AEROSPACE INFORMATION REPORT

AIR5372™	REV. A
Issued 2003-03 Revised 2014-07 Reaffirmed 2024-05 Superseding AIR5372	

(R) Information on Brake-By-Wire (BBW) Brake Control Systems

RATIONALE

The document has been reviewed and updated to the current state of the industry as part of a periodic document review schedule.

AIR5372A has been reaffirmed to comply with the SAE Five-Year Review policy.

FOREWORD

Aircraft braking systems provide the pilot with a means of controlling the deceleration of the aircraft through the use of brake pedals, autobrake, and usually an emergency braking system. Before the advent of BBW systems, aircraft braking systems used hydraulically actuated brakes that were connected to the pilot's and copilot's brake pedals through mechanical cables, static hydraulic systems or linkages. In BBW systems, electrical sensors and wires replace the mechanical methods. Sensors are used to measure the pilot's command at the brake pedals and a Brake Control Unit (BCU) (sometimes referred to as a Brake System Control Unit (BSCU) or Electronic Control Unit (ECU)) sends out signals to electric or electro-hydraulic components that control the braking force. The other main functions that are provided by an aircraft braking system, independently of whether it is BBW or mechanically operated, are antiskid, autobrake, parking brake and emergency braking.

BBW systems are generally required to have a redundant means of applying brakes. These alternate braking or emergency braking systems usually rely on the mechanical levers and linkages that they seek to eliminate, increasing numbers of all electric BBW systems have been implemented over the past 10 years. These alternate braking or emergency braking systems usually rely on a dissimilar technology to alleviate common mode failure concerns.

In addition to the traditional electro-hydraulic brake actuation methods, completely electrically actuated (these are non-hydraulic systems that use electric motors, gearing and linear actuators) braking systems are also covered within this document.

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1. SCOPE

This SAE Aerospace Information Report (AIR) describes the design approaches used for current applications of aircraft Brake-by-Wire (BBW) control systems. The document also discusses the experience gained during service, and covers system, ergonomic, hardware, and development aspects. The document includes the lessons that have been learned during application of the technology.

Although there are a variety of approaches that have been used in the design of BBW systems, the main focus of this document is on the current state of the art systems.

1.1 Purpose

Although the designers and users of aircraft BBW systems are familiar with their functions, features, components, and limitations, there is no readily available documentation that describes the field in breadth. This document seeks to address this need by providing an overview of the current state of the art with respect to function, components, and issues.

The experience that has accumulated from existing BBW systems is presented as an aid to those who are embarking on the design of a new application or who are preparing specifications for a BBW system.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained (for example, refer to FAA FAR 25.735 or EASA CS 25.735; however, other regulatory agencies may apply).

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

AS483B Skid Control Equipment

ARP862 Skid Control Performance

AIR1064 Braking System Dynamics

ARP1070 Design and Testing of Antiskid Brake Control Systems for Total Aircraft Compatibility

AIR1739 Information on Antiskid Systems

ARP1907 Automatic Braking Systems

ARP4754A Guidelines for Development of Civil Aircraft and Systems

AIR5937 Information on Electric Brakes

AS8584 Brake Systems, Wheel, Military Aircraft

2.1.2 RTCA Publications

Available from RTCA, Inc., 1150 18th Street, NW, Suite 910, Washington, DC 20036, Tel: 202-833-9339, www.rtca.org.

RTCA/DO160 Environmental Conditions and Test Procedures for Airborne Equipment

RTCA/DO178 Software Considerations in Airborne Systems and Equipment Certification

RTCA/DO254 Design Assurance Guidance for Airborne Electronic Hardware

2.1.3 FAA (Federal Aviation Authority) Publications

Available from www.acquisition.gov/far.

FAR 23.735 Brakes and braking systems

FAR 25.735 Brakes and braking systems

2.1.4 EASA (European Aviation Safety Agency) Regulations

Available from European Aviation Safety Agency, Postfach 10 12 53, D-50452 Cologne, Germany, Tel: +49-221-8999-000, www.easa.eu.int.

CS 23.735 Brakes and braking systems

CS 25.735 Brakes and braking systems

3. FUNCTIONS AND REQUIREMENTS

3.1 General Requirements

The requirements for a BBW system should specify safety, functionality and performance parameters. The typical functions of a manned vehicle BBW system are manual brake pedal control, autobrakes and antiskid. Also, some form of alternate, parking, and/or emergency brakes are usually included in order to meet safety or operational requirements. (For example, an alternate 'park/emergency' brake may be part of the architecture to lower the criticality and cost of software from RTCA/DO-178 Level A to Level B.) Performance requirements include system response, braking efficiency (including the method of measuring efficiency), stability, reliability, and degraded operation. Reliability includes consideration of the level of redundancy and system separation needed to comply with customer requirements and regulations.

For brake by wire control, careful consideration needs to be given to failure modes within the brake control system that could result in applying braking when not commanded, i.e., 'uncommanded' braking. Uncommanded braking is often an unacceptable failure mode, and the system must be engineered properly to avoid this failure mode. (Uncommanded braking that occurs on takeoff is usually considered a catastrophic event.)

3.1.1 Unmanned Vehicles

In unmanned vehicles, many of the same functions exist as manned systems. However, brake pedals are replaced by computer commands and those commands can come from a human external to the vehicle or autonomously. Although comfort issues (ergonomics) do not apply, differential control is more important as are airframe dynamics. Without a pilot in the loop, who is actually seated in the aircraft, dependence on sensors for feedback control becomes much more important. Although the aircraft lacks a crew and passengers, safety levels have generally remained high.

3.2 Pedal Braking

Usually, the primary requirement for a BBW control system is to measure the pilot’s and copilot's brake pedal displacement (left and right) and command a proportional brake clamping force to decelerate the aircraft. (On unmanned aircraft, commands come from autonomous control or ground-driven commands.) Pedal displacement is in the form of ankle rotation; therefore it is usually measured as an angular displacement in degrees, and the pedal force (pilot ergonomic feel) increases proportionally with increased braking levels. The pilot should be provided with a system that allows deceleration of the aircraft in a smooth and continuous manner by applying the brake pedals. The system should respond to the pilot’s inputs based on the perception of aircraft deceleration in a way that feels natural. In order to close the loop between the pilot’s intent and the response of the aircraft in a proportional manner, the BBW system design must account for the non-linear natures of the system inputs and outputs. The basic ergonomics of pedal force and travel, and the relationship between brake input, clamping force and output torque must be well understood. Also, the same pedals that apply braking are used for rudder control. The kinematics of the pilot’s and copilot’s rudder and brake pedals must assure minimal side effects when operating either or both mechanisms.

Differential braking where the right brake pedal controls the brakes on the right side of the aircraft (right main landing gear brakes), and the left pedal controls the brakes on the left side (left main landing gear brakes) is a basic requirement. This allows the pilot to control aircraft heading using the brake pedals. This is often referred to as differential braking. It may be required to include this feature to achieve acceptable ground directional control in the event of a nose wheel steering or rudder system failure.

3.2.1 Pedal Ergonomics

The brake pedal movement and resistance forces are configured to provide a feel proportional to the desired output, which is generally brake pressure. However, the physical sensation or feedback given to the pilot during pedal control is that of the resulting aircraft deceleration forces. The use of brake pedal position to generate the input command is typically a carryover from mechanical actuation methods, such as master cylinders and hydraulic brake metering valves, where the stroke is an inherent part of the control mechanism.

As the confidence and comfort level with BBW system ergonomics has been proven, the trend has been to reduce overall pedal travel and forces to allow easier actuation. Aircraft brake pedal ergonomics are independent to motion of the rudder pedal, which translates fore and aft carrying the brake pedal with it. The rudder pedal is normally operated through leg motion, while the brake pedal or “toe (ankle) brake” is applied by rotating the foot about the ankle joint. This approach limits the forces and range of motion that can be comfortably and controllably applied. In contrast, ground vehicles use “hanging” type pedals that allow much easier operation because the brakes are applied by pushing forward with the leg.

