Technological Change from Analog to Digital: Aircraft Engine Control System

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Abstract: Brusoni, Prencepe, and Pavitt (2001) posited that the digitization of aircraft engine control systems in the early 1980s caused loose organizational coupling. During this period, the number of control parameters indeed increased significantly with the introduction of full authority digital engine control (FADEC). However, during the period categorized by Brusoni et al. (2001) as the hydromechanical (analog) generation, digital technologies such as analog electronic and supervisory controls were gradually introduced. Moreover, with regard to technological changes in aircraft turbofan engines and control systems, technological improvements in engine power systems were evident in the 1960s and 1970s in terms of the bypass ratio, overall pressure ratio, and turbine inlet temperature. Although engine power systems witnessed negligible technological innovation in the 1980s, control systems improved as the number of control parameters increased due to the advent of FADEC. Subsequently, in the 1990s, great technological strides were made in engine power systems. Hence, technological changes in engine power systems and control systems always occurred alternately. Brusoni et al.'s claim that the decline in organizational coupling was due to the even rate of technological change in engines and control

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systems or the predictability in their interdependence miss the mark in light of the transition history of engine and control systems.

Keywords: analog (hydromechanical), digital, aircraft engine control system, technological imbalance

1. Introduction

Brusoni, Prencipe, and Pavitt (2001) categorized aircraft engine control systems from the 1950s to the 1970s as “hydromechanical” (analog) and those from the 1980s to the 1990s as “digital.” Brusoni et al. (2001) described the scope for change in the organizational structure and knowledge of three companies¹ from the perspective of the evolution of control system technology. However, they barely mentioned the change in control system technology from analog to digital, nor did they focus on the changes in the engine power systems, which are associated with changes in control system technology. Referencing Brusoni et al.’s arguments, this study focuses on the transition of engine control systems from analog to digital and the associated technological changes in the power systems in order to review the technologies analyzed by Brusoni et al.

2. Technological Change of Engine Control System: From Hydromechanical to Digital

Brusoni et al. (2001) focused on the control systems of aircraft turbofan and turbojet engines. A turbojet engine comprises an air intake, a fan/compressor, combustion chamber, turbine, afterburner,

¹ The three companies are assumed to be Pratt and Whitney (hereinafter P&W), General Electric (hereinafter GE), and Rolls-Royce (hereinafter RR).

and tail nozzle. The pilot adjusts the position of the throttle lever to achieve the required thrust. The engine control system provides the necessary thrust by receiving the lever position as input and adjusting the fuel flow, thereby accelerating or decelerating the engine's revolutions per minute (RPM). Furthermore, it confirms whether the thrust corresponds with the pilot's intention and maintains the required thrust levels (Yoshinaka, 2010).

Compared with the digital system, the analog system could control only a limited number of items. The following section discusses the evolution of jet engine control technologies based on Endoh (2004), Sugiyama (2004), Sono (2008), and Yoshinaka (2010).

2.1. Hydromechanical control

The jet engine was first adopted as a source of thrust in aircrafts in the 1930s. Simple mechanical fuel controls comprising cams and levers were used in reciprocating engines, which constituted the majority at the time. The control required by jet engines was comparatively complex, and the existing technology was inadequate. Even in the case of early post-war turbojet engines, variables of fuel flow or bleed valve could only be controlled. Subsequently, advances in the level of precision and miniaturization in the areas of mechanics and oil hydraulics led to progress in the control technologies of aircraft engines. Till the 1970s, the operating mechanism for engine control merely consisted of a hydromechanical system that combined mechanics, such as the axis, gear, spring, bellows, cam, governor, and valve adjustment screws, with fuel pressure.

Hydromechanical control systems consist primarily of a fuel metering unit and an engine speed sensor. The fuel metering unit maintains even fuel pressure on both ends of the fuel metering valve by adjusting the fuel flow through the valve. This method of regulating fuel remains in use today, even though the mainstream technology has shifted to digital electronic controls, given the

number of components involved and the ease of manufacturing.

Engine RPM is detected through a mechanism in which the centrifugal force of a rotor governor directly connected to the engine detects the displacement of the cam using a combination of springs and a device to measure fuel pressure. With advances in steam engine technology, a simple mechanism for RPM detection was already prevalent and was employed in jet engines, with changes in its material composition and additional miniaturization. Furthermore, a three-dimensional cam was developed with a notched surface that facilitated scheduled fuel control and variable stator vane revolution.

