport. Again there are time lags between the recognition of the need for a particular protective device, its design, manufacture and development and finally its proving under service conditions. The evolution of protective and functional controls run alongside each other and combine to make up the complete system.

Attempting to put a time scale to this process, there is probably never less than 5 years and possibly up to 10 years between the inception of a new control concept and its acceptance as the standard for the future. The gas turbine engine was first applied to helicopters in the late 1940's but it was probably not till the late 1950's that the free turbine variant could be said to have established itself. Full authority rotor governing systems started to be designed in the early 1950's, but any true appreciation of the benefits such systems gave to the pilots was not universally registered until the 1960's. The greatly reduced pilot's workload given by these systems and some spectacular rescue operations which otherwise would not have been possible then rendered other forms of control obsolete.

Equal load sharing between engines on multi-engined helicopters, tighter means of rotor speed control, improved fuel filtration and many safety features have been added since 1960. The benefits of these features are now showing up on the more recent helicopters and as far as control performance is concerned a level appears to have been reached beyond which no immediate major change seems necessary. However, because the phases in the evolution of the helicopter engine control system have been individually and separately initiated, each has nearly always resulted in additive hardware. The repetitive super-imposition of new features over the years has led to a quite disproportionate growth in bulk, weight and cost of the control system relative to the engine itself. This is typified in Fig. 1 which illustrates the total engine control equipment on the Rolls-Royce Gnome engine as fitted in the Westland Sea King helicopter. Here an excellent control performance is achieved but in hardware that represents over 20% of the engine weight and cost.

It therefore seemed appropriate to step back, review the situation as a whole and see whether by a closer co-ordination of function it was not possible to create more compact and cost effective control hardware. The more this can be done, the more attractive the small gas turbine becomes for a wider and more universal helicopter market.

Fig.1. Control equipment for Rolls-Royce Gnome Engine

A study was therefore initiated to consider the total control requirements from fuel tanks to engine burners taking into account all associated transducers and the pilot's means of handling the engines from the cockpit. No limitations were to be imposed on engine design; there were to be no relaxations on the rapid response rates now taken for granted in modern small military helicopters; safety standards were to comply in full with stringent civil certification regulations.

The purpose of this paper is to present the outcome of this study in comparison with past and present practices. Very considerable simplifications are shown to be possible. Not only do these lead to substantial bulk and weight savings on the engine itself, but also on the interface arrangements with the aircraft. A safer and potentially more reliable system emerges, easier to handle from the cockpit.

1. GENERAL REQUIREMENTS

Whilst not attempting the complete quantitative definition of a helicopter engine control system as in a procurement specification, this paper needs to cover all functional and safety requirements so that the full scope of the task may be appreciated. To emphasise the particular problems of helicopter operation the following remarks may be regarded as general requirements in the broadest sense:-

(a) Safety, integrity and reliability are of prime importance.

(b) The helicopter pilot's workload is such that he should be given the minimum involvement with engine handling in flight.

(c) Because the engines drive the main aircraft lift generating surfaces (the rotor blades), the flight performance of the helicopter is directly and significantly affected by the behaviour of the engines.

(d) Helicopters are basically low speed, low level aircraft rarely needing to fly above 5000 metres. A design ceiling of 10,000 metres is adequate.

(e) Helicopters need to operate in all climates between the arctic and the tropics. However they do not normally encounter a wide variation of temperature in any one flight.

(f) Helicopters often operate from unprepared sites and should not have to depend on sophisticated ground facilities.

(g) First line maintenance of the helicopter will usually be by replacement of faulty equipment. Simplicity of concept and ease of fault diagnosis are valuable assets of the engine and its control system.

(h) The helicopter's mission is usually of short duration although there could be many missions in one day. The mission pattern does not follow that of the fixed wing aircraft but will often be one of constant manoeuvering demanding repeated large and rapid power changes from the engines.

(j) Helicopters are heavy vibration generators. All equipment must therefore be robust enough to withstand continuous vibration without malfunction.

These are some of the general considerations that have to be taken into account but, as for the procurement of any aircraft equipment, a nice balance needs to be drawn between the conflicting requirements of performance, quality, size and cost. Over emphasis on one facet could seriously affect the others without any significant compensating benefit to the helicopter operators.

2. SPECIFIC REQUIREMENTS

Coming now to the specific requirements expected from a modern helicopter engine control system, these are itemised as follows:-

- Supply of fuel to the engine in a form suitable for combustion.
- Ability to operate on contaminated fuel.
- Fuel on-off facilities.
- Variable geometry actuation, as required
- Completely automatic control of fuel flow.

This last requirement is broken down into a number of subsidiary functions:-

- Automatic engine start and run-up to ground idle.
- Smooth transition between the ground idle and flight regimes.
- Stable free turbine speed governing in all required modes, viz. on-load, autorotation and accessory drive.
- Equal load sharing between engines for multi-engine helicopters.
- Rapid and extensive power changes without surge or flame extinction.
- Over temperature protection.
- Gas generator top speed limitation.
- Prevention of free turbine disc rupture should the transmission fail.

By asking for an overall view to be taken of the complete requirements of a helicopter engine control system, the authors are almost by definition precluding the isolation of any particular function for separate description. Never-the-less there are quite distinct tasks that have to be done. As in anatomy the heart can be described without reference to the rest of the body, so separate functions of the control system can be dealt with on their own as long as their inter-relationship with the other functions is constantly borne in mind.

For the purpose of this paper, it is considered that the specific requirements can best be dealt with under the headings, "Fuel Management", "Fuel Metering", "Fuel Control", "Rotor Speed Control" and "Variable Geometry Control".

3. FUEL MANAGEMENT

Under 'fuel management' are included those functions involved in accepting fuel from the helicopter tanks and processing it for onward delivery to the metering devices. The following are some pertinent features that have to be considered:-

(a) Helicopters may be called on to operate on any available fuel, not necessarily of aviation quality. The engine control system should therefore be designed to accept commercial fuels (petrol and diesel oil) as well as standard aviation kerosenes.

(b) Re-fuelling of helicopters is, as often as not, carried out in the field sometimes with the rotors turning. Under these conditions it is not possible to ensure the standard of fuel cleanliness usually associated with airline operations. The engine control system should therefore be designed from the outset to accept contaminated fuel without being too selective as regards the nature of the contaminant.

(c) Since helicopter engines are usually installed above the fuel tanks, the engine control system should have adequate suction capability to permit the engines to be kept operating without need of assistance from aircraft boosters. This reduces the fire risk in the event of damage to fuel feed pipes. However some external assistance will almost certainly be required for priming the system on starting.

(d) Fuel temperature from the aircraft tanks seldom falls outside the range -40°C to +55°C.

(e) Ice crystal formation in the fuel is not a serious hazard with helicopter operations.

(f) Because of the relatively restricted flight envelope of helicopters as regards forward speed and altitude, the turn-down ratio (the ratio between maximum and minimum fuel consumption rates) is considerably lower for helicopter engines than for most fixed wing aircraft engines. The control system should not therefore need particularly high pressures to maintain good burner performance throughout the operating range.

In the past, functional units of fuel management have tended to be procured separately and often from different manufacturers. Pumps, filters, heaters etc. would then be separately mounted and piped together. The resulting brackets and lengthy pipe runs could be heavy and costly and create problems of vulnerability to dirt ingress, vapour locks and the like. An objective for the future must surely be the closer co-ordination of all fuel management functions and their integration into the total system.

