Fault Isolation Methodology for the L-1011 Digital Avionic Flight Control System

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New L-1011 aircraft are being delivered with digital avionics including an active control system and a flight control system capable of category III automatic landings. Because of the complexity and redundancy of such systems, maintenance has traditionally been an enigma. These new aircraft are equipped with an advanced maintenance system which collects fault data from the digital flight control and active control systems for maintenance action. This report is a description of the general system architecture and an examination of the fault isolation methodology.

Background

THERE are two digital control systems incorporated into the L-1011-500 aircraft, an active control system (ACS) and an avionic flight control system (AFCS).

The ACS provides gust load alleviation and maneuver load control to allow extension of the wings to reduce drag without the need to strengthen the wing structure.[1,2] The AFCS provides guidance and control throughout all phases of flight from takeoff through landing in category III weather minimums. It provides flight director guidance as well as coupled pitch and roll axis control through the ailerons and stabilizer, yaw axis stability augmentation (SAS) and rollout control after touchdown, cruise and approach automatic control, and altitude deviation alerting.

To operate into category III weather with no decision height, the automatic landing control must be fail operational, which means that it continues to operate in a normal fashion after any single system component fails. Similarly, the yaw SAS and ACS are fail operational to guarantee the availability of the structural load alleviation. Other flight control system (FCS) functions, such as heading select, altitude capture and hold, and autothrottle, are either fail passive or fail soft. This means that single failure will cause either loss of the function with no aircraft perturbation or a disturbance which is limited to a safe and acceptable level.

To achieve the required level of safety, multiple sensor, multiple servos, and multiple channels of digital computation are used.[3,4] Failures of sensor or computation channels are detected by comparison, loss of validity, or internal monitoring and reasonableness tests. Failures detected by the monitoring are annunciated to the flight crew via cockpit displays and are stored for maintenance action in a fault isolation/data display system (FIDDS), which is the subject of this report.

Historical Maintenance Concepts

As aircraft and airborne systems have become more complex, there has been a gradual evolution in maintenance methodology. Initially, with simple systems, maintenance action could be directed by pilot complaints entered into the logbook. Also, with the relatively short, mean time between failures (MTBF) of some equipment, periodic removal on a predetermined schedule which automatically replaced parts with high failure rates (such as tubes) became a viable means of preventative maintenance. As systems became more complex, specific manuals were generated to guide and assist the maintenance personnel. Coincidentally, various forms of built-in test equipment became commonplace, including meters, test switches, and fail indicators mounted for convenient access on the front panel.

The evolution of systems that led to the current generation of aircraft having complex, inter-related, but predominantly analog systems, also led to the incorporation of a built-in test (BIT) capability in many units. This capability usually involved either a manually initiated self-test which could be monitored by the maintenance crew or some sort of latching indicator to identify failed components. On some aircraft, these concepts were integrated into a systematic maintenance framework with the use of an airborne data system (such as AIDS) which could record a multiplicity of aircraft parameters for subsequent examination by maintenance or engineering, or by the manual equivalent such as the Lockheed fault isolation reporting method (FIRM). FIRM is a flow chart type of tool which leads the flight crew through a series of observations about the flight deck displays, thus allowing the maintenance crew to determine the nature of the fault and the requisite repair action.

These approaches all suffer from a number of well-recognized problems. They suffer from a degree of inaccuracy which can lead to unwarranted removals, they are inefficient in their use of valuable maintenance time and they lead to inefficiencies in the design of the line replaceable unit (LRU) due to the need to include failure indicator hardware. In addition, use of such systems requires a fair degree of training to correctly assess the meaning of a set of indications and the perseverance to examine the various failure indicators scattered throughout the aircraft.

