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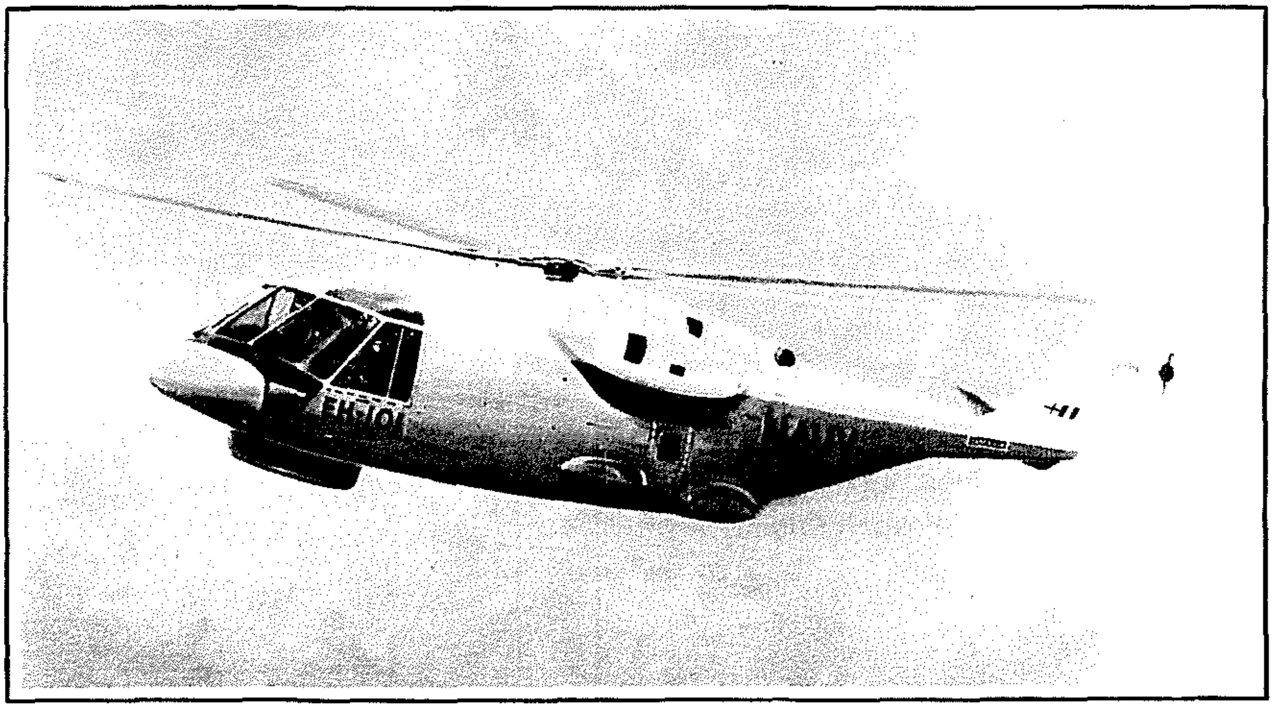
Three-Engine Control System for the Prototype EH-101 Helicopter



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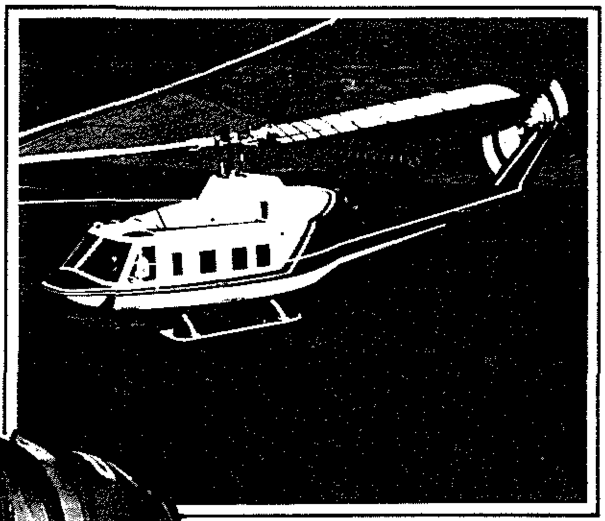