Pumps

Fuel pumping arrangements on helicopter engines have in the past followed one of three lines: the majority have used the fixed displacement gear pump; some British engines have employed a Lucas variable stroke piston pump whilst some of the more recent U.S.A. engines are fitted with the Vickers vane pump.

The piston pump gives good starting characteristics but otherwise its high pressure capability is not necessary for the helicopter role and does not adequately compensate for its high cost and weight.

The vane pump has the advantage of a built-in lift capability whereas both the gear pump and the piston pump need the support of a backing stage to meet the suction requirement. For example the gear pump on the Rolls-Royce Gem engine carries a centrifugal thrower on the same shaft as the main pump driving gear, whilst the piston pump on the Rolls-Royce Gnome engine is backed by a separately driven dynamic filter which combines boost and filter functions.

Experience under battle conditions proves that the gear pump properly protected will give excellent service. Efforts have been made to build dirt tolerant pumps so that fuel filters can be replaced by strainers. Experience however is that with small and efficient helicopter engines consuming fuel on average at a rate of less than 100 g/sec., the necessarily small size of the flow metering orifices and burners will always in practice demand comprehensive filtration irrespective of the pump. This being so, it is just as easy to place the filters upstream of a standard pump and avoid the high cost of a dirt tolerant pump. A boost stage upstream of the filter will counteract the effects of a partly blocked filter.

An arrangement for the future is thus seen as a gear pump running at around 12,000 r.p.m. backed by a simple centrifugal dirt tolerant boost stage mounted on the same shaft, with a filter interposed between the pumps. Although such pumps can operate at higher speeds, little weight or size saving accrues and at the higher speeds the fragility of the drive can become a reliability issue.

The proposed arrangement does not represent any significant departure from established practice, but all the requirements specified are met in essentially low cost hardware.

For trouble free operation it has been shown advisable to restrict the pump delivery pressure requirement to below approximately 4500 kPa (650 p.s.i.) and to this end, and also to avoid a multiplicity of very small burner orifices, the pumping system described should be combined with low pressure fuel injectors. Vaporising burners are eminently suitable. A large number can be used to give even fuel distribution around an annular combustion chamber without resource to too small drillings. They do however need the support of a few atomiser burners around the annulus for light-up initiation.

Filtration

There is little doubt that the problems associated with fuel handling away from regular airfields were neitner appreciated nor understood when the original gas turbine helicopters first entered service. Without exception, the first generation of such helicopters needed supplementary filtration equipment to be added, either on the engine or in the aircraft feed lines before they could be used operationally.

Helicopters are operated quite differently to fixed wing aircraft. They land anywhere and, even in civil use, need to be refuelled with whatever equipment may be to hand. It is by no means unusual to see them being refuelled by hand from cans, with the wind blowing dust and sand about on the open landing ground. Even with proper precautions, low hovering helicopters will beat up a dust cloud some of which may find its way into the fuel tank vents. Contaminated fuel is therefore an ever present hazard and the designers of helicopter engine systems should face this fact firmly and incorporate complete and adequate filtration arrangements as a basic part of any future system. Such arrangements should include the means of field cleaning in situ without disturbance of the element, a means of indication that cleaning is necessary, and facilities for replacing the element on the engine without releasing trapped dirt into the 'clean' side of the system. The filtration arrangements on the helicopter engine, whilst having to meet the standard contaminated fuel tests, need to be designed with a much broader spectrum of contaminant in mind and must on no account be dependant for their proper operation on the presence or absence of water.

Several cost effective designs that deal adequately with all the aforementioned problems are doubtless possible but a practical solution as used on the Rolls-Royce Gem engine is shown in Fig. 2. Here a 10 micron pleated paper element surrounded by a metal shroud and supported from the lid by a hollow bolt is housed within the filter bowl. Fuel from the boost stage enters the bowl tangentially to impart a swirl to the fuel and separate out the larger contaminant particles which settle in the sump. The fuel then passes inward through the element where the finer contaminant is retained. A condition indicator denotes the need of washing and a bypass valve caters for rapid blockage of the element by fine contaminant.

Routine servicing is carried out by fitting a hose to the drain in the lid and switching on the aircraft boost pumps with the engine shut down. Most of the contaminant is then washed away through the hollow bolt without disassembly or risk of contaminating the downstream side of the filter. If, in spite of washing, the element needs to be changed, this can be done by merely withdrawing the lid. No pipe connections need be broken, no fuel need be spilt and the risk of contaminating the 'clean' side of the filter is minimised. With a generous filtration area of around 1000 mm^2 per g/sec. maximum flow, an element should normally last the engine overhaul life.

Here is a compact and inexpensive arrangement that meets all the requirements and is simple to service.

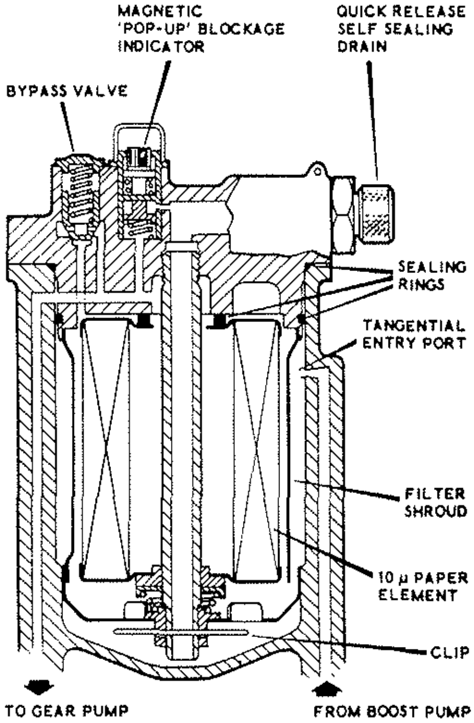


Fig.2. Fuel Filter - Rolls-Royce Gem Engine

4. FUEL METERING

By "Fuel Metering" is implied those flow modulating mechanisms that need to be interposed between the pump and the burners to enable the precise fuel flow rate to be set and maintained for any operating condition of the engine within the flight envelope. The actual method of modulating the mechanisms is here termed "Fuel Control" and is dealt with later. The fuel metering system of a helicopter engine has to cater for the following engine states at all ambient temperatures between arctic and tropical conditions:-

- Shut down - anywhere within the flight envelope, both for normal and emergency use.
- Light up - at sea level or on altitude airfields.
- Relight - in the air, usually with a limit on altitude.
- Ground idle - at sea level or on altitude airfields.
- Accessory drive - at sea level or on altitude airfields.
- Flight - any power between zero nett power (autorotation) and maximum contingency power anywhere within the flight envelope.

Contrary to what appears popular belief it is not possible to use a single tap to provide for flow metering. If the desired engine flow rate is less than the pump's output,a path must be provided for the surplus. Moreover, since flow rate through an orifice is a function not only of the orifice area but also of the velocity of flow, the accurate metering of flow through an orifice will demand a control over both orifice area and flow velocity. At least two valves are therefore required, one in the direct flow line and one spilling off it as shown in Fig. 3. This diagram illustrates the simplest possible metering system that can be used in conjunction with a fixed displacement pump running at varying speed. In practice, fuel metering systems used on gas turbine engines have tended to supplement this simple arrangement with additional modulating means. Although it is beyond the scope of this paper to describe all the variety of systems used in the past, the metering system used on the Rolls-Royce Gem engine and illustrated diagrammatically in Fig. 4 may be taken as a typical example of a modern and quite satisfactory arrangement.