When the problems associated with the existing maintenance techniques are examined, it becomes apparent that what is needed is a centralized location to which the maintenance crew can go to determine what to do to repair the aircraft. The information provided should be in a format which requires little or no special training, rather than encoded in an obscure manner. The failure information should be presented along with a description of the problem or indication that the repair action would correct, so that the problems entered in the log can be addressed directly and specifically. This last item is needed to reduce unwarranted removals of equipment which is entirely unrelated to the logbook complaint.[5]

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L-1011 Maintenance System

The need for a centralized, comprehensive, and intelligible maintenance system is addressed in the L-1011 by the fault isolation/data display system (FIDDS). The FIDDS consists of a CRT-type display with a keyboard (Fig. 1) located on the flight engineer's panel, and a data collection and storage computer located in the forward electronic service center under the cockpit floor.

The computer receives failure data from the ACS and AFCS systems while the display presents the information in English phraseology which matches the aircraft manual usage. The display and keyboard are used by the flight crew to enter data into the flight data recorder and to monitor current fault data when desired.

To avoid affecting aircraft dispatch ability and safety, the FIDDS is designed to encompass no flight-critical functions. It is not required for dispatch and it cannot stimulate or initiate self-test in any other system or piece of equipment; nor can its failure in any way adversely affect the operation of any flight system.

The total function of the FIDDS is to receive, format, recall, and display data supplied by other systems. The FIDDS does not perform fault isolation; that function is accomplished in the ACS or AFCS systems because that partition of system functions reduces the amount of information which must be sent to the FIDDS, and because it reduces the chances that a change in either flight system will require an accompanying change in FIDDS.

The FIDDS has four primary modes of operation:

1) Documentary entry—allows the flight crew to enter flight and date information to the flight data recorder.

2) Flight data recall—recalls inflight failures.

3) Present status—displays any currently detected faults to aid troubleshooting.

4) Autoland summary—presents a summary history of the aircraft autoland activity.

The FIDDS operational modes are selected from an index page which is displayed when ON or INDX is selected and the system of interest (ACS or AFCS) is selected from a second index page, see Fig. 2.

Flight data recall stores inflight information in a push-down stack so that the most recently occurring event is available first; previous events may be viewed by scrolling the display with the forward (FWD) and back (BCK) keys. A maximum of 30 ACS and 70 AFCS events may be stored. As new events over the limit occur, the oldest events are dropped off the bottom of the stack.

Each event recording consists of two pages of data. The first page contains the aircraft number, flight and leg number, date, time, the cockpit indication and the cause thereof, and a "FID" code. The FID code is a hexadecimal number which can be used by the flight crew as part of their inflight failure observations using the FIRM system. It can also be used by the maintenance crew to locate specific diagnostic or repair procedures in the aircraft maintenance manual. The second page scrolls the first page up one line to add three lines of expanded data to the bottom of the display, including nature of fault, flight parameters, and some autopilot modes. (See Fig. 3.)

In normal operation, maintenance personnel would access flight data recall for the desired system, scroll the display until the squawk (log entry) of interest was found, and then repair or replace the indicated cause. Isolation of failures is carried out to the LRU level whenever possible, so the item

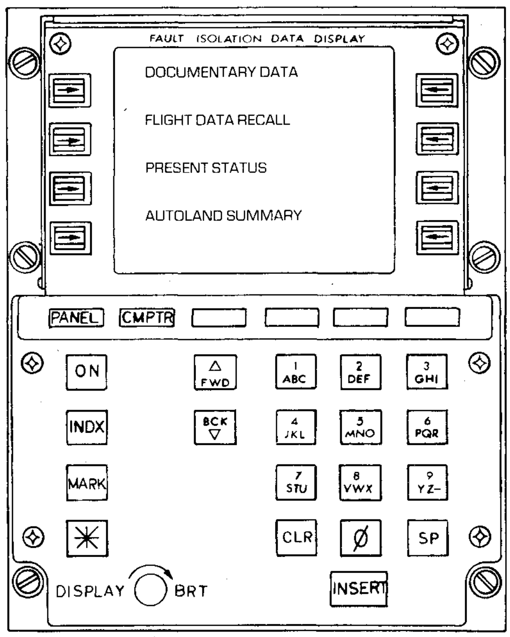

Fig. 2a Index page.