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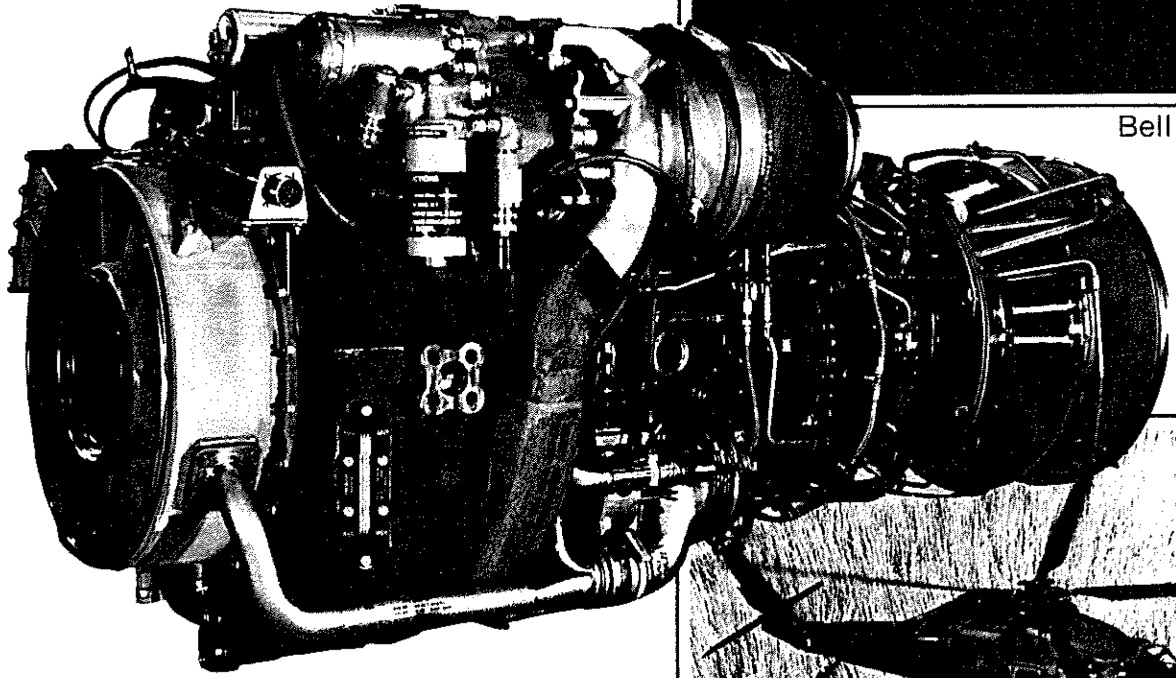
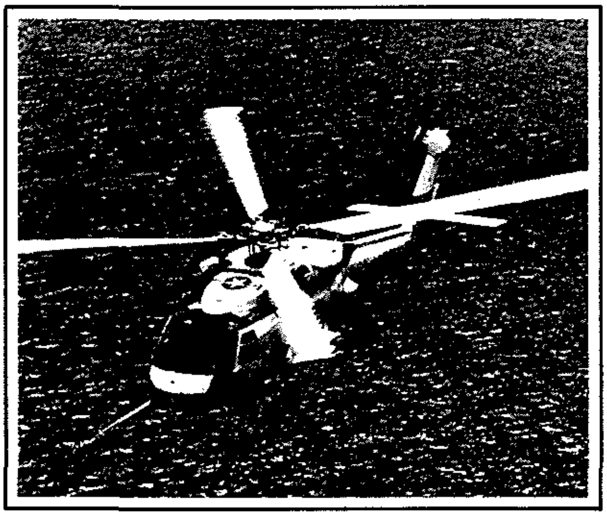