Fuel from the pump is metered into the system through an acceleration control valve with the surplus taken away through the main spill valve. These two valves combine to regulate the flow into the system to an amount that can be accepted by the engine for satisfactory acceleration. Steady state running conditions are held by removing the acceleration surplus and this is done by opening the speed control spill valve. Further opening of this valve causes the engine to decelerate. Yet another spill valve,

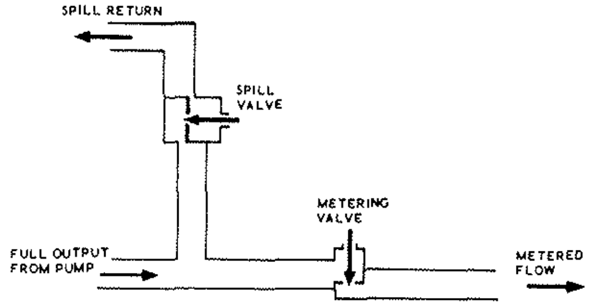


Fig.3. Fuel Metering System - Minimum Requirements

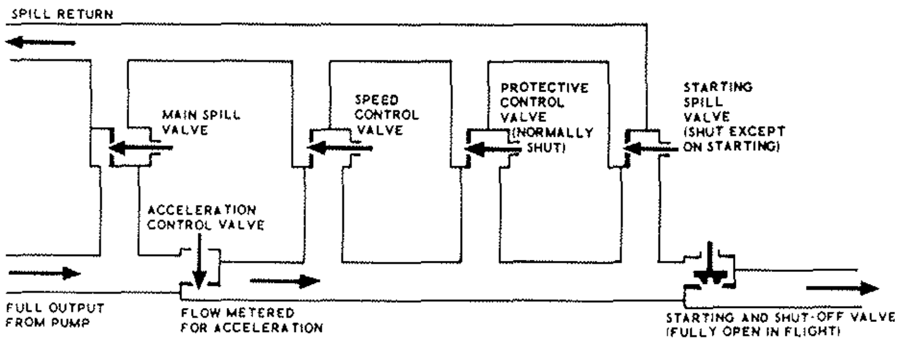


Fig.4. Fuel Metering System - Rolls-Royce Gem Engine

normally closed, can be opened to protect the engine from overspeed or overtemperature. The starting valve, which here also acts as the shut-off cock, requires an additional spill valve to allow flows below the acceleration schedule to be set at low engine speeds.

Since the cost and weight of a fuel metering system is related to the number of valves, the most compact and cost effective arrangement must be that which most closely approaches the system shown in Fig.3. The actual metering system to be proposed for the future cannot however be defined until the method of fuel control has been established.

5. FUEL CONTROL

"Fuel Control" here implies the methods and actuating means by which the valves in the fuel metering system are positioned to obtain the exact fuel flow rate needed by the engine to meet the demands of the moment. Moreover it also implies the means used to vary the flow rate for changing engine demands, the means of limiting the flow rate to keep the engine within safe operating conditions and all precautionary measures that need to be taken to ensure flight safety. Fuel control covers such a wide variety of functional tasks that, coupled with the already wide assortment of metering arrangements and actuating methods in use, there become an almost infinite number of viable possibilities. This wide choice is probably the main reason why the control system of any new engine tends to be markedly different from those before it. This is not to criticize adversely any particular control system since most have, after development, proved adequate for their task. In general however, because of the lack of any common pattern, there has been little carry over of the benefits of development from one control system to the next, either from manufacturer to manufacturer or within one manufacturers' own organization. This has led to a much slower overall evolution of control systems in comparison with other parts of the gas turbine, for example the axial compressor, which are all based on a similar theory. The authors contend that if a framework could be laid down for a small gas turbine control system that would become generally acceptable in principle, then development would be less diversified, evolution would be directed towards a common goal and the whole industry would benefit. The user would also benefit by a really cost effective system in an attractively sized package.

Before however such a framework can be formulated a clearer understanding of "Control" in all its aspects will be needed.

Steady State Control - the positioning of the flow metering arrangements to set a specific engine running condition.

Referring again to Fig. 3 and recalling that flow rate is a function of orifice area and flow velocity, normal helicopter engine practice is to use the metering valve as the flow area modulating means and arrange for the spill valve automatically to regulate the velocity through it.

On the Rolls-Royce Nimbus engine (which powers the Westland Scout and Wasp helicopters) the spill valve is a simple spring loaded relief valve maintaining a fixed pressure upstream of the metering valve, itself positioned by the speed governor. Such a system does not give an accurate hold on flow but it does satisfy the not too exacting requirements of a single engined helicopter. A more common practice is to use a spring loaded spill valve, balancing the spring closing force on the spill valve against the pressure drop across the metering valve. A constant velocity is thus maintained through the metering valve irrespective of its flow area or the environmental conditions. Many U.S.A. engines use this method as does the Rolls-Royce Gem engine.

On the Rolls-Royce Gnome engine the metering valve is again positioned by the rotor speed governor but an aneroid capsule is incorporated in the spill valve spring loading mechanisms such that the metering valve pressure drop is reduced in relation to ambient pressure. Thereby the velocity and consequently the flow through the metering valve at any given valve setting is automatically reduced with altitude to maintain an approximately fixed power rating during climb. Though first introduced on the Rolls-Royce Dart engines for use on the fixed wing Vickers Viscount aircraft, the Gnome system has been shown to have two important advantages when considering the overall requirements of a helicopter engine: it allows the full range of the metering valve movement to be used at all altitudes so that set positions can be used for starting, idling, maximum power etc., and it also automatically provides a reduction in gain of the system with altitude, aiding stability by assuring that the speed governor makes a similar correction for a given speed error throughout the flight envelope. This is such a straightforward way of providing all the altitude compensation necessary that it is seen as a major contribution towards the simplification of future control systems.

Transient Control - the means of changing rapidly and safely from one steady state flow condition to another.

With the spill valve automatically holding pressure or pressure drop constant, engine deceleration is obtained by closing the metering valve; acceleration by opening it. The main concern with deceleration is to assure that the fuel flow is not reduced so far or so fast that the combustion flame is extinguished. Control of acceleration has to assure a smooth and rapid increase in power without causing rough combustion, compressor surge or turbine overheating. The manner whereby acceleration is controlled has a pronounced if not dominant influence on the complexity, reliability and cost of the whole system.

On the very first British gas turbines, the Rolls-Royce Welland and the De Havilland Goblin (both of pre 1945 vintage) the pilot provided the only limitation on acceleration. These engines with their simple centrifugal compressors were found not to damage themselves on surge and a cockpit indication of jet pipe temperature allowed the pilot in the main to restrain his demands within safe limits. To this day the Rolls-Royce Nimbus helicopter engine has no acceleration control as such and can in fact be accelerated through surge without damage or overheating. With the advent of axial compressor engines, acceleration controls became a necessity. Surge was found not only to halt the increase of power but also to lead to very rapid overheating to the extent that if not stopped within one or two seconds, turbine blades could be partially burnt away. Though many helicopter engines use a mixed compressor system i.e. axial stages followed by a centrifugal stage, and this combination appears to behave in surge more like a centrifugal compressor engine, any generally acceptable control system for the future would need to be comprehensive in its acceleration control capability.