Increased precision and miniaturization enabled the utilization of these systems in aircraft jet engines. However, the notched surface of three-dimensional cams did not facilitate the fine-tuning of the preset fuel schedule, and controlling it based on exhaust gas temperatures was difficult.

2.2. Analog electronic control

In the late 1950s and 1960s, sophisticated technology expedited the improvement in the performance of the engine power system, for example, through the use of afterburners in fan engines for military purposes and a double axis in fan engines for civilian use. Given such advances in technology, conventional hydromechanical control systems were no longer adequate for the sophisticated engines. This technological challenge was resolved by controlling variable tail nozzles in turbojet engines with afterburners or by employing transistors to control the fan rotation of double-axis fan engines, which prevented the exhaust gas temperatures from exceeding a set limit. Thus, an electronic control unit was added to the conventional hydromechanical mechanism. The analog electronic system was adopted because electronic sensors were commonly used to measure exhaust gas temperatures and fan rotation speeds.

Most analog electronic control devices complement hydromechanical control devices by transmitting output via a solenoid valve or torque motor. From the 1950s, the development of the torque motor in the U.S. enabled the input of a large variety of electronic sensor signals into hydromechanical control devices. The servo valve² enabled direct control of the fuel metering valves and actuators in subsequent digital control devices. The number of control parameters³ increased with the advent of the analog electronic control devices.

2.3. Digital electronic control (Supervisory control)

The 1970s saw improvements in high-density integrated circuit (IC) technology and its application in microprocessors, chip manufacturing, software languages, compilers, and simulation technology. Due to these advancements, digitization of the jet engine control technologies gradually progressed. Digitization brought about significant improvements in signal reliability. In addition, complex control logic could be incorporated due to large-scale memory devices and software development.

The first digitized system was called supervisory control (SVC). A basic engine control system utilized a hydromechanical device that was fine-tuned more accurately and optimally using SVC. The number of control parameters⁴ increased from conventional levels, which contributed to improvements in specific fuel consumption (SFC), thrust-to-weight ratio, and ease of maintenance. An advantage

² The servo valve is connected to a nozzle-flapper or hydraulic relay valve, which enables the control of a powerful hydraulic actuator by using minimum power.

³ Control parameters include main fuel, afterburner fuel, compressor variable stator vane angles, and tail nozzle area.

⁴ Control parameters include main fuel, afterburner core, afterburner fuel, fans, compressor variable stator vane angles, tail nozzle area, and compressor air bleed valves.

of this system was that SVC failure would not be fatal, and engine control could be maintained. However, given its large size and weight, the system was not widely adopted for civilian use. In contrast, its first practical application was for military engines (P&W's F100) in 1974, and it remains in use in many military engines.

2.4. Full authority digital engine control

Reliability of semiconductors improved significantly in the 1980s due to advancements in manufacturing processes and higher density in ICs. These improvements resulted in the B757s and B747s equipped with PW2037s and PW4000s manufactured by P&W, followed by the adoption of full authority digital engine control (FADEC) in civilian aircrafts. Subsequently, it was proven that the electronic devices were reliable under severe conditions, leading to their utilization in practically all civilian aircraft engines currently in use.

The FADEC system controls the engine's entire output digitally and has significantly increased the number of control parameters.⁵ It also employs a redundant system design in items such as its electronic circuit boards in order to meet reliability demands. The conventional twofold FADEC system employs one active channel for controls; controls can be switched over to the other standby channel in case of a failure. The interchange is conducted based on self-diagnosis through a built-in test and a watchdog timer, and the standby channel is constantly in operation to improve fault coverage. Data exchange between the two channels facilitates the detection of failure and system reconfiguration after failure.

After the 1980s, engines underwent a change in favor of a high

⁵ Control parameters include main fuel, ramjet fuel, air compressors, low-pressure turbine variable geometries, variable area bypass injectors, tail nozzle area, selector valves, intake ramps, intake bleed valves, intake bypass doors, turbine inlet plugs, and turbine outlet doors.

bypass ratio (BPR) and the promotion of variable cycle engines. In the process, control technologies became increasingly important to secure the competitive advantage of engine efficiencies.