General Electric
T700 Turboshaft Engine

Sikorsky UH-60A Black Hawk

Hughes AH-64 AAH



Sikorsky SH-60B LAMPS Mk III

Three-Engine Control System for the Prototype EH-101 Helicopter

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Abstract

The T700 control system configured for installation in the three-engined WG.34A helicopter (prototype for European Helicopter Industries EH-101) provides for a versatile control system which may be operated normally to provide helicopter propulsion or may be operated as a totally independent system to power airframe avionics and power accessories. It is designed to maintain constant speed for accessories or load share with second and third engines and is independent of position in the aircraft. The total system is automatic and provides not only constant rotor speed but also closely matched torques.

This paper discusses the modification made to the T700 control system to provide the above capabilities. Also included is some discussion of the need for these modifications and the present status of the design.

List of Symbols

ECU	Electrical Control Unit
HMU	Hydromechanical Unit
Np	Speed of engine output shaft or power turbine
Q	Engine output torque

Introduction

The T700 engine was developed in the early 1970s and is now firmly in production as the powerplant for the U.S. Army Black Hawk UH-60A helicopter. It is also being used on the U.S. Navy Seahawk SH-60B, the Army Advanced Attack Helicopter AH-64 and the commercial Bell 214ST. All of the previously noted applications are twin engine powered. On Sept. 19, 1979, UK Supply Treasury Delegation executed a contract with General Electric Company, U.S.A. for installation studies and engineering support of the prototype EH-101 program. A major effort included in this contract was the design and development of a modified T700 control system capable of three engine control.

Two major modifications were required to enable the following unique aircraft requirements to be met:

1. The ability to automatically load-share between three engines rather than two while maintaining the currently available isochronous or constant speed governing capability of the T700 engine.
2. The ability to run as a separate accessory drive mechanism wherein one of the three engines could be manually declutched from the main rotor to drive the accessories. In this operational mode, the engine being used to drive the accessories should not load-share with the other two engines and should have the ability to maintain constant and stable accessory speed despite the fact that the accessory load and inertia is significantly less than that of the normal helicopter rotor.

The remainder of this paper will discuss these two special features, their requirements, implementation, advantages and operational status.

T700 Base Line System

Prior to the discussion of the modifications, it would be helpful to review the pertinent aspects of the original T700 control system. It will then be easier to discuss the changes as they differ from the basic T700 system.

The T700 control system was designed to relieve the pilot from constant engine monitoring and to allow him to be as free as possible to fly the helicopter by enabling the engines to "fly themselves." Desirable features of the system include:

- Automatic starting
- Single power lever position for flight
- No adjustment or rigging changes needed following any control system component replacement
- Isochronous or constant output shaft/power turbine speed control
- Turbine inlet temperature limiting
- Gas generator speed limiting and overspeed protection
- Separate power turbine overspeed protection
- Single or dual engine installation capability without modification or adjustment

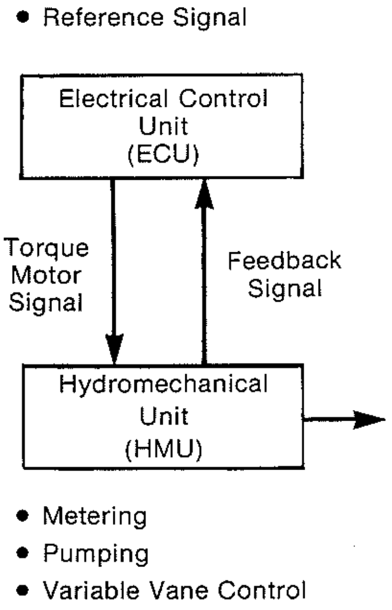
It was determined that the basic design of the system should be one that maintains constant or isochronous engine power turbine speed (and therefore rotor speed) for all steady-state flight conditions. A more complete description of the T700 control system design and its operation is given in References 1 and 2.