The smaller helicopter engines of today such as the Allison 250, the United Aircraft PT6, and the Rolls-Royce Gem engine which all use "mixed" compressor systems, have their fuel for acceleration limited according to a scheduled "linear" relationship with compressor delivery pressure. The larger U.S.A. axial compressor helicopter engines, such as the General Electric T.58 and T.64 and the Lycoming T.53 and T.55 use a variable stop to limit the extent of opening of the metering valve during acceleration with the stop position scheduled by a three dimensional cam as a function of compressor speed and compressor inlet temperature. This latter method allows the generation of complex schedules to match the requirements of multi-stage axial compressors with several variable geometry features. All these engines are meeting their requirements for rapid accelerations but at considerable cost.

When the Gnome was licensed by De Havilland from General Electric's T.58 in 1957, no equipment existed in Britain for manufacturing the 3-D cams. The decision was therefore taken to reproduce the complex overfuelling schedules in the only other way known i.e. electrically. The permitted T.58 overfuelling at each operating condition was converted to a turbine temperature rise and a corresponding variable limit set of power turbine inlet temperature against compressor speed and inlet temperature. A large number of Gnome engines using this means of acceleration control are in regular use on Westland Whirlwind and Wessex, Agusta Bell 204 and Vertol 107 helicopters, giving comparable acceleration times to the parent T.58.

With demands for still faster engine response to match the needs of more rapidly manoeuvering military helicopters, the shortcomings of acceleration control by scheduling began to show up. The delays and lags in sensing true readings of rapidly changing engine pressures and temperatures at the control were found to need quite substantial modifications to the theoretical schedules to achieve the required response rates. The accurate measurement of compressor inlet temperature, particularly under icing conditions, has never really been achieved. Compressor pressure measurement is apt to be affected by dirt, water and ice and is vulnerable to small leakages. Turbine temperature measurement is at best the average of a few point readings around the annulus. Achievement however proves that these shortcomings can be overcome but a simpler and more reliable method can surely be provided for the future.

On a later mark of Gnome engine a departure from established methods was made in that it was decided to control the rate of increase of power more logically by controlling the rate of increase of fuel flow. On this engine, with the metering valve positioned by an electric motor and an electrical signal of compressor speed also being used, there was no difficulty in limiting the motor drive rate nor in varying the drive rate limit as a function of compressor speed. The actual rate limit schedule derived is shown in Fig. 5. This single characteristic, in conjunction with the altitude compensated

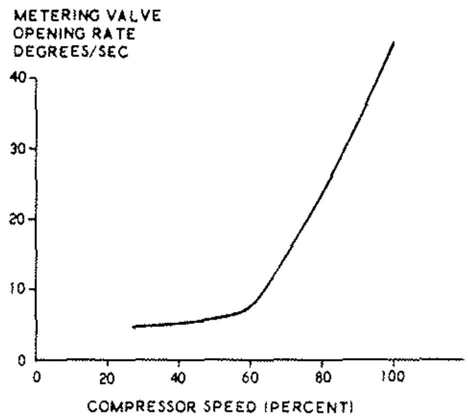


Fig.5. Acceleration Control on Rolls-Royce Gnome Engine - Metering Valve Opening Rate Limit

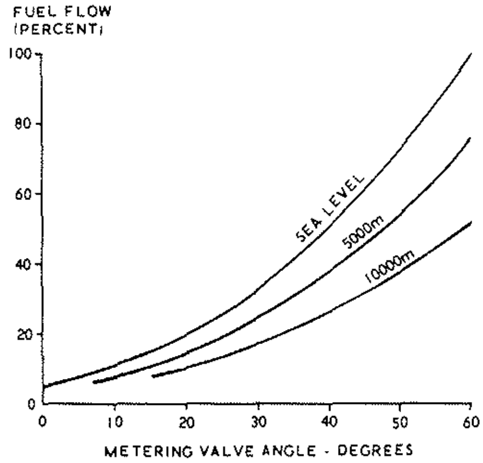


Fig.6. Acceleration Control on Rolls-Royce Gnome Engine - Metering Valve Flow Characteristics

pressure drop control already described, with flow characteristics as shown in Fig. 6, is now in use on all Gnome engines in the Westland Sea King helicopter. These engines have equally as fast accelerations as the T-58 engines in the parent Sikorsky SH-3D aircraft over the entire flight envelope. Deceleration is controlled by setting a limit to motor drive rate in the closing direction together with a stop to limit the extent of closing. This system has been flying in routine Naval service on many Sea King helicopters since 1968 and has seen duty in many parts of the world, both in hot and cold climates.

Calculations have shown the method of acceleration control by limiting the increase of fuel flow rate to be quite general for the helicopter engine application. It offers a significant simplification over other methods. No measurement of compressor pressure or ambient temperature is needed at all, and though free turbine inlet temperature measurement will still be required for overheat protection, it plays no part in the normal acceleration control of the engine. Whereas rate control has been used on both the Napier Eland and the Rolls-Royce Adour engines, the difficulty of introducing it mechanically forms a powerful inducement to go to an electrical system so that advantage can be taken of this simple method of acceleration control.

Limiting Controls - these serve two purposes; to keep the engine within its own safe operating conditions irrespective of other demands and to protect against faults which could otherwise lead to flight safety hazards.

These two aspects need different treatment since operation of the former can be a normal occurrance and calls for stable limiters, whereas protection against faults is only necessary abnormally, and hopefully rarely. The main concern with both is to prevent an accident, but with the latter it is also necessary to ensure that the pilot has the best chance of taking the right corrective measures without risk of adding to the danger. Overspeed and overtemperature limiters have in the past been applied in many ways. A common method shown in Fig.4 is to open up a further spill path for the fuel downstream of the metering valve. Alternatively, the level of pressure drop to which the main spill valve controls can be reduced, or a further restriction imposed in series with the main metering valve. Since on free turbine helicopter engines there are at least two shafts to protect against overspeed and a single unit cannot satisfactorily combine two separate mechanical movements, each overspeed limiting control has tended to be an independent device, with its own bleed valve or the like. With electrical systems it is normal practice to allow quite separate limiting controls to actuate a single valve. By passing the signals through a logic gate, interaction between loops is avoided and the engine can still be protected against exceeding whichever limit is immediately at risk.

The failure of the helicopter that demands the most exacting protective means is that of the transmission between the engine and the rotor system. Should this break at full power, the free turbine becomes completely unloaded and accelerates towards self destruction unless preventive action is taken within a fraction of a second. The risk on a well developed helicopter is small and many military aircraft accept the risk with no protection at all. Should the military helicopter later be adopted for civil use, its background history could persuade the certification authority that such protection is unnecessary. If not however, and for new civil aircraft, a fast acting overspeed governor will almost certainly be needed. This can be an expensive item if dealt with on its own, and not incorporated into the system at the outset. Mechanical governors are inherently limited to a response rate no faster than 60 to 100 milliseconds and though used on many helicopter engines to-day (e.g. on the Rolls-Royce Gem) the free turbine inertia then has to be made sufficiently high to limit the run-away rate to that which allows the governor to respond before disc bursting speed is reached. Such a demand is looked on as an unacceptable penalty on engine weight for the future. The more modern helicopter gas turbines today are needing response rates of between 25 and 35 milliseconds which seems to necessitate an electronic device. However, if this very fast response requirement is accepted from the outset, it can be accommodated within the basic system without a lot of additional complication.