The level of resistance that the brake pedal provides to the pilot as a function of pedal stroke is referred to as “feel.” Usually, pedal feel will be set up to emulate conventional systems that provide an increasing level of resistance as the pedal is rotated through a stroke of up to 20 degrees. However, there are some systems where very little stroke provision is made and pedal forces are the predominant parameter for control. Various ergonomic specifications and experience on simulators and in-service systems provide guidelines for pedal curves that effectively match pedal force and position for optimal feel. Section 6.1.1 lists the lessons learned on brake pedal operating characteristics. Figure 1 shows the consensus of the most recent experiences with pedal ergonomics, which also forms the basis for similar updates in AS8584.

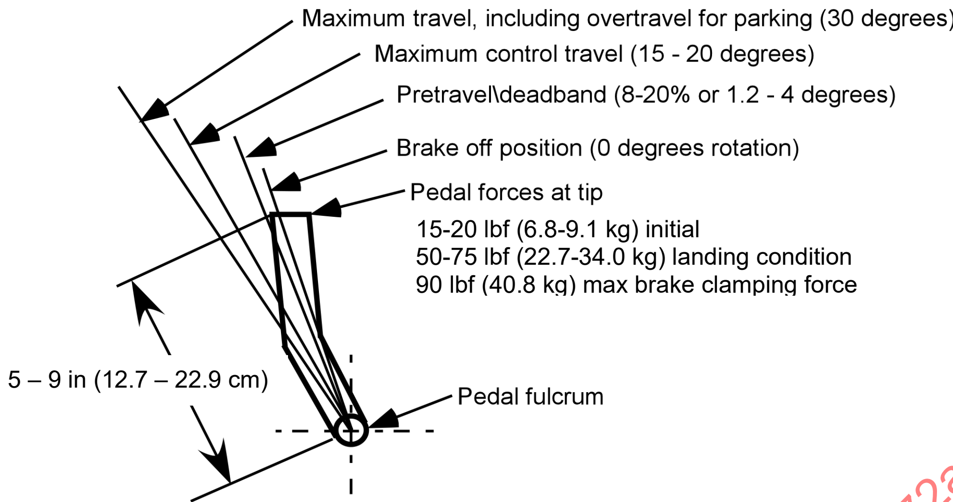

FIGURE 1 - BRAKE PEDAL ERGONOMICS

3.2.2 Pedal Laws

The relationship between pedal position or force and brake clamping force is defined by a “pedal curve” or “pedal law.” The slope of the curve represents the gain of the brake pedal system at any point on the curve. The goal of the pedal law design is to enable control of vehicle deceleration in a predictable and proportional fashion. If a pedal law is directly configured for deceleration, as opposed to the more conventional brake clamping force (or hydraulic pressure) control, then attention should be given to providing predictable feel and directional control as well as deceleration. The selection of an optimum pedal law requires the designer to have a good empirical knowledge of brake behavior and pilot ergonomics. This challenging area, as much art as it is science, has been the subject of continued discussion and debate. Historically, most systems have evolved with a ‘segmented’ (sometime referred to as non-linear) curve where low initial gain is used at low pressures when braking levels are insufficient to initiate skids. Antiskid activity can result in sudden large clamp force reductions that require the metering system to have a high gain in order to respond promptly. Non-linear-gain pedal curves have proved helpful in controlling torque-sensitive brakes.

The relationship between pedal travel, pedal force, and brake clamping force can be configured at the pedal input device for the desired gain relationship, and the gain and curve can be tailored in the control circuits of the BCU. Alternatively, the hydraulic valves can be configured to provide non-linear gain characteristics as shown in Figure 2. The electrical control circuits can be tailored for optimal gain characteristics more readily than the pedal transducer. The level of torque produced by a brake in response to a given brake clamping force varies greatly with the design, lining (brake) material used, physical condition, humidity factors, usage and temperature of the friction elements. In addition, the slope of the brake clamping force versus brake torque curve varies with speed. Since brakes are generally designed for maximum energy and minimum coefficient conditions- at low speeds and light clamping force levels, the change in torque for a given clamping force increment tends to be larger than that produced at high speed and high clamping force. The low speed region of pedal control is also called “taxi braking”, where aircraft behavior depends primarily on system and pilot interaction for smooth control. The clamping force onset should be as smooth as possible, especially with carbon brakes with their high torque gain at various brake temperatures. At brake-metered pressures above roughly one third of system pressure, the gain can be increased continuously or in two or more linear gain changes to allow full clamping force to be achieved rapidly when necessary. Step changes in brake clamping force may need to be avoided. Pedal curves and control laws that fail to account for these known non-linear relationships lead to complaints of brake sensitivity or “grabby brakes” from pilots.

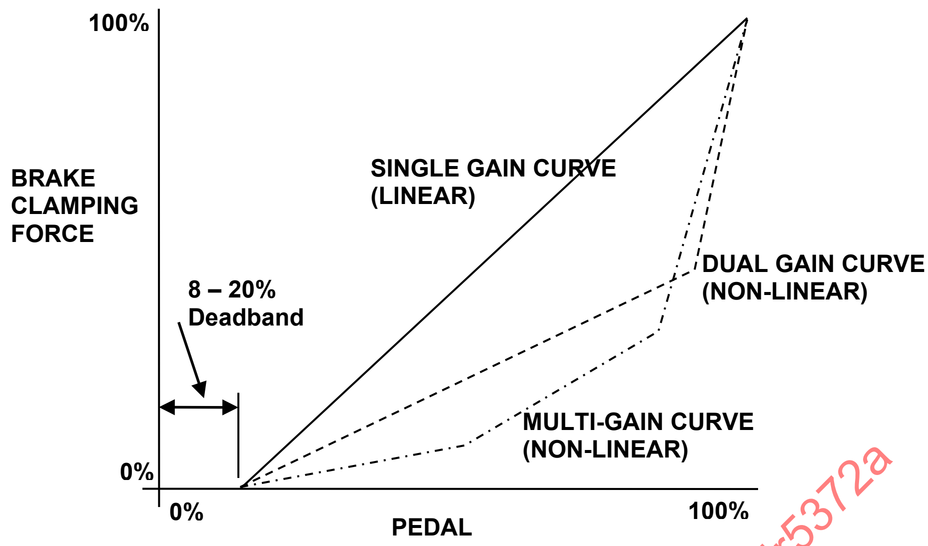

FIGURE 2 - BRAKE CLAMPING FORCE VERSUS PEDAL POSITION

3.3 Antiskid Function

The antiskid function is an essential feature of the brake control system (refer to AIR1739, ARP1070, ARP862, and AS483B for more information and regulations FAR 23.735, 25.735, CS 23.735, and CS 25.735). Control of the aircraft during braking cannot easily be achieved without antiskid protection when the nominal torque/drag output is greater than the tire-runway can support due to the characteristics of ice, rain, or any contamination. In addition, the inclusion of an antiskid system significantly improves stopping efficiency and cornering capability, and protects against hydroplaning, wheel lockup and tire skid-through. An antiskid system measures the speed of each wheel and uses the information to reduce the brake clamping force to the brake of any wheel that is on the 'verge' of skidding. Antiskid systems are usually considered to be 'passive' in that they can only reduce brake clamping force and cannot increase clamping force to a level above that commanded by the pilot pedal inputs or autobrake commands.

The antiskid function in a BBW system can be integrated into the system since it can be provided by the basic BBW control elements. The antiskid control algorithms can be implemented in the BBW BCU and control can be provided through the BBW control valve. Usually an Electro Hydraulic Valve (EHV) is associated with each main wheel's brake; however in some cases a single valve may control multiple brakes – as in paired wheel control braking. This may be in normal mode or in a degraded mode of operation. In an electrically actuated braking system, control is provided by the BBW BCU modulating the position or force commands to the Electrical Mechanical Actuators (EMAs).

3.3.1 Skid Control

Modern antiskid systems measure the speed of the wheel that is being braked and compares it with the synchronous speed. The synchronous speed is the speed that an 'unbraked' wheel, or some other reference source, would have.