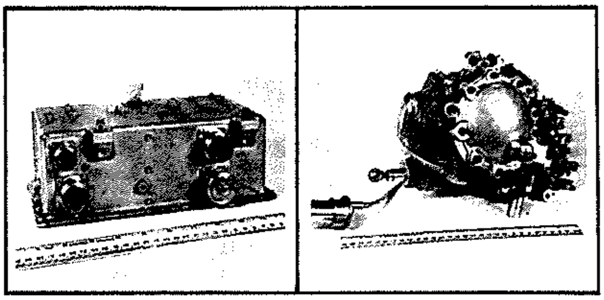
Basic Functions of the T700 Control System

The specific characteristics pertinent to the prototype EH-101 modifications center around the isochronous governor. The basic requirement of this governor is to provide isochronous power turbine governing to automatically adjust engine power to maintain constant rotor speed at all rotor loads. The basic components of the control system (see Figure 1) are the electrical control unit (ECU) and the hydromechanical unit (HMU). The hydromechanical control unit provides fuel metering and fuel pumping as well as other functions necessary to the control of the engine.

Governing is accomplished by electronic comparison of actual power turbine speed to a desired reference speed in the ECU. The ECU then effects fuel flow changes by trimming the metering valve servo through a torque motor in the hydromechanical unit (HMU).

Basic T700 Control System Components





Electrical Control Unit (HMU)

Hydromechanical Unit (ECU)

Figure 1

The HMU is trimmed in order to reduce the difference between actual power turbine speed and reference speed to zero (see Figure 2). This error signal is first modified by dynamics designed to ensure adequate stability and minimize wander about reference and to maximize response rates for varying flight conditions. The modified signal is then used to position the torque motor electronically to maintain zero error. Once the error has been reduced to zero, the ECU must maintain the HMU trim signal which was needed to trim fuel flow to obtain zero error. To do this, an integrator is used.

An integrator is designed to move only in the presence of an input signal. When the input signal becomes zero, the integrator stops adjusting output and maintains this constant output signal. This is the basic operational characteristic of an isochronous governor.

However, integrators are designed with finite slew rates to ensure stability, and fixed saturation levels to ensure proper operation. This usually results in a slow response time and large variations from speed reference during transients. In order to improve governing characteristics, a proportional signal was put in parallel with the integrator to provide an instantaneous but proportional signal to the torque motor. Judicious selection of the gains of the integrator and proportional amplifier maximizes stability while minimizing speed error and transient response times. The isochronous governing is thus accomplished by a proportional plus integral governor. A detailed discussion of this technique is given in Reference 3.

Comparison of Multiple Engine Droop and Isochronous Governing

A governor which allows for small variations in power turbine speed is called a droop governor. Droop governors inherently load-share because power is proportional to speed error. The degree of load-share error is dependent on control-to-control and engine-to-engine variations. However, the primary task of the T700 isochronous governor is to maintain constant power turbine speed without regard to the power required. Measured power turbine speed is continually compared to a built-in electronic reference as previously described (see Figure 3). The governor is designed to operate so that the difference (or error) between actual speed and reference speed is zero. For single-engine applications, this poses no particular problems.

In a twin-engine installation with isochronous governors, however, a unique problem arises. Assume that an aircraft has two engines, #1 and #2 as shown on Figure 3. Also, assume that due to control tolerance, the #1 engine power turbine reference speed (Np ref) = 100%, while the #2 Np ref = 101%. Since both power turbines are geared together, the actual power turbine speeds must be equal while the engines are engaged to the rotor system. However, the #2 engine control