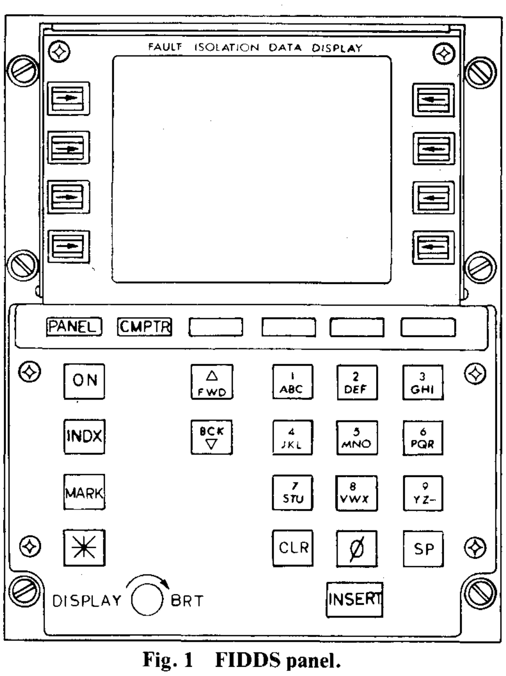

Fig. 1 FIDDS panel.

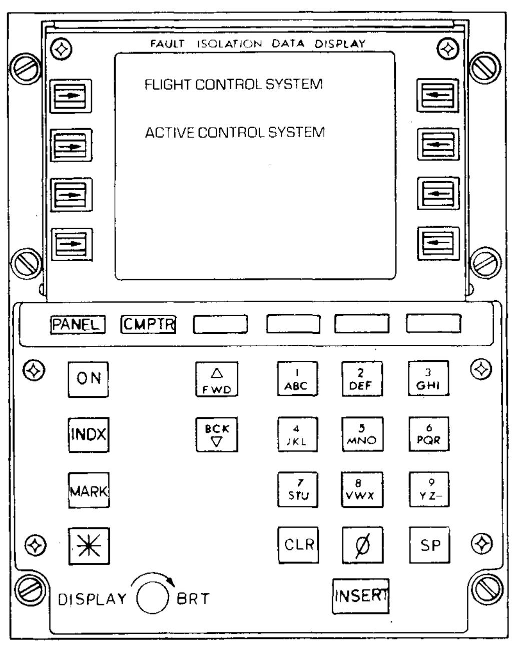

Fig. 2b Second index page.

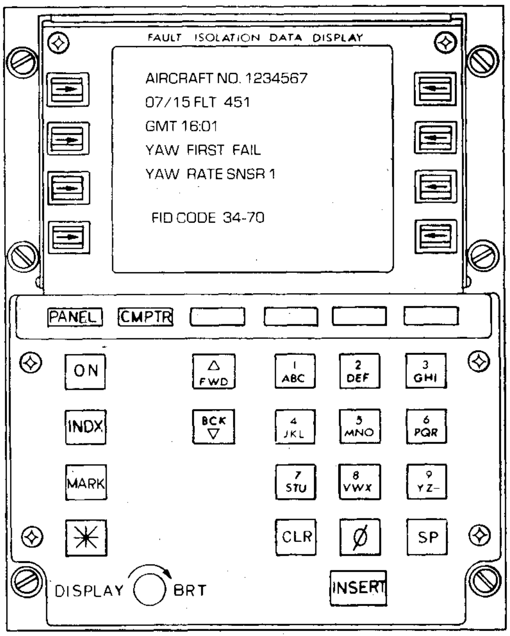

Fig. 3a Flight data recall.