Safety

It is outside the scope of this paper to discuss the safety requirements in detail, but some general remarks relevant to a helicopter engine control system need to be made since safety is an overriding requirement which influences the total concept. Civil certification requirements call for protection against any single fault of any likelihood in the engine or its control system and also against a second fault if one could have developed before or during flight without being noticed. Two potentially dangerous faults are readily identifiable in the basic metering system of Fig. 3 - the metering valve going fully open and the spill valve closing right off. In either case the engine is driven to high power. To protect against the metering valve being stuck open, a second valve needs to be included in the engine flow line so that the flow can be reduced or shut off. If the spill valve is blocked and the metering valve then closed, pressure would build up sufficiently to burst the system and therefore a pressure relief valve is necessary to provide an alternative spill path.

Consideration of the effects of faults in the control system must also take into account the effect on the aircraft. As stated previously the engines drive the main lift generating surfaces of the helicopter and hence failures leading to rapid power loss or increase are to be avoided. For example a sudden loss of power during a low level hover could cause the helicopter to lose height and crash unless very quickly corrected and a sudden gain of power during a low level descent could rapidly drive the helicopter rotor system beyond its safe rotational speed.

It must therefore be a prime consideration for the future that not only are the certification requirements met but that the system is so designed that should faults in the control occur, their effects on the flow rate to the engine are limited. Moreover, since the pilot has no other way of immediately knowing which control system on a multi-engined helicopter has failed, an unambiguous signal of failure is looked on as a necessity to avoid the possibility of him taking the wrong corrective action. Here is another strong argument for going to electrical control for the future. It is difficult to see how any improvement in the capability of mechanical systems as regards both assurance of any particular failure mode and the provision of fault indication can be made.

6. ROTOR SPEED CONTROL

Rotor governing is the function which really separates the helicopter engine from all other gas turbines. It is a complex subject involving considerations not only of each individual engine but also of the effects of other engines, the pilot's involvement and the overall performance of the aircraft.

In the early days of gas turbine application to helicopters, the control of the main metering valve was from the pilot's twist grip, interlinked to the main rotor collective pitch lever as on piston engined helicopters. This meant that throughout the flight, the pilot had to watch the rotor speed instrument and constantly adjust the twistgrip to keep the speed within defined limits. Like riding a bicycle, it was not as difficult as it sounds but it demanded constant attention with no period of relaxation permitted.

The next brief phase superimposed a limited authority trim governor on the manual control. This helped to the extent that the pilot then needed only to assure manual control within a power band and the governor would trim the power within its limited capability to hold the rotor at the required speed.

Around the early 1950's design work started in France and the U.S.A. on full authority rotor governing systems. Before the end of that decade these systems had began to establish themselves through their quite remarkable easement of the pilot's workload, freeing him of any necessity to take part in control of rotor speed throughout flight.

The different facets of rotor speed control will be briefly dealt with under separate headings.

On-load Governing

As the pilots became accustomed to automatic rotor speed control they found they could pay more attention to aircraft handling, speeding up their manoeuvres and thus testing out the capability of the governor to hold the rotor on speed. Pitch applications which had been made in 6 to 8 seconds were now made in 2 seconds or less and the response of the governor assessed by the extent it permitted the rotor transiently to depart from the selected speed. This, together with the development of more sophisticated rotor systems demanding even tighter speed control, led to the design of fast response governors with various forms of load change anticipators, and to the use of new control modes. One of the stability problems that had to be overcome arose as follows:-

The rotating system of a helicopter effectively consists of a number of fairly heavy inertias interconnected by long flexible shafts as depicted in Fig. 7. Such systems have natural torsional resonances of quite low frequencies, usually between 2 and 10 Hz. A fast acting governor will respond to such frequencies and can readily set the fuel flow oscillating in sympathy. Since the resulting

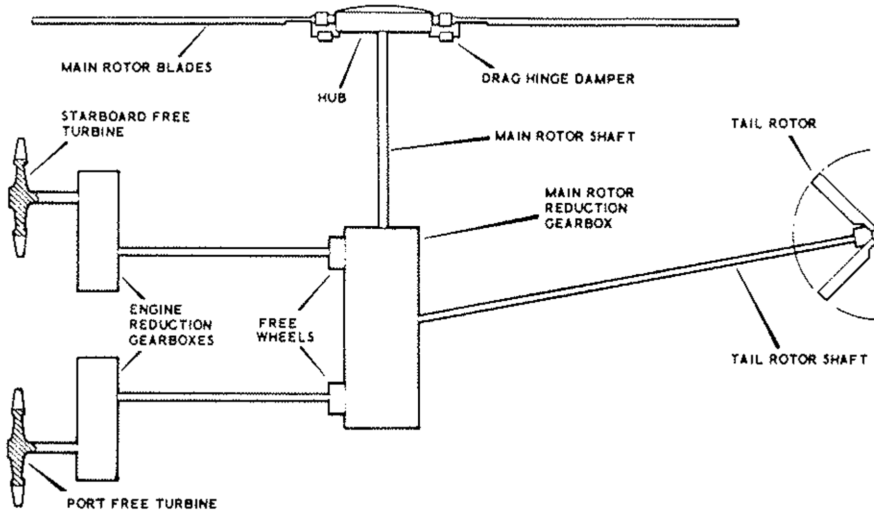


Fig.7. Typical Helicopter Rotor and Transmission System

power change oscillations will be transmitted directly into the helicopter main and tail rotors it can be felt in the aircraft as a most unpleasant positional shake. In extreme cases the oscillating fuel flow can amplify the disturbance to the extent of causing structural damage to the aircraft.

All manufacturers of gas turbine engines for helicopters have come across this problem and have had to introduce damping and tuning means of one sort or another. The problem has now largely been overcome but this does not imply that it no longer exists. Since the resonant frequencies depend on the particular helicopter rotor and transmission design, any future engine control system to be universally applicable should have flexible tuning arrangements.

Autorotation

To allow the helicopter rotor system to continue to rotate after engine failures it is normal practice to introduce free wheels in the transmission as indicated in Fig. 7. These free wheels also play a part in the overall handling of the aircraft, since to allow the fastest descent rate the engine power input into the rotor needs to be reduced to the lowest possible, and this is assured if the rotor system is made to overrun the free wheels, leaving the free turbines running unloaded. They still however need to be speed controlled. This imposes a considerable governing problem, since from controlling the speed of a system with the heavy inertias of the main and tail rotors, the governor suddenly has to control the speed of the free turbine on its own with virtually no additional inertia. Speed oscillations in autorotation can cause mechanical damage to the free wheels. Although not currently a universal requirement, control systems of the future should have the capability of satisfactory control in this flight mode.

Load Sharing

With the advent of twin or multi engined helicopters not only have the on-load and autorotational governing requirements to be met but new requirements are brought into being. In the first place since the main reason for more than one engine is safety, the good engines have in case of need to restore the power of a failed engine rapidly and without pilot's intervention. This reinforces the requirement for full authority governing but also adds the need for good response and stability in the engine out case. Interaction between the engines with oscillatory load transference must also be precluded. More particularly such helicopters have repeatedly prompted the demand for similar behaviour between engines. Though probably as much for the pilot's peace of mind as for technical reasons, there is no doubt that confidence is instilled if engines share the demanded power equally and if all cockpit instruments respond to a load change in a similar manner. Now that individual engine torque measurement is becoming standard cockpit information, similarity of behaviour implies a similarity of torque reading over the full load range, even with engines of different service life.