ECU Basic Functional Block Diagram

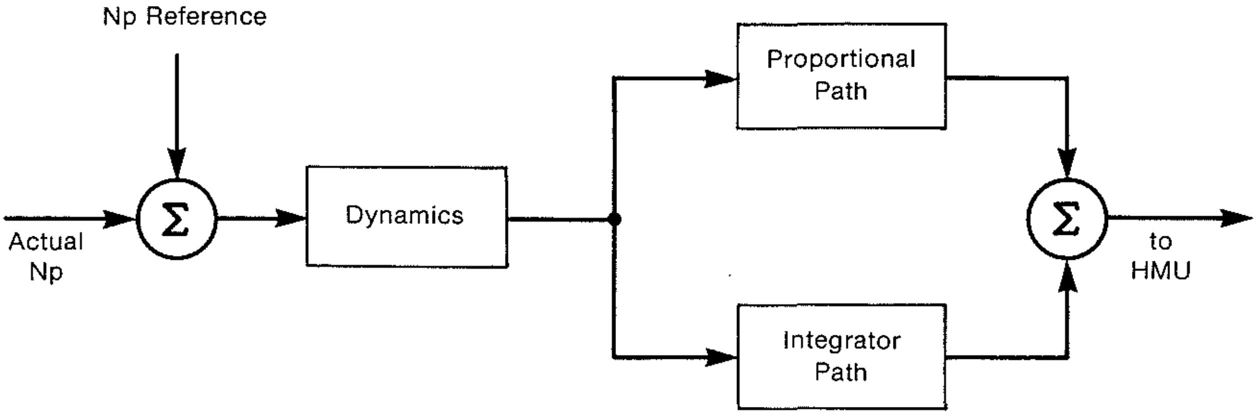


Figure 2

will increase power to make Np = 101%. The #1 engine then will decrease power to satisfy its governor by making Np = 100%. This increasing of the power of engine #2 and decreasing of the power of engine #1 in an attempt to satisfy the two Np governors with unequal speed settings will continue until one or the other of the engines reaches a limiting power level (idle or max power as an extreme).

If the power requirement of the helicopter is such that one engine can support the rotor at 101%, then the #1 engine will reduce to zero torque and free wheel. Note that the clutches used are of freewheeling or overrunning type.

If, however, the power requirement is more than one engine can deliver, the #2 engine will accelerate to maximum available power. The #1 engine will then supply the necessary additional power to run the rotor at 100%. Therefore, if nothing is done to cause both ECUs to have exactly the same reference, one engine will freewheel at a lower reference while the other carries all the load or one will run at topping power and the other will supply the remaining required power.

There are several solutions to this torque split problem. For example, a single external reference would avoid the problem of two separate references being unequal. Precisely matched references in each ECU could be used but it would increase manufacturing costs. The solution chosen, because of its versatility and lower cost, is the use of some related engine parameter as a trim on the power turbine speed electronic reference of one of the ECUs in the twin-engine installation. Since torque is a measure of engine power and because it is typically the parameter helicopter pilots desire to match, it is used as a signal to ensure that both power turbines have matched speeds and closely matched power levels.

Before discussing this load-sharing system, one should address the question, "If the isochronous governor causes this load-share problem, why not employ a droop governor?" To answer the question, let us compare droop-governing vs isochronous.

Droop-Governing Versus Isochronous

Although a droop system does provide some inherent load-sharing, it suffers from several disadvantages relative to an isochronous system including:

- Larger errors in load-sharing accuracy

Basic Twin-Engine Installation

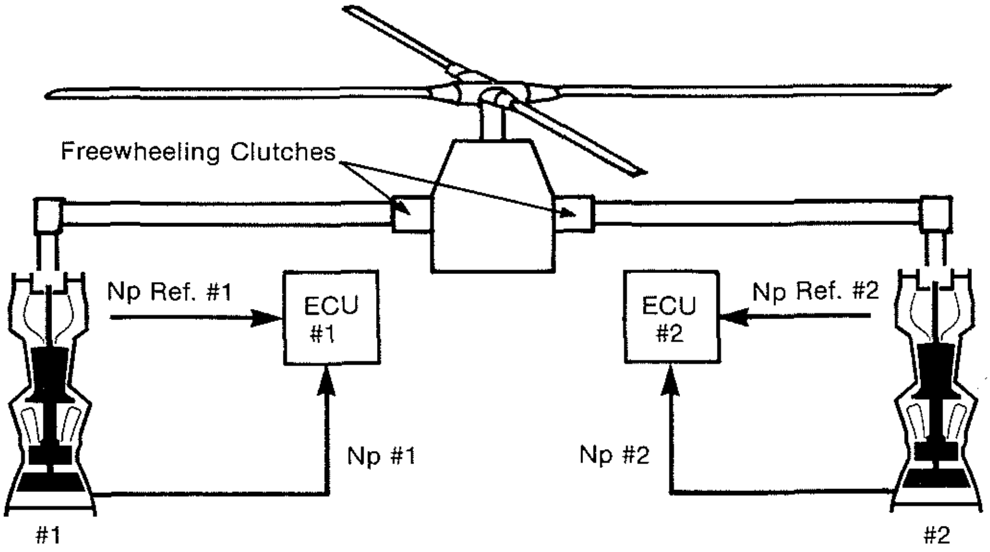


Figure 3

- Need for continual pilot adjustment during flight to maintain constant speed and accurate load-sharing
- Need for rapid pilot response following engine failure to obtain maximum power from the remaining engine
- Need for rigging adjustments on each engine or control system following component change, including a rigging check flight

On the other hand, isochronous systems do not have the above disadvantages but do require a load-share system.

Now one might ask "Are the trade-off's described about the droop system significant enough to warrant the complex task of load-sharing in a multiple engine isochronous system?" Since the isochronous concept does so much more automatically for the pilot, which in turn allows the pilot to pay more attention to the act of flying, then clearly, from the workload viewpoint alone, ischronous is the way to go. It is an advancement in the state of the art in which "automatic" and "computer" have become bywords.

Torque-Sharing as an Np Reference Bias

Now that the basic function of an isochronous governor and the inherent problem of load-sharing with this type of system have been discussed, the method selected to guarantee exact references for all controls in a multi-engine system can be explored.

The details of the T700 twin-engine torque-sharing system are shown in Figure 4. For discussion purposes, assume the #1 engine control has a lower speed reference. The power turbine speed reference ($N_{p\ ref\ 1}$) of the control system for engine #1 is compared to the measured power turbine speed (N_{p1}) of engine #1 with a resulting speed error (Err 1). Because $N_{p\ ref\ 1}$ is assumed not to be equal to the reference of the other engines' control system (N_p ref 2), a signal must be created that will cause the references to become equal. As previously mentioned, the signal used is the difference between the two torques which are algebraically combined as shown on Figure 4 (For engine #1 the difference is shown as Q_{error1}). After the signal has been converted by an appropriate gain from ft-lb to % rpm, it is then added to the speed reference (shown as Np ref 1 bias). This results in N_p reference values for both engines of precisely equal magnitudes. Thus, equilibrium will be reached with matched power turbine speeds and a small torque difference (split), usually between 1 and 2%. As the error in Np references causes an increasing torque difference between engines, the increasing torque difference causes a greater correction of Np reference until the two references are equal and the torque difference ceases growing.