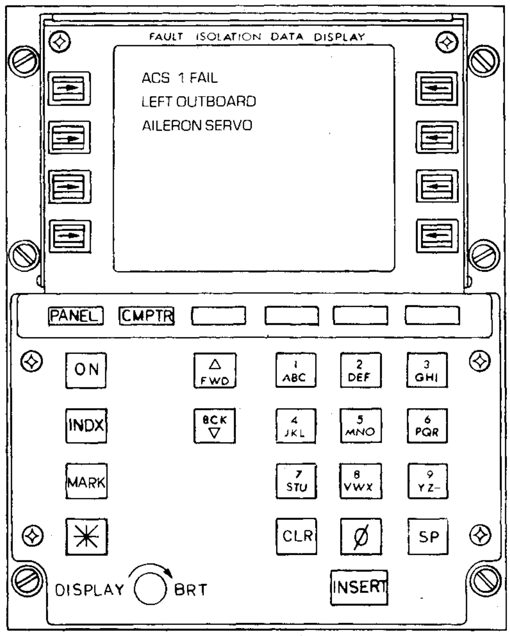

Fig. 4a Present status.

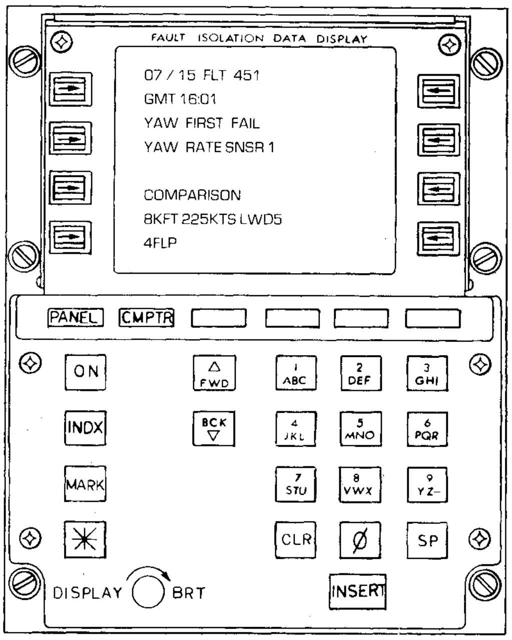

Fig. 3b Flight data recall, second page. Additional data provided: COMPARISON—sensor failed due to comparison monitor threshold exceedanced, 8K FT—sensor failed while at 8000 ft altitude, 225 KTS—sensor failed while at 225 knots airspeed, LWD 5—sensor failed while in a 5-deg left wing down bank, and 4 FLP—sensor failed while the flaps were at the 4-deg position.

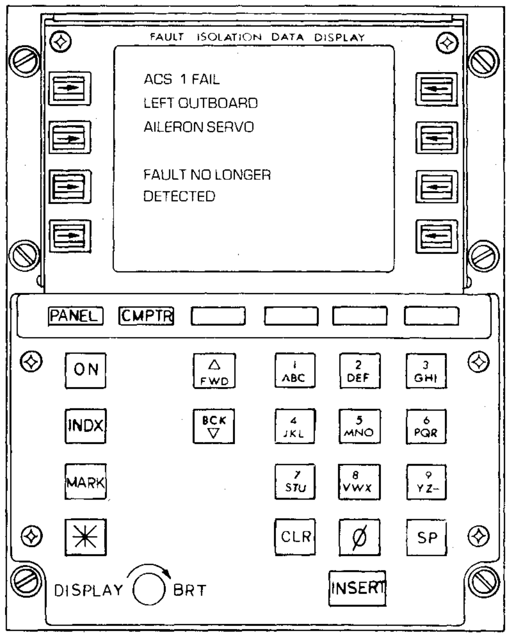

Fig. 4b Present status—after repair.

displayed as the cause usually corresponds to a specific replaceable item. The second page of data is provided solely for the use of engineering in diagnosing intractable problems which might be intermittent or dependent on the flight condition. Maintenance personnel may mark the display indicating corrective action with a star (*), A (adjusted), S (swapped), R (repaired), or X (replaced). These characters provide a history of maintenance action to aid in the diagnosis of recurrent faults.

It is not possible to clear the fault storage memory while the unit is installed in an aircraft. This feature is included to remove the temptation to repair an item by clearing the display. However, to avoid potential confusion should a FIDDS computer be moved from one aircraft to another, the aircraft number is stored with each event; if the aircraft number stored differs from the current aircraft number (entered via the documentary data entry mode), the advisory "CHECK AIRCRAFT NUMBER" is displayed. The display of the advisory alerts the maintenance crew that the fault displayed may not be relevant to the particular aircraft being repaired.