3. Evolution of Engine Core and Control System

This article focuses on turbojet and turbofan engines. Brusoni et al. (2001) characterized the rate of change in engine and control system technology as “even/uneven.” However, changes in engine technology were not explicitly reviewed. Therefore, this section focuses on the representative products manufactured for civilian use by P&W, GE, and RR and examines the transition of the BPR,⁶ overall pressure ratio (OPR),⁷ and turbine inlet temperature (TIT)⁸ as parameters for engine technology. The improvement in SFC, which is the focus of turbofan engine development, requires advancements in the BPR, OPR, and TIT (Ishizawa, 2013; Kato, Pallot, Sugihara, & Aotsuka, 2013; Yoshinaka, 2010). BPR and OPR values considered are based on data from Japan Airlines (2005) and Rolls-Royce plc (2011), whereas TIT values are based on data from Yoshida (2007). The improvements in control device technologies also involve changes in the number of control parameters. The number of control

⁶ The ratio of the mass flow of air that enters the engine core (for burning fuel) to the mass flow of air that bypasses the core chamber and passes through the fan only. The lesser is the amount of air that passes through the core chamber (a high BPR), the lesser is the amount of fuel consumed for the same amount of thrust generated.

⁷ The degree to which air is compressed by a compressor. It is expressed as the ratio of pressure at the rear of the compressor to that at the front. The higher the pressure ratio, the better the SFC and efficiency with respect to thrust output.

⁸ The temperature of gas in the combustion chamber just before it enters the turbine in a turbine engine. In general, the higher the TIT, more is the power generated for a given amount of mass flow of air into the turbine. To maximize power, design and manufacturing technologies with respect to materials and configuration that can withstand high temperatures are required.

parameters is based on data from Endoh (2004).

In the 1950s, turbojet engines comprised the mainstream in engine technology. The turbojet engine mechanism involves the intake and subsequent compression of air. The turbine rotates by the energy of pressured, high-temperature gas generated by combustion; in addition, the gas exhaust is ejected rearward at high speeds in order to provide thrust. There is no bypass in turbojet engines. Turbojet engines at the time had an OPR of approximately 5–11, a TIT slightly under 1000°C, and either one or two control parameters (see Table 1). Given the noise and poor fuel efficiencies at cruising speeds, turbojet engines were eventually replaced by turbofan engines in civilian aircrafts.

The turbofan engine was first utilized in 1952 in RR's Conway. Turbofan engines are equipped with a fan in front of the core engine chamber. The total thrust comprises thrust generated by the engine in addition to the thrust generated by a fan that is driven by the air intake. Consequently, SFC improved significantly. Early turbofan engines had a low BPR of approximately 0.25–3 and an OPR of around 12–15. TIT remained unchanged at slightly under 1000°C. There were either one or two control parameters when the RR Conway debuted, but this number increased to 5 when an analog electronic control system was introduced in GE's CJ805-3B in 1958 (see Table 2).

From the late 1960s to the 1970s, a high BPR of approximately 4–5 and an OPR of approximately 24–30 were achieved. TIT increased from 1100°C to around 1300°C. The impetus that drove the development of engine technology was the development of wide-body planes, such as the B747, DC-10, L1011, and A300. Simultaneously, SVC was adopted for military use but was yet to be employed in the civilian sector, which still favored conventional analog electronic controls. Therefore, the number of control parameters was relatively unchanged compared with the prior period (see Table 3).

Table 1. Turbojet engines in the 1950s

	BPR	OPR	TIT	No. of control parameters
GE J47	0	5.4		2
P&W JT3C	0	11		1–2
RR Avon	0	7.5	Slightly under 1000°C	1–2

Table 2. Turbofan engines in the 1950s and 1960s

	BPR	OPR	TIT	No. of control parameters
GE CJ805-3B	3	13		5
P&W JT3D	1.5	12.5	Slightly under 1000°C	1–2
RR Conway	0.25	15	Slightly under 1000°C	1–2

In the early 1980s, the reliability of digital technology improved to a level that was acceptable for civilian application, prompting the use of FADEC. BPRs, OPRs, and TITs improved marginally. TIT levels were unchanged up to the mid-1990s, and temperatures of around 1300°C were considered the upper tolerance limit. With the introduction of FADEC, the number of control parameters increased significantly to around 11 (see Table 4). As a result, long cruising distances became possible for wide-body planes such as the B747, B767, and MD-11.