Twin-Engine ECU Load-Share Function Block Diagram

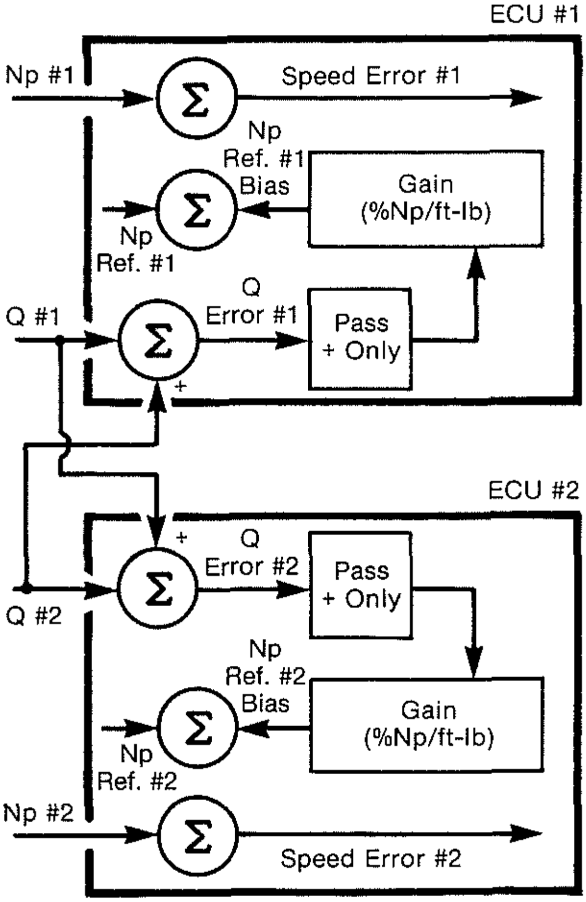


Figure 4

Specifically, as power is increased on the engine with the lower reference, so too, will torque increase. When the measured torque difference equals the difference between N_p references, the references will be matched (by the addition of the torque difference signal) and the torque difference will cease to increase.

To provide protection from a total power loss due to the loss of one engine, an authority limit is included that passes a signal only in the direction to increase the reference to match the higher engine.

Responding to only the higher engine, has been called "Match the Maximum" principle. This principle protects from power losses due to one engine reducing power to match the other engine through load-share. It also negates the philosophy that uses one engine as a "Master" and the other as a "Slave."

Typically, N_p reference errors between two controls is a half percent or less. Additionally, an authority limit has been selected to limit the amount of up-trim of an engine to high power induced by a failure of an engine on the other side.

System Benefit

Although torque-sharing is essential to the T700 control system for proper operation of isochronous, multiengine, single-rotor helicopter systems, it offers these additional advantages:

- Extending engine life by minimizing the power required from both engines
- Extending transmission system parts service life by equalizing engine torques
- Automatically matching torques which is commonly done by the pilot
- Providing additional assurance that the control system is operating properly when the torques are matched
- Reducing power recovery time in the event of engine malfunction

Extension of Two-Engine Load-Share to Three-Engine Load-Share

The extension of load-sharing from two engines to three engines is fairly straightforward.

Assume engine #1 is to load-share with engines #2 and #3. The torques of engines #2 and #3 are compared and the higher of the two torques is passed to the load-share circuit of engine #1 (see Figure 5). From this point, load-share becomes identical to two engine load-share where if engine #1 is of higher torque than the passed signal it will do nothing. If it is lower, #1 will trim up. Engine #2 and Engine #3 will have similiar logic. Since each engine compares itself to the maximum of the other two, the engine with the highest torque will ignore the other two engines regardless of which is higher.