Accessory Drive

Yet another requirement has been added in recent years. With modern multi-engined helicopters the transmission arrangements usually provide for disconnecting the main and tail rotors and running the generators and hydraulic pumps from one engine on the ground for aircraft serviceability checks or even for stand-by external electricity generation. This duty was previously carried out manually without too much concern for speed. Modern methods of governing have shown however that it is possible for the rotor speed control to take on this task and free the pilot of one more burden.

The Total Speed Control Problem

Any solution to the total helicopter engine speed control problem for the future should satisfy all of the aforementioned requirements. A brief survey of methods used in the past shows that, whilst some of the requirements have been met relatively simply, the achievement of all of them has only been possible with the most complex and expensive controls.

Historically the first governors were mechanical flyweight governors directly modulating fuel flow. This however led to on-load instability necessitating the addition of damping devices, lag-lead mechanisms, or the like. With the on-load stability problem solved the auto-rotation stability problem called for a substantial reduction in system gain at low loads. Where tackled, this led to further mechanical complexity. Since all governors at this time were spring loaded proportional devices their matching capability over the load range was dependent on the precise matching of the spring rates. These could not be readily adjusted but needed careful selection on build and, in the event, load matching over the range with this simple type of governor has not proved adequate and calls for constant pilot attention. Where acceptable load sharing has been achieved on a basically hydromechanical system it has only been done at the expense of further complication, cost and weight. The United Aircraft twin PT6 and the General Electric T58-10 engines use additional load matching controls which balance a measured engine parameter (torque and temperature respectively) by trimming one governor against the other. The Rolls-Royce Gem engine achieves acceptable matching by using a fulcrum arm adjustment within the governor to set up the rate of each governor within close limits.

With the Rolls-Royce Gnome electrical speed control system no difficulty has been experienced from the outset in load sharing by accurately holding any desired droop law slope. On the later marks as fitted in the Westland Sea King helicopter a manual slope trim adjustment is fitted so that dissimilar engines can be precisely matched against aircraft instruments, and this facility is much liked by the operators.

Both the Gnome and the Gem engine speed control systems give good stability and response in all governing modes with excellent load sharing. On the Gnome, discrete electrical stabilising filters are selected for each mode whereas the Gem uses mechanical lag-lead stabilization in conjunction with an indirect method of governing similar to that first introduced by Bendix for the Allison T-63 engine. This type of governing, whereby the free turbine governor resets the datum of the gas generator governor which in turn modulates the engine fuel flow, has been shown to be a very effective way of achieving good response and stability on the helicopter. Such a governing method could also be implemented electrically, when full advantage could also be taken of the ease of setting and adjusting any desired droop law. This would give entirely adequate matching without interconnection of control systems and without additional hardware. It would also give the flexibility necessary to achieve all the speed control requirements for any future helicopter engine.

Before proceeding to the total system it is still necessary to consider how best to control the variable geometry features that a future engine might have.

7. VARIABLE GEOMETRY CONTROL

So as to be applicable to any future helicopter gas turbine engine, provision must be made in the total system for variable geometry control. It is not possible to generalise about the form this variable geometry would take: compressor stator vanes, compressor bleed, turbine nozzles etc. are all features which could be varied to improve engine performance and handling. Each of these would have its own requirements for control and actuation, a common link being that control would normally be required as a function of a non-dimensional engine parameter and operation of the variable geometry would be necessary when the engine was under both automatic and reversionary control.

Where on U.S.A. engines a 3-D cam is already provided for acceleration control it is normal practice to utilize another surface of the cam for variable geometry control, actuation being by high pressure fuel. On the Gnome engine a speed signal is generated mechanically and is combined with an ambient temperature signal to servo control a high pressure fuel actuator. Neither of these arrangements are seen as the answer for the future since they are not self-contained and place constraints on the design of the rest of the control system. The approach taken on the Nimbus engine which employs an independent unit using compressor delivery pressure for control and actuation is considered more satisfactory. An independent electronic control is not thought to be a cost-effective solution, especially bearing in mind the transducer requirements.

For the future therefore self-contained pressure ratio devices, perhaps using fluidic techniques, may well offer the simplest and cheapest variable geometry controls.

8. THE TOTAL SYSTEM

What then is the control system of the future? None of the systems currently in helicopter use is looked on as the answer : either they fail to meet some essential requirement, or they impose a restraint on engine design, or they have unacceptable bulk, weight and cost. How did this situation arise?

It would be incorrect to state that when designing control systems for the first generation of helicopter engines the total requirements as then foreseen were not all taken into account: they were. The escalation of these systems into the multiplicity of units typified by the Rolls-Royce Gnome system depicted in Fig. 1 therefore still needs to be explained. The explanation probably lies not unnaturally in a lack of understanding generally at that time of the potential of the helicopter. This led to the subsequent necessity to be ever adding to existing hardware to keep pace with evolving demands as helicopters and their engines developed. When the control system requirements of the Rolls-Royce Gem engine came to be specified in 1967, a much better realisation of the practical necessities was available, based on some 10 years experience on many different systems. A sincere effort was then made to co-ordinate the functions into more compact hardware, the success of which may be judged from the illustration in Fig. 8. Here the total requirements are met by just two units with the addition of two

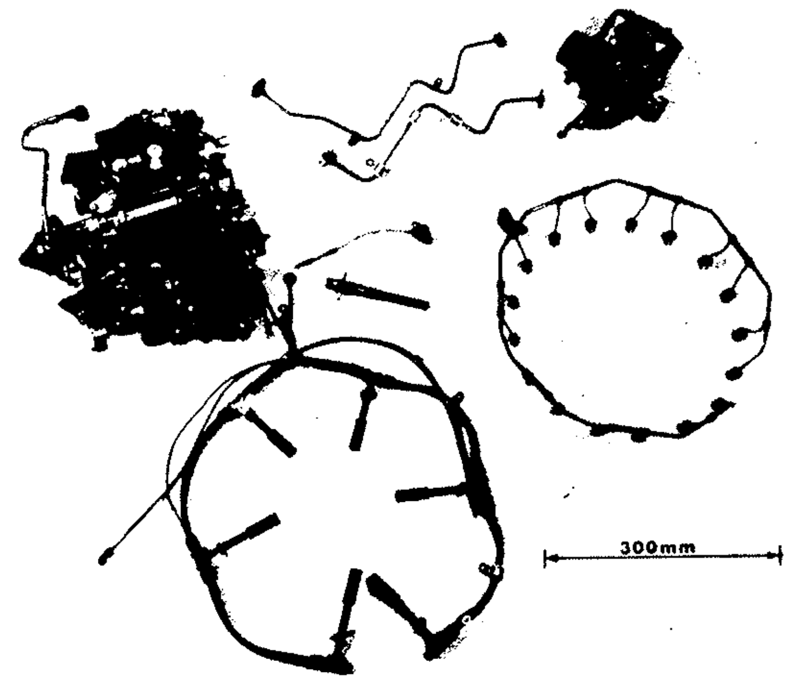


Fig.8. Control Equipment for Rolls-Royce Gem Engine

small speed probes and a thermocouple harness. The performance of the Gem system matches that of the Gnome in almost all respects in hardware that is under 10% of the engine weight and cost. However, the Gem type of system is not really looked on as forming the basis of systems for the future, since it imposes restraints on the engine design that may not be acceptable except for the smaller sizes of helicopter engines. For example it demands an engine design without variable geometry and which can accept a linear overfuelling relationship against compressor delivery pressure.