When the brake is applied, the tire slips or may stretch at the point of contact with the runway, which has, for the wheel speed, the same effect as increasing the diameter of the tire. This causes a difference or 'slip' in measured wheel speed compared to synchronous speed. The antiskid control laws may be designed to detect the slip value or use the peak of the 'mu-slip curve' at which the tire has stretched to the point where it actually reduces adhesion with the runway surface and begins to go into a skid. The control system provides a brake clamping force reduction signal to the brake control valve or EMA to keep the wheel on the verge of a skid so that stopping efficiency and cornering capability are maximized. A fully modulating antiskid function can provide enhanced control for optimized braking performance on contaminated runways. The system seeks to maximize the use of available tire-runway friction coefficient (Mu) regardless of aircraft speed, weight, or runway conditions, while optimizing tire wear. Sophisticated control laws, feedback of valve current, brake clamping force (or hydraulic force) and nonlinear computing elements are combined to result in an adaptive control system.

The antiskid system must be designed to be compatible with the dynamic behavior of the aircraft structure (refer to AIR1064). Dynamic coupling between the antiskid system and main landing gear can lead to problems with landing gear strut oscillations and pitching of truck (more than two wheels/brakes on a gear) beams. The wheel speed transducer must have sufficient resolution to support the frequency response needed for dynamic compatibility.

3.3.2 Hydroplane Protection

On very slippery or highly contaminated (flooded) runways, the wheels may fail to spin up properly and may lock up as a result of hydroplaning or very low friction runway surfaces. These situations, and the potential for tire damage (such as tread rubber reversion), are avoided through the use of hydroplane protection logic. Protection schemes may use an external reference such as IRS (Inertial Reference System) ground speed, other aircraft status signals or an ‘unbraked’ nose wheel speed to detect gross differences between wheel speed and aircraft speed. For example, when deep and sustained skids occur the brake control valve may be commanded to zero or a very low brake pressure. When the wheel velocity returns to an acceptable percentage of the aircraft reference speed the brake valve is enabled to follow commanded or antiskid levels of brake pressure. Other logic signals are sometimes used to turn the function off in the air so that the control valves are not being continuously commanded to reduce pressure.

3.3.3 Touchdown Protection

If the brakes are applied before the aircraft touches down, the antiskid system will not detect any wheel speed, as the wheels will not spin up upon touchdown. Therefore, many modern brake-by-wire systems disable braking during the touchdown phase of the flight. This touchdown phase may be determined by the aircraft configuration and landing gear signals.

3.3.4 Locked Wheel Protection

The majority of antiskid systems compare the speeds of different wheels and command a full clamping force release to the brake of any wheel that is moving significantly more slowly than its neighbors, or a derived aircraft speed. Because of the tire, wheel and brake inertia, and unusually low runway friction scenarios, achieving rotation may take a relatively long time. Locked wheel protection generally intervenes in antiskid activity to aid in the recovery from a deep skid that can occur in adverse conditions.

3.4 Gear Retract Braking

To avoid the condition where a tire with loose flailing tread can cause damage inside the landing gear’s bay (wheel well) and avoid gyroscopic forces during retract, it is common practice to apply the aircraft brakes for a short time after takeoff to bring the wheels to a stop before retracting the tires into the wheel well. This is also done to reduce the vibration from freely rotating brake, wheel and tire assemblies. The function is usually achieved automatically by applying brake clamping force as part of the gear retraction sequence. In a BBW system, the braking command can be generated by the BCU on the basis of the signals it receives from the landing gear lever or other logic inputs. The BCU is designed so that antiskid is not active during gear retraction. The BCU can also be used to control the deceleration rate of the wheels during gear retract braking so that the inertia loads imparted to the landing gear are reduced.

3.5 Parking Brake

For commercial aircraft, the airworthiness regulations require a parking brake that once set by the pilot will continue to hold the aircraft for an extended period without any further attention or the need for an active source of hydraulic power (refer to FAR 23.735, 25.735, CS 23.735, and CS 25.735). For hydraulic brakes, the most common method in use provides a way of applying and trapping hydraulic pressure in the brakes. This requires a means of storing hydraulic pressure such as an accumulator, and it also requires that the hydraulic components of the parking brake system have a low rate of leakage to the return side of the hydraulic system. Parking brake pressure can be applied through the pedals, through a hand lever, or through an electrically controlled valve. Parking can be on-off type control, modulating, or it can simply provide low leakage shutoff for one or more parts of the conventional system. The parking brake system can also be used for applying the brakes when the primary braking system has failed. In this case, a proportional method of control is preferable to an on-off valve or electrical switch, especially when the antiskid function is not available.

With electric brake systems the parking requirements are the same therefore, the park brake function may lock the mechanical portion of the EMA, not allowing the applied brake force to be released. The major differences being that active power is required to release the park brake and some modulation may be required to account for thermal effects during brake cooling.

The parking system may use some of the same components as the normal system, or may be provided by separate components. Some parking systems function only on one part of the system in the case of a redundant 'two-system' configuration, while others may include parking control on more than one system. These considerations are part of the system architecture definition and subsequent component selection.

3.6 Autobrakes

Aircraft equipped with BBW systems often have an independent, automatic means of brake application that can be selected by the pilot as an alternative to using the pedal brakes. (Additional information can be obtained from ARP1907.) These 'autobrake' systems typically use EMAs or electrically operated hydraulic valves to control braking force, the same control equipment as the normal BBW system, and the BCU uses a deceleration signal from the aircraft IRS or generates one based on wheel speeds to decelerate the aircraft at one of a range of constant levels selected from a control panel. Pilots of aircraft equipped with autobrakes generally use the system during the landing, and then revert to the pedal brakes for taxi operations. A Rejected Take-Off (RTO) feature, which automatically applies full brake clamping force when the pilot aborts a take-off at high speed, is also a common feature of autobrake systems. (An autobrake system could also deploy a tailhook, if fitted, in an 'RTO-like' event.) An autobrake function can be added without the need for extra EMAs, control valves or shuttle valves by arranging for the existing equipment to be commanded by either an autobrake controller or the brake pedal input, depending on which is selected. For autobrakes, it is important for the EHVs to be accurate to ensure that equal braking force is applied to all the aircraft brakes. This is also true of EMAs but less so since each EMA is independently controlled. (On hydraulic brakes the hydraulic pressure is the same for all pistons.) This is because there are usually multiple EMAs on a single brake – so any variation is shared among several elements. Unbalanced brake clamping force and differences in the torque gains of the brakes can lead to asymmetric braking, and this would require pilot intervention to keep the aircraft headed straight on the runway. Yaw correction can be provided by the autobrake system acting on the differential braking or even the nose gear steering system.

3.7 Other Features

Since brake control is electrically implemented in a BBW system, making changes to the logic in the control unit and adding electrical signals from other systems or sensors can easily incorporate additional functions and features (refer to ARP4754A and other references in Section 2). Augmented directional control to assist in steering, or nose wheel braking may be provided. Changes such as these require considerable analyses and testing to avoid undesirable or unsafe side effects to the system as a whole.

It is worth noting that although software has the appearance of being easily changed; in reality BBW software is usually of a critical enough level to warrant an extensive software process and testing overhead (refer to RTCA/DO-178). In the case of changes to airborne electronics the same is true (refer to RTCA/DO-254).

3.8 System Safety, Reliability and Accuracy

Usually transport airplane airworthiness regulations, or the customer, require the brake system and associated systems to be designed to stop the aircraft safely after a single failure has occurred. The failures that should be considered are the malfunction of an electrical, hydraulic, pneumatic, or mechanical component and the loss of a single source of electrical or hydraulic power. Other significant failures are the application of brakes during the high-speed end of takeoff, and asymmetric braking.

The system must be configured to reduce the probability of failures to an acceptable level. For safety related failures, the level of hazard associated with each possible functional failure should be assessed, and an acceptable functional failure probability assigned accordingly. For economic failures, such as the inability to dispatch the aircraft because a function is unavailable, a similar assessment can be performed. The architecture of the system should then be analyzed to determine if the required probabilities of failure are supported by the design. Where the consequences of single failures are unacceptable, redundant elements may be added or the system architecture modified until the required level of safety is achieved. It is not uncommon to add components such as hydraulic pressure transducers to detect uncommanded brake pressure from an EHV, for example, and then to add a solenoid shutoff valve in the hydraulic pressure line to the EHV so that it can be isolated.