Three-Engine Load-Share Functional Block Diagram

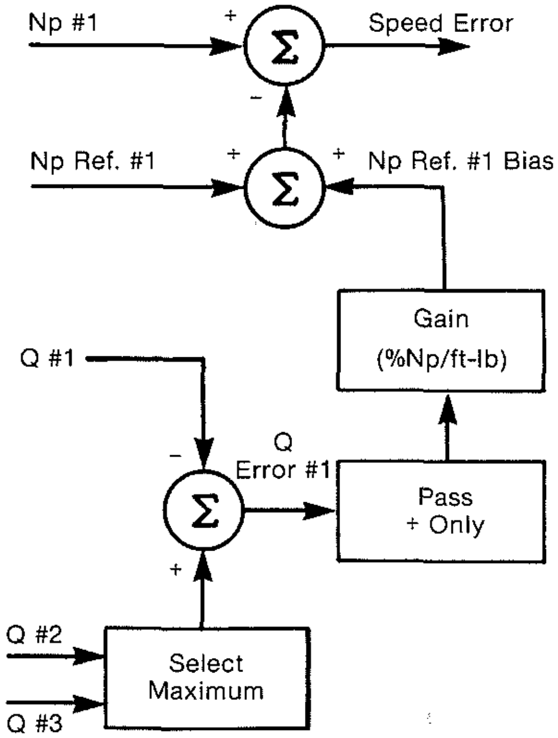


Figure 5

The other two engines, both with lower torque than the highest will trim up to the highest. Because of this method of load-sharing, the control system is completely independent of the number of engines operating at any time. Should one or two engines be shut down during operation, then the remaining engine(s) will not be affected because of the "Match the Maximum" principle.

The Need for Accessory Drive

Installation of the T700 in the EH-101 demands a very versatile control. Not only is two and three engine load-sharing required, but a specific mode of operation called accessory drive mode is also needed. This mode of operation allows for the use of one engine to support the aircraft accessories in place of an APU. The center engine was selected to support the accessory function, but all ECUs are to be universal (i.e. mounted on any of the three engines).

The first engine to be started would be done so electrically, and once started, would provide the power to support the aircraft generators and avionics as well as power to start the other two engines. Since this engine is to be decoupled from the rotor system during accessory drive operation while the other engines will be coupled, load-share must be deactivated.

The T700 is designed to power a rotor system with typical associated masses. It is, therefore, not enough just to disable load-share. The very light inertia of the accessory package presents a problem of stability. How these two items (load-share disabling and stability) were handled will be discussed in the next few paragraphs.

The Effect of Load-Share During Accessory Drive

While the center engine is operating in the accessory drive mode, it will be decoupled from the rotor system and carry a typical load of 50 to 100 HP. While it is in this mode at these power levels, it will also be in the governing mode so that any higher torque signal from either of the other two engines would normally cause the center engine to increase in an effort to load-share.

However, there would be no load to absorb the torque increase except the accessories. This would result in a maximum power turbine speed increase of up to 3% above reference (the load-share authority limit) and very undesirable effects when re-engaging the clutch. In order to function under these new operating conditions, the ECU is designed to ignore the load-share signals when it is placed in the accessory drive mode. Note that the engine in the accessory drive mode will be a completely different "system" than those providing power to the rotor system. This one engine will not effect the other, and the helicopter may be operated with the two outboard engines providing power to the rotor while the third engine acts purely as an APU holding constant aircraft generator speed.

Multi-Gain Control System and Its Effects on Accessory Drive

Consider again the basic design of the T700 control system for steady-state operation. The gain of the governor, which effects the engine's acceleration rate, was selected to be tailored for operation of a given rotor system. These dynamics proved unacceptable for stable operation of the light inertial load of autorotation and indicated the need for a control system with multigain capability that would automatically select the appropriate gain to suit the mode of operation.

The T700 basic control system is designed with this multi-gain capability. Gain selection is a function of either speed error or torque with selection being accomplished in the ECU. At low torque, which is the condition when the aircraft is in autorotation, the low gain is automatically selected. However, to prevent excessive rotor speed excursions, the control automatically switches back to high gain when the speed error exceeds reference by a specified amount. While in accessory drive, the low gain function is pre-selected by the pilot.

Summary

The basic T700 control system represents an advanced state-of-the-art control system which minimizes the pilot's workload through automation of many tasks normally performed by the pilot. It is a departure from purely hydromechanical control systems to more modern analog computers and electronic components.

The basic T700 control system was modified to provide three engine load-sharing as well as proper operation in the accessory drive mode. This modification was accomplished while maintaining the basic T700 control system features and without creating a unique control to be used only on the engine position which incorporates the accessory drive feature.

Controls with these design features have been successfully engine-tested in a cell by simulating a second and third engine, and by running a light inertia load similar to the accessory drive mode. Actual three-engine operation in an aircraft is the next step in development.

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