Since the flight data recall mode stores information in a nonvolatile manner, interlocks are used to prevent the storage of extraneous and nonrelevant events which might be caused by normal maintenance activity on the aircraft. Events will not be stored in the memory unless two of the three aircraft engines are running. For most faults, the aircraft must also be airborne for storage to occur. The engine interlock is used because it is common for maintenance action to defeat the aircraft on-ground logic, but it is quite unusual to run engines.

The present status mode is available at any time by selecting it from the index page, and selecting the desired system from the second index page. It is primarily intended to assist ground personnel with their troubleshooting efforts, recognizing that any ground problems may be the result of other maintenance action (such as opening a circuit breaker) as well as actual component failures. Thus, present status assists the maintenance technician by displaying what needs to be done to clear a particular cockpit indication. Making this information available on an immediate basis reduces confusion and saves time by answering the "What's wrong now?" type of question. When a fault or event is displayed in present status and the cause is corrected, the component or cause portion of the display is replaced with FAULT NO LONGER DETECTED. This display confirms to the technician that the corrective action has been successful. If the cockpit indication is still displayed due to another cause, operating the forward or back keys will display the information. (See Fig. 4.)

Fault Isolation Methodology

Fault isolation is accomplished externally to the FIDDS in the ACS or AFCS. The rationale for this is that these systems are responsible for generating the cockpit indications for which fault isolation is required and thus the cause of the indication should be readily available. In practice, the application has not been quite that simple.

The software structure of the ACS and AFCS can be viewed as consisting of two loops, one called "foreground" and one called "background." The foreground loop performs all real time and flight critical calculations, the background loop uses time that is left over to perform noncritical, nonreal time functions (see Fig. 5).

The foreground loops drive all the cockpit indications which FIDDS stores; however, to avoid exceeding the available execution time, the fault isolation software resides in background where it can operate without being constrained by duty cycle considerations. This division of tasks solves the real-time operation problem, but requires that substantial portions of the foreground software be duplicated in the background to determine the cause of indications. In addition, in the AFCS, the background is so lengthy in its execution time (several seconds) that the conditions existing at the time an indication is first presented must be frozen in a "hold array" so that the data used for fault isolation will match the data upon which the original indication was based.

The fault isolation equations are themselves rather straightforward. In the ACS, since there are only 3 potential indications and 25 possible causes, all equations are examined every pass through background. The AFCS is rather more extensively entwined with other aircraft components and performs a task which requires much greater pilot interaction. Thus the AFCS has 25 indications and 115 potential causes. If the fault isolation equations were executed each pass through background, the execution time of background would become quite long.

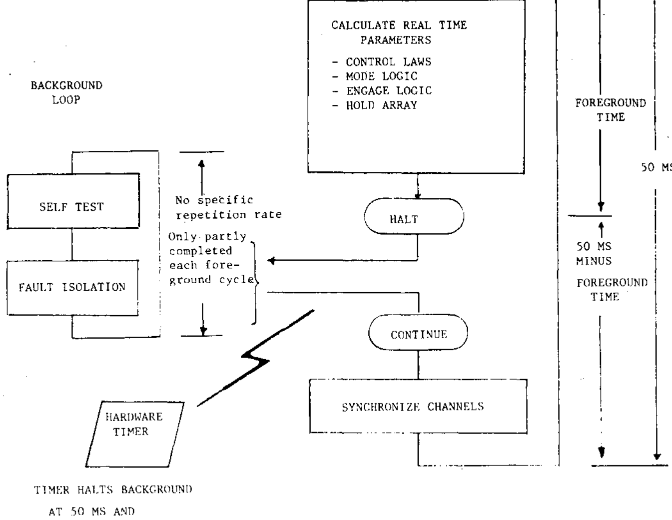

Fig. 5 Software structure: the background loop executes in the time after the foreground loop is completed.