A further 7 years has passed since the Gem system was conceived. Not only has our understanding of the helicopter's requirements further advanced but this period has been accompanied by rapid developments in electronic technology which make electrical control much more attractive for the future even for the small helicopter engines. Electronic development has been especially marked in the advances made in micro-miniaturisation of circuitry, particularly those circuits associated with simple digital computers. Here, the commercial pressures of the small electronic calculator market have prompted the era of the "computer on a chip", and this is bound to revolutionise not only helicopter engine control but also the whole of the gas turbine control field. Such integrated circuits are already in quantity production and are small, light, cheap and becoming cheaper.

The size, weight and potential cost of an electrical control system based on this type of component are hence now seen as very important advantages for the future. There are many other benefits of such control systems which should also be noted. They offer flexibility and the potential for growth of functions during natural evolution without the sort of complication we have seen before. Flight safety can be markedly improved by arranging that most failures occur only in a defined mode, with minimum risk to the aircraft and unambiguous fault indication to the pilot. This overcomes the principal deficiency of current electrical analogue systems. The pilot's work load can be further reduced by the more rational cockpit layout which is possible with such a system. The ground crew's task can also be eased by utilizing the self check-out and monitoring capabilities inherently available. Lastly, it is a natural step for a digital system to be controlled by electrical signals only - a "fly-by-wire" arrangement, with attendant weight and cost savings in the aircraft. Once these benefits have been fully appreciated by both manufacturers and operators alike it is envisaged that they will become firm requirements for the future. This leads directly to the conclusion that future helicopter engine control systems will be based on a simple digital computer. The arguments advanced for integration of equipment imply that this computer will become a basic part of the engine-mounted control. Reliability requirements necessitate that the computer must be designed from the outset for a high vibration, high temperature environment, utilizing fuel cooling to keep component temperatures down.

It is a straightforward matter to calculate in the computer the required fuel flow, particularly since the simple control laws previously outlined depend in the main only on readily available speed and position signals, but the computed flow requirement must be implemented through an interface which has to be compatible with a digital computer and also consistent with the fuel metering and control requirements previously described. The interface arrangement suggested here is indicated diagrammatically in Fig. 9. It consists of an hydraulically balanced, rotary metering valve positioned by a stepper motor

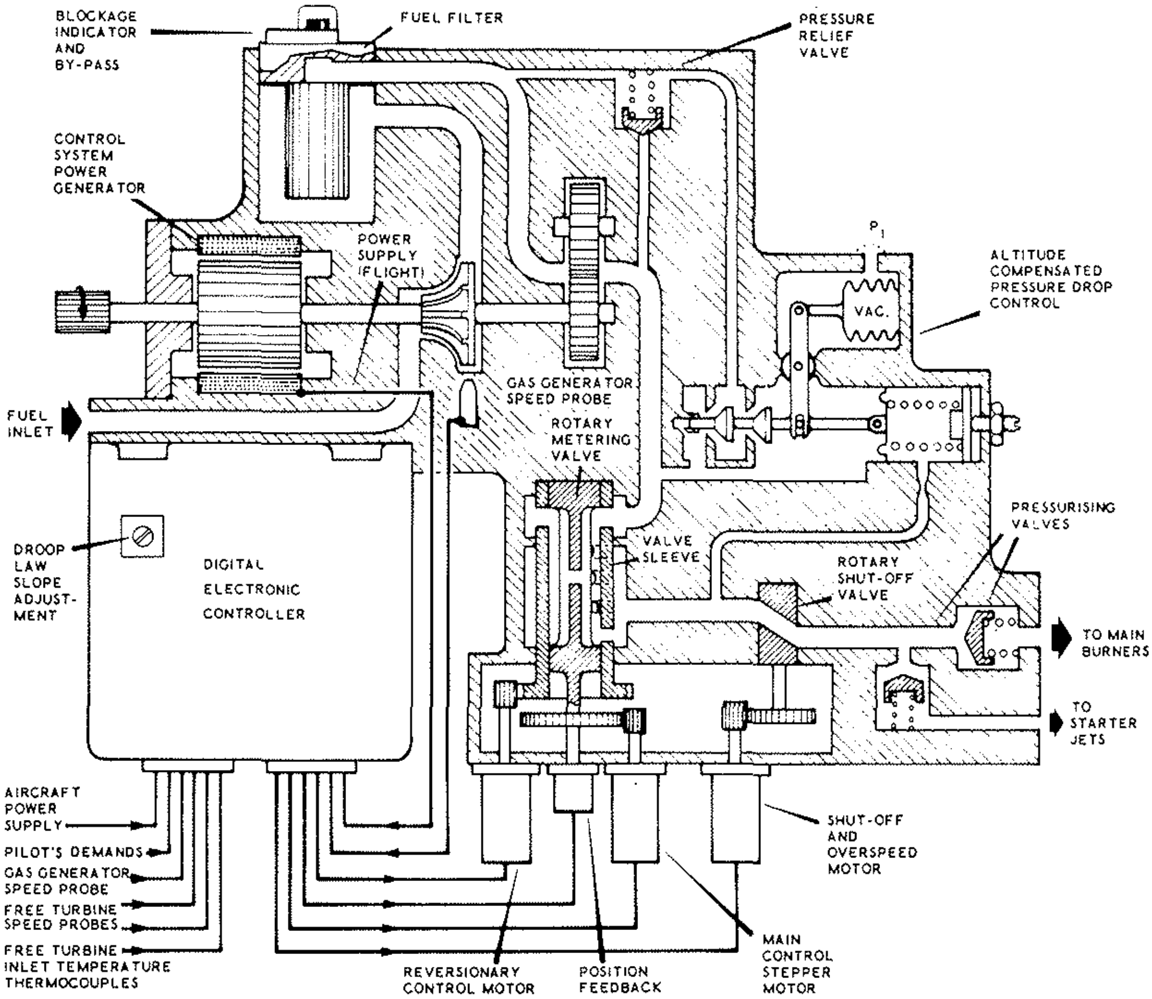


Fig.9. Proposed Control System for Future Helicopter Gas Turbine Engines

driving through a reduction gearbox. Rotation of the metering valve varies the flow area whilst flow velocity is set by an altitude compensated pressure drop control. This gives all that is necessary for accurate fuel metering. Valve position is sensed by a simple rotary transducer. Control over energising of the motor windings and control of motor drive rate for acceleration can be exercised simply and directly by the computer. The low torque of the throttle ensures low power dissipation. Speed of operation is adequate and the entire arrangement is basically "fail-freeze" and hence acceptable from the safety aspect. Speed control would be by an indirect mode, with the free turbine governor resetting the gas generator speed control loop. The rotor speed governor would operate proportionally against a preset droop law with a facility for trimming the slope of the droop law on installation for accurate matching to a second engine. A separate fast-acting motor combines the functions of pilot's shut-off cock and emergency protection and duplication of speed signals assures the necessary complete independence of these functions from the normal control and limiting channels.

A simple reversionary control can be provided with little additional complication by including a separate rotatable sleeve around the main metering valve. The pilot can then control fuel flow by turning this sleeve relative to the valve at a set slow rate using an independent motor driven off a separate power supply and operated directly by switches on the collective pitch lever. A failed computer would automatically "freeze" the main metering valve and select the reversionary motor.