Confidence in the reliability predictions for mechanical components has been established over a long history of use, whereas reliability predictions for electrical and electronic components are considered to be less dependable. For BBW systems and electric brakes with their dependence on electronics, this has driven a more conservative approach requiring higher levels of redundancy. Unlike mechanical brake systems, BBW systems are susceptible to the effects of electromagnetic interference (EMI), high intensity radio frequency (HIRF) and lightning (potentially direct and indirect effect). The advent of powerful radar systems for air traffic control and military surveillance has increased the levels of EMI HIRF in the environment that a system may be exposed to. The need to recover from or operate during exposure to electrical radiation has led to an increase in the complexity of the electronic filters used for protection. The associated increase in parts count demands a robust design approach to avoid a reduction in reliability and the need for additional redundancy.

It's desirable to achieve system reliability requirements without the need for routine maintenance checks. This requires the system to be free of undetectable failures and this is generally achieved by the use of monitoring components. Monitoring devices such as hydraulic pressure sensors, electric current sensors, motor speed or force sensors are often included as part of the control system to aid in the isolation of failures and facilitate system functional testing. These diagnostic aids must be implemented carefully to minimize their effect on overall system reliability. The reliability can also be improved by self-test routines, such as a pre-landing test in the control software. If multiple paths (different means to apply braking) exist, e.g., normal – emergency or normal – alternate, then either testing both systems or alternating operation of both systems assures latent failures or component failures are minimized. Also maintenance operations such as hydraulic brake bleeding must also be facilitated by the design.

Pressure, force or other sensors are often used to augment the accuracy of the valves or EMAs that are used for controlling the individual brake forces. For example, pressure readings are used by the BCU to ensure that all the brakes on a given side of the aircraft are at the same pressure and hence doing approximately the same amount of work. Similarly in electrically actuated braking systems monitoring force, motor speed or the motor current applied to the EMA is used to ensure balanced forces are being applied. Without this corrective feedback, BBW systems could have significant differences in the energy absorbed by the brakes.

4. SYSTEM ARCHITECTURE

The main components of a typical system include a BCU, pedal input devices, wheel speed sensors, electrically controlled hydraulic valves or EMAs, and in the case of electric brakes an EMAC (Electro-Mechanical Actuator Controller). The BCU provides signals to the aircraft flight displays for indication of system status and usually communicates with the On-board Maintenance System (OMS) (sometimes also referred to as Central Maintenance System (CMS)) to facilitate troubleshooting. In addition to the pedal inputs, the system may receive signals from the throttles, landing gear lever, Weight-On-Wheels (WOW) signals, landing gear downlock signals, IRS, and other sensors that provide information about the operational mode of the aircraft. Wheel speed signals from the BCU may also be provided to other aircraft systems such as landing gear system and\or nose gear steering, spoiler, and thrust reverser systems for use in enabling logic.

The architectures of BBW systems include partitioning schemes for limiting the effects of component failures, the loss of an electrical system, and the loss of a hydraulic source. Dual cavity brakes, redundant EMACs, dual hydraulic systems, hydraulic accumulators, emergency electrical power and combinations of these methods can provide redundancy of the electrical and hydraulic systems. Hydraulic shuttle valves can be used to maintain separation between independent hydraulic systems to minimize the transfer of fluid (other means are also available). Fuses are installed to limit the loss of hydraulic fluid and possible loss of the associated hydraulic system if a leak develops. Partitioning is also used in the BCU and here the approach is to use multiple, independent control channels, and redundant inputs and outputs for signals. Modern BCUs are digital controllers, although analog controllers are in use, and some microprocessor – based systems use analog control for back-up channels.

It is common to incorporate some segregation into a BBW system. For example, this may be implemented by creating a BBW architecture that is segregated by 'Inboard-Outboard', 'Primary-Secondary', Fore-Aft, etc. The Inboard – Outboard system has one BCU channel controlling the inboard brakes and another totally independent channel controlling the outboard brakes. With the loss of one channel the aircraft still has half its brakes. In a Primary – Secondary system one channel controls the aircraft's brakes, and if it fails the backup (secondary) system takes over all the aircraft's brakes.

Others architectures may include an 'active-active', where both channels are operating, but only one channel is actually in control of the output and 'control-monitor' where one system operates and a different system monitors its operation to determine if it is failing. Also, distributed control systems have been used where functionality is spread across several processing elements.

These same schemes are applicable to electric braking systems. However, other interleaved schemes are more practical with electric brakes than with hydraulic systems. This is because of (1) the ease of routing power and (2) the ability to raise the EMA forces beyond 'typical maximums' for short periods of time.

In the following figures, the BCU functionality is located in what the figures refer to as the Electronic Control Unit. Figure 3 shows the basic components that form the control loop of a BBW system, Figures 4 through 8 show the range of architectures that are in existence. These figures show primarily variations of Inboard – Outboard systems, and Table 1 lists examples of EHV BBW applications. The following abbreviations are also used: SV (Solenoid Valve), PS (Pressure Sensor), F (Fuse), W (Wheel speed sensor), and POV (Park Operated shutoff Valve).