The approach used for the AFCS was to set up a hold array and an event or squawk detector in foreground which will latch the state of relevant variables whenever a fault isolatable event occurs. When the hold array is not latched, the fault isolation software performs certain reasonableness tests for which there is no corresponding failure indication. A failure detected by these tests is stored by FIDDS as NO FAIL INDICATIONS.

Whenever the hold array latches a set of fault data, the fault isolation software first determines what the indication (squawk) was. Based on the squawk, the software then accesses a lookup table which lists, in order of likelihood, which components could have been responsible for each squawk. The software then executes the fault isolation equations for the appropriate squawk in the order specified in the table, stopping when one of the equations returns a positive result. Each fault isolation equation is capable of returning five possible results:

1) False—this component did not cause the event.

2) Comparison—this component caused the event due to exceeding a comparator threshold.

3) Validity—this component caused the event due to loss of its associated validity.

4) Reasonableness—this component caused the event due to some unreasonable condition (such as negative airspeed).

5) Other—this component caused the event due to some cause unrelated to comparison, validity, or reasonableness tests.

This nature of fault information is what is shown on the second page FIDDS display.

In addition to generating fault isolation information for transmittal to FIDDS, the AFCS continually sends out a word which contains the altitude, airspeed, mode, and configuration information which FIDDS stores for the second page. Since the continued receipt of this word indicates to FIDDS that the AFCS is healthy and capable of sending fault isolation information, it is called the "I'm OK" word (which shows true creativity in selecting a mnemonic). If 5 s pass without the receipt of an I'm OK word, FIDDS determines that the associated AFCS computer has failed and it stores "CHECK POWER OR FCC" (FCC stands for flight control computer, which performs the AFCS computations). The reason for the "CHECK POWER" suggestion is to avoid removals of the FCC when the real problem was a circuit breaker that was open.

Rather than sending an I'm OK word with configuration information, the ACS continually sends fault information with a NO FAULT bit set. The continued receipt of these words indicates to FIDDS that ACS remains healthy.

Interface

The ACS and AFCS interface with FIDDS via ARINC 429 (mark 33 DITS) low-speed serial digital busses. Data on this bus consist of an 8 bit label and 24 bits of data including parity. Data are ternary Rz with a data rate of 12.5 KB/s.

Because of the differing amount of information to be transmitted, the ACS and AFCS use the busses differently. The ACS uses two words (with separate ARINC 429 labels) with the squawk and fault (event and component) information packed in discrete bits. The AFCS also uses two words, one as the I'm OK word, the other as the fault word. Within the fault word, five bits are used to indicate the squawk, six bits are used to indicate the LRU or component, four bits are used for the nature of the fault, and five bits are spare. For each item, the AFCS generates a binary number; these binary numbers are packed together to form the fault word. The I'm OK word is generated from packed discretes for the mode and configuration information, and from binary numbers for airspeed, altitude, and attitude.

Since FIDDS must not only store information for flight data recall, but also provide current fault status on a continuing basis to the present status mode, all current fault information must be available all of the time. With the packed discrete interface such as used by ACS, this is inherent and new faults can be determined by comparing the current value of the fault words to the last value. This technique does not work for the AFCS because only one squawk combination can be transmitted per word. Thus a means of identifying whether a fault is old or new is needed for FIDDS to determine whether to store the event or merely to keep track of it for present status. The ARINC 429 characteristic conveniently provides a sign/status matrix at the end of the word format, which can be used to serve this function. Whenever the AFCS detects a new fault it transmits it twice as "valid data" (00 in the sign/status matrix), and thereafter as "no computed data" (10 in the sign/status matrix).

FIDDS, in turn, stores anything from the AFCS with a valid sign/status matrix (unless it received the same thing within the preceding 30 s), and sorts all AFCS events by squawk for present status. Once in the present status array, an item will remain there so long as an update is received every 5 s. If this condition is not met it is removed from the array and, if it is being viewed on the FIDDS display at the time, the display will say "FAULT NO LONGER DETECTED."