Table 3. Turbofan engines in the 1970s

	BPR	OPR	TIT	No. of control parameters
GE CF6-50	4.3	31	1300°C	2
P&W JT9D	5.0	24	Slightly above 1100°C	3
RR RB211-524	4.4	28.0–29.0	Slightly above 1200°C	3

Table 4. Turbofan engines in the 1980s

	BPR	OPR	TIT	No. of control parameters
GE CF6-80C2	5–5.3	30	Slightly over 1300°C	11
P&W PW4000-94	4.8–5.0	27.5–32.3	Slightly under 1400°C	9

Note: FADEC was adopted in the RR RB211-524 engines employed in the B747-400 models.

Till the 1980s, only wide-body planes with three or four engines were capable of long cruising distances. However, in the 1990s, demand emerged for engines with higher thrust performance, better fuel efficiency, and improved reliability so that long-distance flight could be accomplished by wide-body twin-engine aircrafts. Due to improvements in engine cooling technologies, such as the development of super alloys for fan blades, thermal barrier coating, three-dimensional blade airfoil, film cooling, and transpiration cooling, manufacturers were able to develop engines with a BPR of

Table 5. Turbofan engines in the 1990s

	BPR	OPR	TIT	No. of control parameters
GE GE90-94B	8.3	40	1500°C	11
P&W PW4000-112	7	38	1500°C	
RR Trent800	6.2	40	1500°C	

6–8, an OPR of 40, and a TIT of around 1500°C (see Table 5). Control systems using FADEC, which was already prevalent, were able to adapt to the changes in engine technology; these engines were placed in planes such as the B777 and A330.

4. What Does Brusoni et al. (2001) Focus On?

As described in Section 2, what Brusoni et al. (2001) refer to as “hydromechanical” corresponds to the hydromechanical analog electronic control and SVC from the 1950s to the 1970s, and what they refer to as “digital” corresponds to FADEC subsequent to the 1980s. Therefore, Brusoni et al. (2001) regard the introduction of FADEC in the 1980s as digitization.⁹ Although control parameters

⁹ Conventional studies have claimed that the introduction of new technologies proceed smoothly when there is some form of effort to promote integration, such as process overlap or close communications between the concerned organizations (e.g., Iansiti, 1997). On the other hand, others argue that technological development should be pursued separately in cases where there is drastic change or where the integration of technology is not encouraged in the existing market or by its customers, given the uncertainties associated with a drastic technological change (Yasumoto, 2006). Furthermore, cost and quality considerations are also important during the introduction of new technologies (e.g., Ichikohji,

increased significantly with the adoption of FADEC, the introduction of digital technology in control systems also gradually progressed during this “hydromechanical” period.¹⁰

As shown in Section 3, although engine BPRs, OPRs, and TITs significantly improved from the 1950s to the 1970s, not much improvement was seen in control technologies during this period. Conversely, in the 1970s and 1980s, while progress in engine technology was relatively stagnant, control devices advanced significantly with the introduction of FADEC. However, increased sophistication in design, manufacturing technology, and materials technology in the 1980s and 1990s again resulted in improvements in BPRs, OPRs, and TITs.

The history of engine power systems and control devices is characterized by significant advances in one while the other stagnates. Therefore, the argument put forth by Brusoni et al. (2001)—the degree of organizational coupling decreases¹¹ due to the even rate of technological change among components, given the maturity in engine control technology or the predictability of product-level interdependencies—seems to have missed the mark. Instead, there may have been other reasons for the decrease, such as management crises¹² or reduction in development risks.¹³

2012).

¹⁰ Brusoni et al. (2001) regard the transition from hydromechanical to digital as a radical shift in technology. It is likely that Brusoni et al. considered the introduction of FADEC as a disconnected technological shift (Shintaku, 2005) or a rupture in the trajectory of technological progress (Takahashi, Shintaku, & Ohkawa, 2007, 2013).

¹¹ Brusoni et al. (2001) use a matrix developed by Orton and Weick (1990) to explain the shift from tightly-coupled organizational forms to loosely-coupled forms or from loosely-coupled forms to a decoupled form.

¹² RR was placed into receivership in 1971, nationalized until 1987, and subsequently privatized again.

¹³ Since the 1990s, the number of suppliers involved in development and the scope of their involvement expanded at all three companies under the name of Risk & Revenue Sharing Partners (RRSP). Additionally, a joint venture between GE and P&W, Engine Alliance (established in 1996),

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