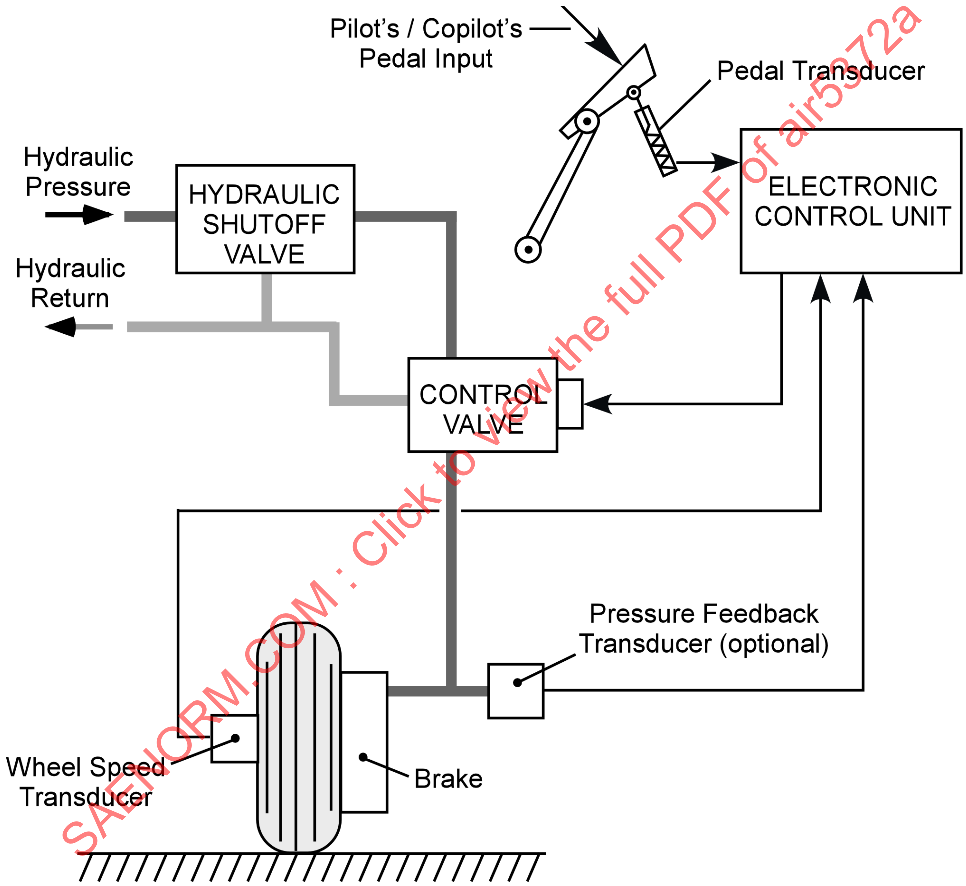

FIGURE 3 - BRAKE-BY-WIRE SYSTEM BASIC COMPONENTS

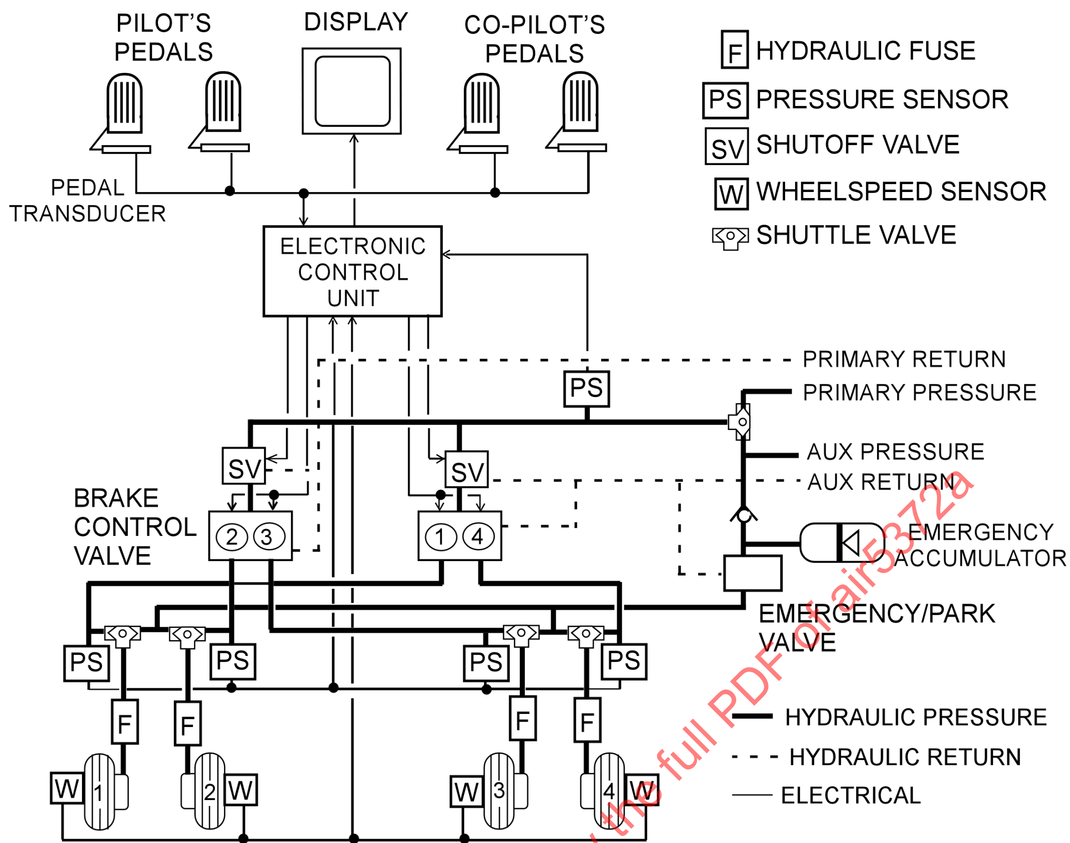

FIGURE 4 - SINGLE CAVITY BRAKE WITH SINGLE HYDRAULIC SYSTEM

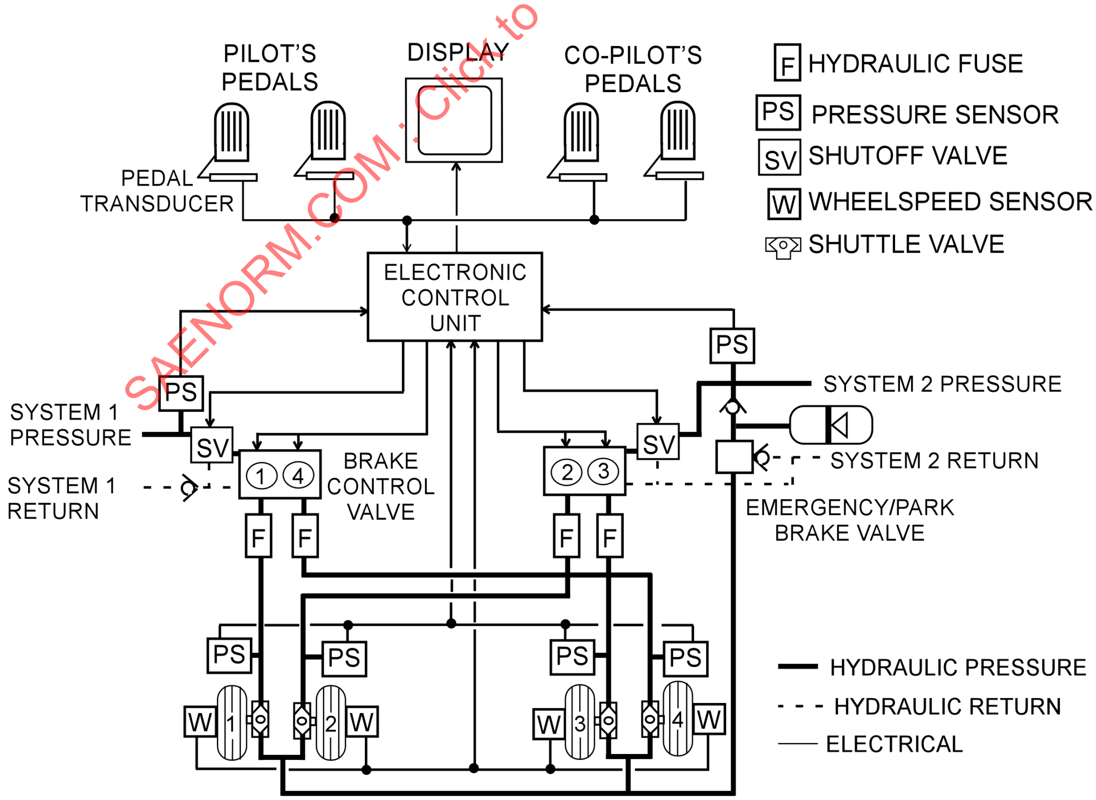

FIGURE 5 - SINGLE CAVITY BRAKE WITH DUAL HYDRAULIC SYSTEM

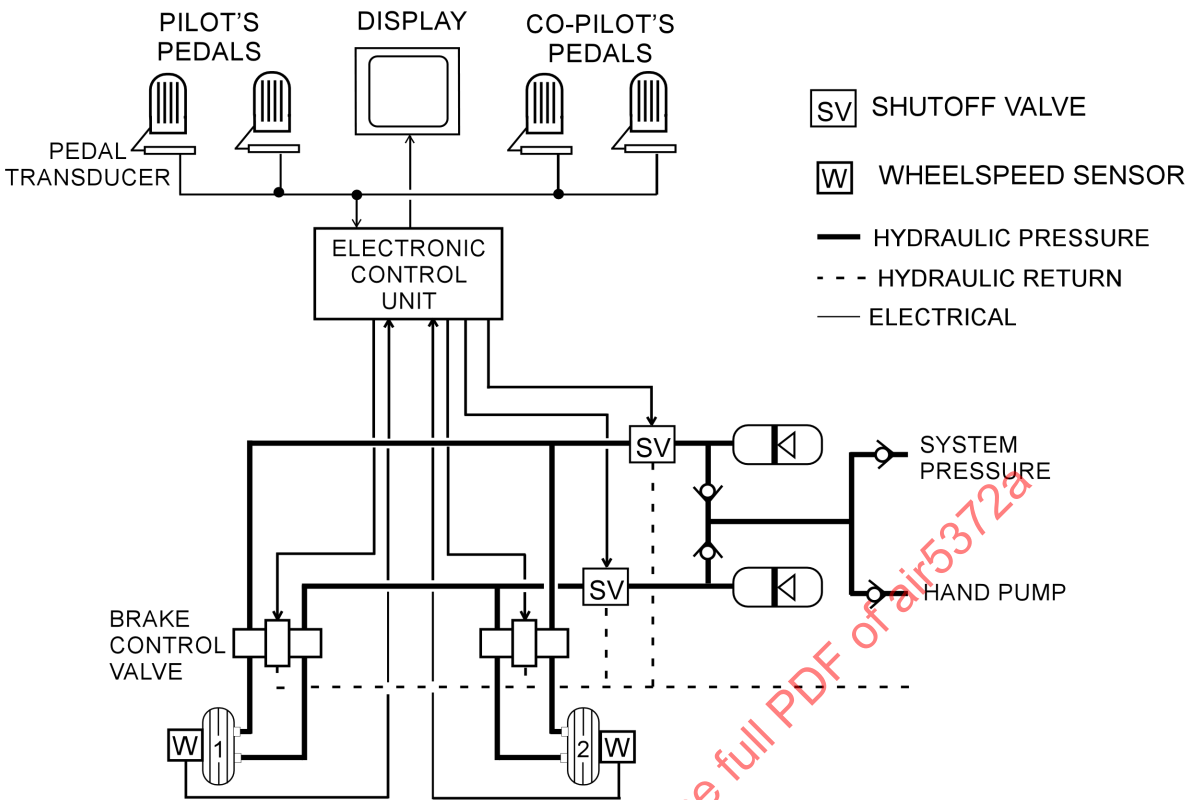

FIGURE 6 - DUAL CAVITY BRAKE WITH SINGLE HYDRAULIC SYSTEM

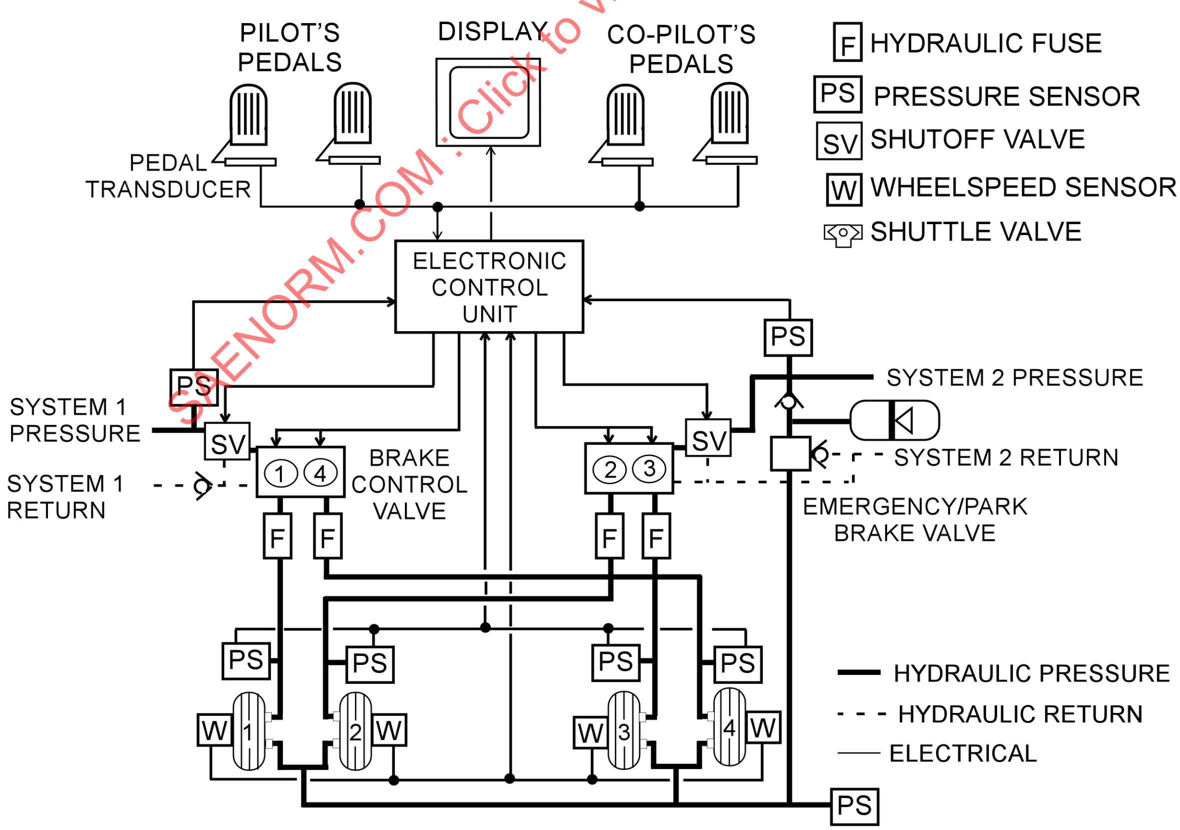