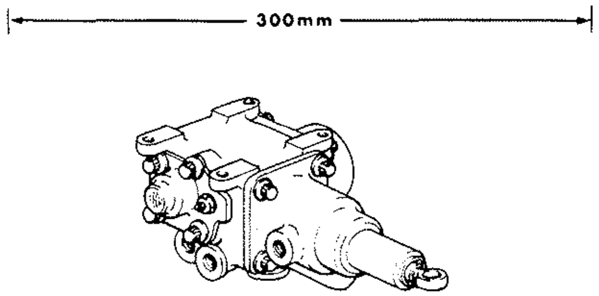
One feature of this system not referred to before arises from considerations of total system integrity. This is an engine - driven generator to self-power the control system in flight and allow full operation following an aircraft supply failure. The provision of this integrated power supply also minimizes potential hazards resulting from possible susceptibility to external radio-frequency interference - a particular problem with helicopters since their operation can often involve flying very close to powerful radio or radar transmitters.

Fig.9 is intended to be indicative only of the type of system envisaged for the future, it is not within the scope of this paper to discuss the detailed design of the hardware. The authors' purpose will have been served if it is apparent that by adopting the "total systems approach", a system can be arrived at which is inherently simple and yet which adequately meets all the stated requirements.

An indication of what such a control system might look like for a small helicopter engine is given in Fig. 10. The total system shown would weigh less than 7kg, of which the electronics account for less than ½ kg and the variable geometry control less than 1½ kg. The system could be adapted for larger, more complex engines with only a small increase in size and weight. The philosophy of an integrated electronic/hydromechanical package can thus be seen to lead to significant savings in hardware.

Further savings to the aircraft can be achieved by adopting the "fly-by-wire" approach, with the cockpit controls part of the basic system. Fig. 11 shows the form such cockpit controls might take. As envisaged here they consist of a single panel with engine mode being selected by push buttons or switches and rotor speed datum and transition by rotary knobs. Simple switches on the collective pitch lever enable the pilot to control the engine in the reversionary mode.

An illuminated display can be used for fault diagnosis or the like. Once again, the purpose of the diagram is to illustrate the sort of rationalisation that is possible and is not an attempt to define the details.



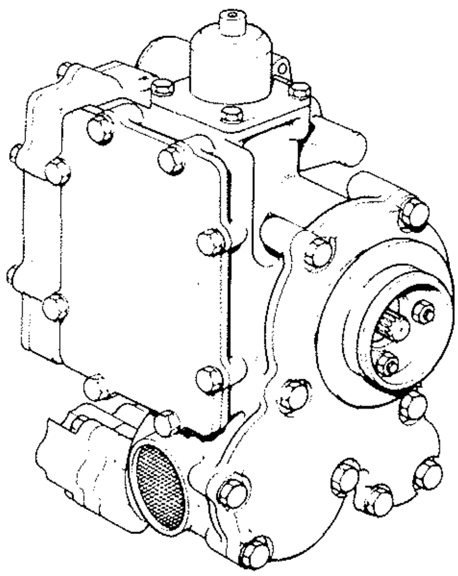


Fig.10. Control Equipment for Future Small Helicopter Engine

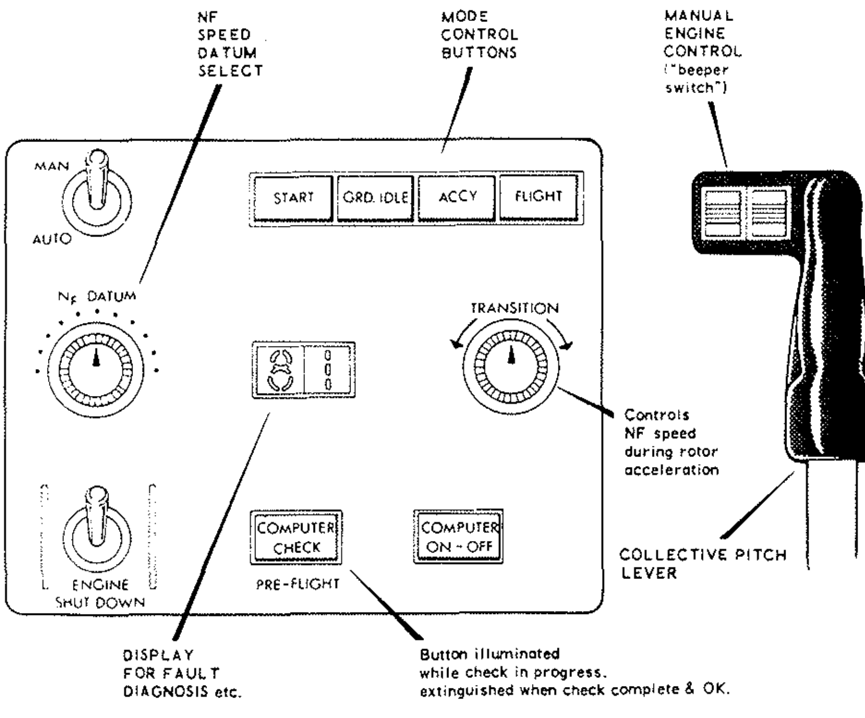


Fig.11. "Fly-by Wire" Cockpit Controls

CONCLUSIONS

The study to define a helicopter engine control system for the future has shown how very effective the "total systems approach" can be. If all requirements are considered together as inter-related parts of a whole, there emerges a completely different system with an altogether simpler concept from any system in service today.

The following are the main findings of the study:-

(a) All requirements for fuel pumping, suction, filtration, filter cleaning etc. can be accommodated together in simple and compact hardware.

(b) By considering all modes of free turbine speed control and power matching together and in relation to the fuel metering arrangements, a simple governing system can be arranged without need of superimposing matching controls, integrating governors, or the like.

(c) A simple digital electronic computer driving an altitude compensated metering valve via a stepper motor and working only off speed and position signals can give all that is required for fuel control with a high level of integrity.

(d) Rate control of the metering valve is a simple and effective means of acceleration control for helicopter engines and avoids reliance on pressure and temperature transducers.

(e) The need to provide a fast-acting fuel cut-off control for transmission failure eventualities can be utilised to provide for normal on-off and other safety controls independent of the main metering valve control without further multiplicity of fuel valves.

(f) A digital system lends itself to "fly-by-wire" cockpit control which simplifies the aircraft-engine interface. Self check-out largely eliminates the dependence of the control system on separate ground test equipment for first line serviceability, and failure warning displays leave the pilot in no doubt as to which engine has failed.

(g) By incorporating an electrical generator in the control system of each engine backed by the aircraft's electrical supply for starting, all supply failure contingencies are covered and the risk of interference by external high frequency radiation is minimized.

(h) The separation of the variable geometry control from the rest of the control system results in simple hardware which operates in either normal or reversionary modes of control.

This paper has been entitled "Helicopter Engine Control - The past 20 years and the next." Our experience is drawn from the past; our interest is in the future. We have seen the helicopter develop and for our part, have assured that the engine control meets each new requirement as it has evolved. The pace has been fast with little time to take the broad view and consider the requirements as being inter-related parts of a whole rather than specific individual needs. Now that this has been done however, the type of arrangement diagrammatically presented in Fig. 9 and pictorially indicated in Figs. 10 and 11 emerges. There is no currently known requirement that such a system cannot meet, nor any known performance achievement that cannot be equalled or surpassed. The substantial weight and cost benefits together with enhanced safety and reliability, ease of handling and ground support gives confidence to our belief that it will be this type of helicopter engine control system that will be needed to meet the challenges of the next 20 years.

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