Hardware Configuration

The ACS, AFCS, and FIDDS computers are all based on the CAP-6 processor, which is a 16 bit, microprogrammable, stack-oriented machine. The microprogrammability allows the incorporation of frequency used procedures (such as compare or limit) as instructions. The CAPS-6 computer is vastly more powerful than required for the FIDDS function, but is used for commonality with the ACS and AFCS. The ACS and FIDDS computers share a common ¾ ATR long chassis (per ARINC 404), although the majority of the circuit cards and the side plane interconnect are different.

The input and output of the FIDDS computer is primarily via ARINC 429 low-speed busses, although a limited number of discretes are provided. The FIDDS computer interfaces with the digital flight data recorder via either an ARINC 573 or 429 bus and with either a ARINC 585 or 429 clock. All of these interfaces are handled with DMA (direct memory access) hardware to simplify the software and maximize the growth potential. The software occupies 8 k out of the 32 k available of 16 bit words stored in 2 k by 8 EPROM memory with 2 k of random access memory (RAM). The nonvolatile fault storage memory is CMOS RAM powered from an internal NiCd battery. The battery can support the memory for a minimum of 72 h. The computer weighs 10.7 kg and consumes 75 W. Forced air cooling is provided per ARINC 404.

The FIDDS panel contains a special-purpose processor built from discrete logic which stores the current display and drives the CRT as well as interrogating the keyboard. The display is refreshed at 80 Hz and the characters are stroke written to provide maximum clarity. The FIDDS panel is 7.125 in. high by 5.750 in. wide by 6.625 in. long and mounts on standard rails. It weighs 4.5 kg, consumes 40 W maximum, and is cooled by free convection only.

Field Experience

The FIDDS system was used during the development of the AFCS to locate problems in the flight test aircraft and vehicle simulator (VSS or iron bird), and is currently in use by the airlines and the Lockheed production flight line personnel. It is unfortunate that specific numeric data have not been collected on the system performance so that the maintenance effort on FIDDS-equipped aircraft (with digital AFCS) could be compared to the maintenance effort on the non-FIDDS-equipped aircraft (with analog AFCS). In the absence of such data, only a subjective evaluation is possible.

Since the digital AFCS was first certified (February 1981) there have been two updates to the FCC fault isolation software (another is pending), and changes were needed to include customer requested modifications, as well as to improve the reliability of the stored indications. The majority of the problems encountered resulted from external equipment not acting in the expected manner, or from usage of the system by the flight crew in unexpected ways.

Even without any of the improvements, the FID system quickly became the first thing to examine when troubleshooting the development aircraft or the VSS. The FIDDS was also enthusiastically accepted on the Lockheed flight line since it greatly reduced the time needed to locate production problems such as crossed wires or unmated connectors.

When the system entered regular airline service, it was greeted with a certain bit of skepticism, both because it was a new and unfamiliar development, and because it suffered from a few frequently incorrect LRU condemnations.

Once the nature of the problems became known and the system became familiar, it was accepted and became an integral part of the maintenance crew's "tool box." It has proved to be a great help in reducing maintenance troubleshooting time, particularly for subtle or intermittent faults. As an example, there have been a number of marginal or intermittent electrohydraulic valves (EHV) and servo solenoids which have been successfully located by FIDDS. Since the FIDDS display indicated the exact component to replace, the troubleshooting time was limited to the time required to confirm the failure, to locate and install a replacement, and to retest to show that the problem was corrected. This required only 2-3 h. Similar servo-related problems which have occurred on L-1011s equipped with analog AFCSs have required several days of intensive troubleshooting, often with help from Lockheed, to locate and repair the problem. Thus, the FIDDS can clearly reduce maintenance downtime. Because the FIDDS identifies a specific LRU to replace, it reduces the use of "shotgun" approach to maintenance and improves MTUR (mean time to unit removal), thus reducing spares required and service expenditures.

Conclusions

As systems become more automated and more complex, the skill required to maintain them will certainly increase. This paper has explained how this problem was addressed in a specific commercial application by the inclusion of a FIDDS system on the aircraft. Field experience has shown that the system is needed, and is effective in reducing the maintenance problem on a very complex system to a manageable level.

Acknowledgment

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