FIGURE 7 - DUAL CAVITY BRAKE WITH DUAL HYDRAULIC SYSTEM

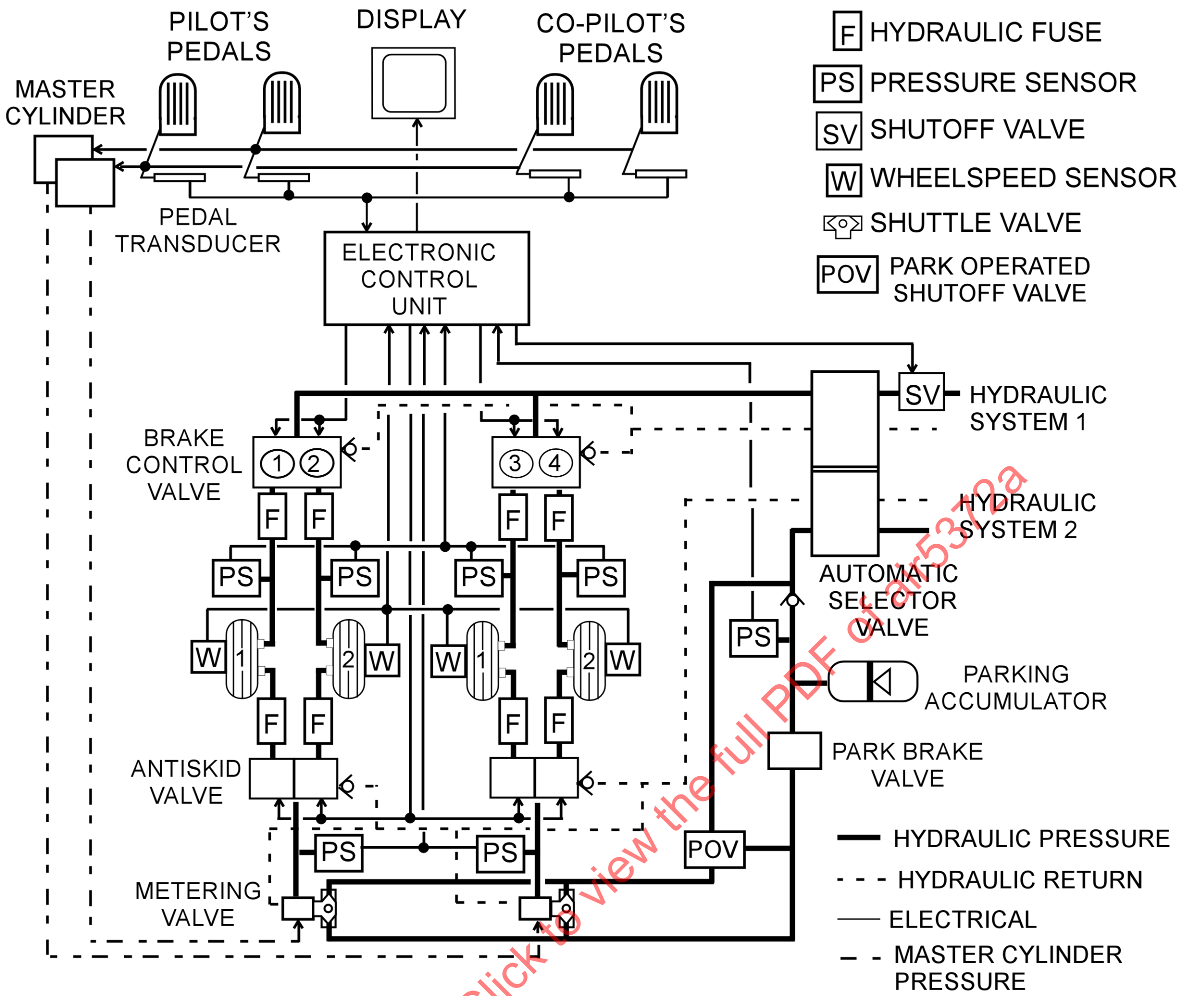

FIGURE 8 - DUAL CAVITY BRAKE WITH DUAL HYDRAULIC SYSTEM, BBW PRIMARY, ON-OFF BBW PARK, AND HYDROMECHANICAL AUXILIARY

Below in Table 1 is a list of various aircraft's electro-hydraulic brake control system architectures showing some of the key system parameters. (Other systems besides electro-hydraulic are not reflected in the table.)

TABLE 1 - EXAMPLES OF BRAKE-BY-WIRE APPLICATIONS

Aircraft Model	Manufacturer	Aircraft Type	#Wheels/Brakes	Max. Pressure (psi)		Valve Type	Brake Type	Pedal Data		System Configuration and Remarks
				Brake	Sys			lb	Angle	
B-70	North American	Bomber	8/4	4000	4000	Flapper-Nozzle 4-way	Steel			Torque feedback, brakes between co-rotating wheels - oronite fluid
Space Shuttle	Rockwell	Research Vehicle (NASA)	4	2000	3000	Flapper-Nozzle 4-way	Carbon, dual cavity			Dual redundant
Concorde	Aerospatiale (France) and British Aircraft Corporation (UK)	Commercial Transport	8	3150	4000	Flapper-Nozzle 4-way	Carbon, dual cavity		14 degrees	BBW primary, hydromechanical Aux, on/off BBW park torque limit control - oronite fluid
F-16	Lockheed-Martin	Fighter	2	2300	3000	Pressure proportional Solenoid	Carbon, dual cavity	15-55 lbf	0-10 degrees	Dual simultaneous BBW 1st production BBW
F-117	Lockheed-Martin	Fighter	2	2800	3000	Pressure proportional Solenoid	Carbon			Similar to F-16
IDF	TAS	Fighter	2	2300	3000	Pressure proportional Solenoid	Carbon, dual cavity			Similar to F-16
JAS39A JAS39B	SAAB-Scania	Fighter	3	4000	4000	Flapper-Nozzle 3-way	Carbon	22-105 lbf	0-15 degrees	Dual BBW primary mains plus nose wheel on 1 system - hydromechanical park auxiliary
F2	Mitsubishi	Fighter	2	2300	3000	Pressure proportional Solenoid	Carbon, dual cavity			Similar to F-16
G-IV	Gulfstream	Executive/ Business	4	3000	3000	Flapper-Nozzle 3-way	Carbon			BBW primary hydromechanical park auxiliary
Eurofighter	EFA Typhoon	Fighter	2	4000	4030	Flapper-Nozzle 3-way	Carbon	15-80 lbf	0-10 degrees	Dual redundant BBW primary hydromechanical park auxiliary
A-300 A-310 A-319 A-320 A-321 A-330 A-340 A-340-500/600	Airbus	Commercial Transport	8 8 4 4 4 8 10/8* 12	2550	3000	Flapper-Nozzle 3-way	Carbon, dual cavity		14 degrees	Dual BBW primary hydromechanical auxiliary system. On/off BBW park * Center landing gear not braked Dual BBW primary and auxiliary
LJ45	Learjet	Executive/ Business	4	3000	3000	Flapper-Nozzle 3-way	Carbon, single cavity			Dual pressure input, Inbd/Otbd BBW primary, hydromechanical park auxiliary
EMB 145/140/135	EMBRAER	Regional transport	4	3000	3000	Flapper-Nozzle 3-way	Carbon, single cavity	15.4-84 lbf (7-38 kg)	0-15 degrees	BBW primary hydromechanical park auxiliary

TABLE 1 - EXAMPLES OF BRAKE-BY-WIRE APPLICATIONS (CONTINUED)

Aircraft Model	Manufacturer	Aircraft Type	#Wheels/Brakes	Max. Pressure (psi)		Valve Type	Brake Type	Pedal Data		System Configuration and Remarks
				Brake	Sys			lb	Angle	
Global Express	Canadair	Executive/ Business	4	3000	3000	Flapper-Nozzle 3-way	Carbon, single cavity			Dual redundant BBW primary hydromechanical park auxiliary
Rafale	Dassault Aviation	Fighter	2	2500	5000	Flapper-Nozzle 3-way	Carbon, dual cavity			Dual redundant BBW simultaneous application hydromechanical park auxiliary
Falcon 2000	Dassault Aviation	Executive/ Business	4	2550	3000	Flapper-Nozzle 3-way	Carbon, dual cavity			Dual redundant BBW simultaneous application hydromechanical park auxiliary
Falcon 900	Dassault Aviation	Executive/ Business	4	3000	3000	Flapper-Nozzle 3-way	Carbon, dual cavity			Single hydromechanical auxiliary
F-22	Lockheed-Martin	Fighter	2	3750	4000	Flapper-Nozzle 3-way	Carbon, single cavity			Dual redundant BBW Brake control, antiskid and decel control
Hawker 4000	Raytheon Airplane	Executive/ Business	4	3000	3000	Flapper-Nozzle 3-way	Carbon, single cavity			Dual BBW primary dual hydromechanical park/auxiliary
ERJ 170/190	EMBRAER	Regional transport	4	3000	3000	Flapper-Nozzle 3-way	Carbon, single cavity			Dual BBW primary dual hydromechanical park/auxiliary
FD728	Fairchild/ Dornier	Regional transport	4	3000	3000	Flapper-Nozzle 3-way	Carbon, dual cavity			Dual BBW primary dual hydromechanical park/auxiliary

5. HARDWARE COMPONENTS

A discussion and description of the hardware components most frequently encountered in BBW systems are included as an aid in understanding overall system operation. For the sake of brevity, only the more commonly used components are discussed.

5.1 Pedal Input Command and Pedal Force

Various electromechanical, electronic, and optical devices may be used to convert the pilot's or copilot's pedal motion to an electrical signal proportional to desired brake pressure. These devices include electrical linear potentiometers, Linear Variable Differential Transformers (LVDTs), rotary potentiometers, Rotary Variable Differential Transformers (RVDTs), fiber optic position sensors, and similar position-sensing components. Regardless of the means employed to sense pilot pedal input, the end result is an input to the BCU that produces an output signal to the brake hydraulic pressure control valve or EMAs, which then produces a brake clamping force proportional to pilot command. In specialized circumstances, force transducers can be used to provide a pedal command with little or no travel.

Generally the pedal position is restrained by a spring of some sort, thus the measured position is also indicative of applied force. The feedback force of the pedal is sometimes supplied as part of the brake pedal sensor and sometimes external to the sensor. For failsafe reasons, the sensors usually incorporate a small spring to assure the brake pedal sensor naturally applies "no braking." Therefore, if a sensor comes loose from its mounting, the sensor fails to 'no braking position.' One of the most important safety aspects of a BBW system is not to have uncommanded braking, i.e., braking when not commanded by the crew.

5.2 BCU, BSCU, or ECU

The control circuitry is the "brain" of the BBW System. A number of basic and ancillary functions are provided, regardless of the detail of the control concept. These functions include: conversion of pilot's pedal input, if applicable, to a control signal, conversion of wheel speed to an electrical signal, computation, valve current control signal or brake force command generation, feedback, diagnostics, self-test, and auxiliary control functions. The computational functions, whether implemented in hardware by analog sub-circuit logic, or by software in the case of digital systems, embody the control laws for pedal braking, antiskid, gear retract braking, and autobrakes. Manufacturers use different computational techniques and circuitry to meet these basic requirements. Some systems operate with a monitoring function active in parallel with the control function described above. The monitoring subsystem, or channel, evaluates the control channel's operation to verify the system is continuing to operate normally. If the monitoring channel detects a failure it can disable the control channel.

5.3 Brake Control Valves

5.3.1 BBW Control Valve

The BBW Control Valve is the basic interface between the low power electronic control circuit and the aircraft hydraulic brake system. The valve configuration and performance are selected to provide the necessary hydraulic pressure control as determined by the pedal law desired. It is also common for the valve to be used by the antiskid function of the control system for pressure reduction during skid conditions. The most commonly used valve characteristic provides for increasing pressure output for an increase of input valve current. This provides an inherent bias to reduced brake pressure or loss of brake pressure when the electrical signal is lost.

5.3.2 Accessory Valves

Shutoff valves are often included in BBW systems to reduce leakage during non-braking modes or when the parking brake is set. They can also be used to block input hydraulic pressure to the EHVs to isolate failures (and act as an interlock) or as part of the scheme for meeting failure mode requirements such as the inadvertent application of brakes during takeoff. Selector valves and shutoff valves can be used to switch between redundant hydraulic systems, or isolate failures where loss of braking could occur. The redundancy, reliability, and utility requirements of the particular aircraft drive the specific functionality and the type of devices selected.

5.3.3 Brake Control Valve Types

Brake systems are "dead headed" in that hydraulic fluid flows to and from the brake actuator but not through it. Because of this, the electrically operated brake valves, or servo control valves, are generally configured as hydraulic pressure control devices as shown in Figure 9 (4-Way First Stage) and Figure 10 (3-Way First Stage) have a "3-way" configuration on the power output stage. The input pressure is ported to the brake or to the hydraulic reservoir return line. The valves are generally hydraulic amplifiers, where a low-power, electro-hydraulic first stage controlled by the valve drivers in the BCU modulates a small hydraulic "control flow" to vary the pressure applied to the moving element of the power output or second stage. This reduces the amount of electrical power needed to control brake pressure.

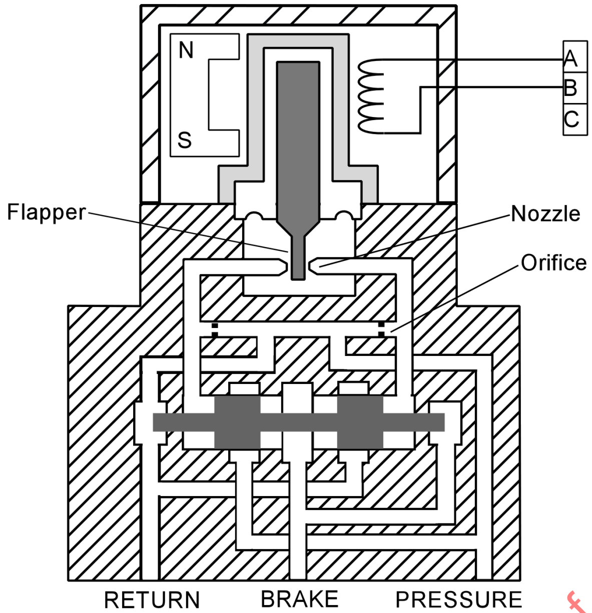

FIGURE 9 - SERVO VALVE WITH 4-WAY FLAPPER-NOZZLE FIRST STAGE

Another form of valve that uses an electrical signal to directly control the valve output without the need for an electro-hydraulic first stage is becoming available. This is typically called a Direct Drive Valve (DDV), and can use a linear or rotary electrical motor to position a valve element to provide a given hydraulic output. These devices do not require a control flow, and are thus inherently very low-leakage devices. DDVs do not have the very small orifices that are used in the first stage of hydraulic amplifiers and are more forgiving to hydraulic contamination. These attributes are the primary reasons for their development.

5.3.3.1 Servo Valve with 4-Way Flapper-Nozzle First Stage

The schematic of a typical BBW valve with a 4-way flapper-nozzle first stage is shown in Figure 9. The second stage is a spool and sleeve. A permanent magnet torque motor in the first stage operates the flapper. The hydraulic bridge built around the flapper consists of two variable nozzles and two fixed orifices. The nozzles and orifices are supplied with system pressure. When the flapper moves away from a nozzle, supply pressure flows through it to return, and the pressure at the associated, fixed orifice is reduced. Motion of the flapper between the nozzles causes the opening at each nozzle to vary: one increases as the other decreases. In this way, a differential control pressure can be applied across the second stage spool through the fixed orifices. The second stage spool is also supplied with brake feedback pressure at one end and return pressure at the other. The pressure forces from the first stage and the brake and return ports are summed at the ends of the spool and work to move it until an equilibrium position is reached. The pressure at the brake is thus a function of the electrical command to the torque motor. By careful selection of the sizes of the nozzles and orifices, 4-way flapper-nozzle servo valves can be designed to have a linear gain slope characteristic, which is a desirable feature. This type of valve has two disadvantages when compared with 3-way valves. Since the flapper always uncovers a pressure nozzle, the internal leakage rate of a 4-way first stage valve tends to be high. In addition, 4-way valves tend to be more affected by return pressure variations.

5.3.3.2 Servo Valve with 3-Way Flapper-Nozzle First Stage

The schematic of the 3-way first stage servo valve is shown in Figure 10. It is similar to the 4-way servo valve except that the two nozzles are connected one to pressure and the other to return, and there are no upstream fixed orifices. The position of the flapper controls the pressure in the first stage chamber. When the pressure nozzle is covered and the return nozzle is uncovered, the chamber pressure is close to return pressure (it is worth noting that the return is not zero pressure, i.e., there is a back-pressure level in the return line). When the flapper position is reversed, the first stage pressure is close to supply pressure. In most BBW valve applications, the flapper is mechanically biased so as to seal off the pressure nozzle when no current is applied. As in the 4-way valve, feedback pressure from the brake is summed with control pressure so that equilibrium can be reached between the torque motor command and the pressure applied to the brake.

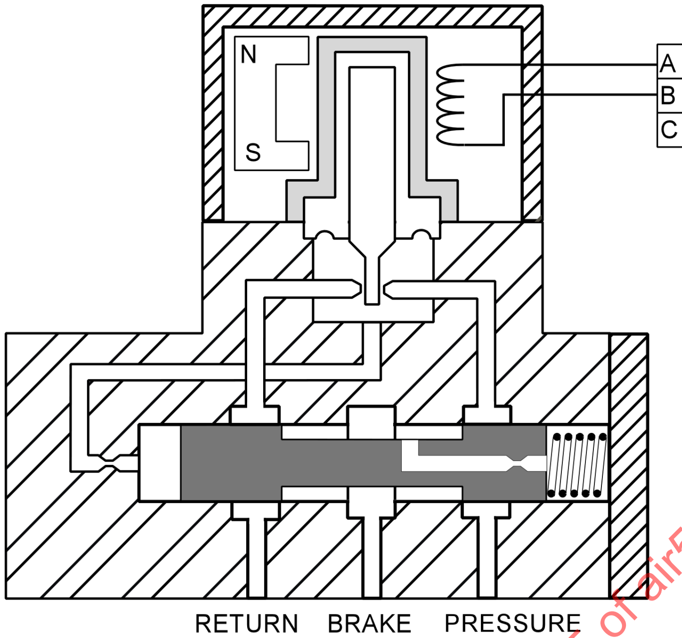

FIGURE 10 - SERVO VALVE WITH 3-WAY FLAPPER-NOZZLE FIRST STAGE

3-way first stage servo control valves have the inherent advantage of increased simplicity in both the first stage and second stage. The second stage spool does not require two precision-lapped fits on either end, as does the 4-way. An additional benefit is that the control pressure applied to the spool can be close to full supply pressure with a 3-way first stage, where only 50% can be developed with a 4-way. This additional pressure is equivalent to increased force for enhancing frequency response.

5.3.3.3 Servo Valve with Jet Pipe First Stage

The 'impingement jet', more commonly known as a 'jet pipe' or 'deflector jet' servo control, consists of a permanent magnet torque-motor that positions a nozzle above an outlet port or receiver. In some valves there is a single receiver port and the receiver pressure depends on the alignment of the jet. In others there are two ports positioned side by side so the stream is divided into a differential pressure between the ports.

The receiver pressure is applied across the opposite ends of a second stage or power spool. The second stage spool is connected to the jet pipe with a spring that acts as mechanical force feedback to the torque motor.

The same as in a flapper-nozzle valve, an electrical input to the torque motor coil causes the hydraulic fluid stream or "jet" to unbalance the quiescent condition of the receiver. This in turn causes the second stage spool to regulate the control port pressure levels commensurate with the electrical signal. Jet pipe valves leak more than other types of valves and because of this have not found common usage on brake control systems.

5.3.3.4 Proportional Solenoid Valve

Proportional control of a solenoid to provide progressive pressure change as a function of electrical input can be implemented through continuous or pulsed signal control depending on the valve and circuit type. The continuous-function type is similar to the flapper-nozzle type in that a smooth output versus input current is achieved. The pulsed type depends on rapid on-off signals to achieve a progressive curve.