NATIONAL TRANSPORTATION SAFETY BOARD
Office of Aviation Safety
Washington, D.C. 20594

AIRWORTHINESS GROUP FACTUAL REPORT ADDENDUM 5
MD-10 BRAKE SYSTEM

June 20, 2008

A. ACCIDENT DCA06FA058

Location:	Memphis, Tennessee
Date:	July 28, 2006
Time:	1125 Central Daylight Time (CDT)
Aircraft:	FedEx Express Flight 630, McDonnell-Douglas (Boeing) MD-10-10F, N391FE

B. AIRWORTHINESS GROUP

Chairman:	Clinton R. Crookshanks National Transportation Safety Board Denver, Colorado
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C. DETAILS OF THE INVESTIGATION

1.0 Brake System Description

The dual redundant brake system is similar in arrangement and function on all DC-10, MD-10, and MD-11 airplanes. A schematic of the system is shown in Figure 1. The major components of the system are the brake pedals (left and right) coincident with the rudder pedals at the captain's and first officer's positions in the cockpit, the two dual brake control valves (DBCV), installed in the left and right main landing gear (MLG) wheel wells, the four anti-skid manifolds (ASM), two each on the left and right MLG's, and the eight brake assemblies, one on each MLG wheel. Each brake is actuated by 8 brake pistons connected to two independent hydraulic passages, 4 pistons on each passage. The brakes are activated by depressing the upper portion of the rudder pedals from either pilot position. The left brake pedals and right brake pedals are mechanically connected together beneath the cockpit floor. Two separate left pedal cable loops and two separate right pedal cable loops each mechanically operate the input lever of one side of one DBCV. Each DBCV receives 3000 psi hydraulic fluid from separate aircraft hydraulic systems; hydraulic system 1 supplies the left DBCV (brake system 1) and hydraulic system 3 supplies the right DBCV (brake system 2). In response to input lever movement, the applicable side of each DBCV meters the 3000 psi hydraulic fluid to the output port, regulating the line pressure ("metered pressure") in proportion to brake pedal travel. Each metered pressure fluid output is connected to one of the four ASM's. Note that the metered pressure from the left DBCV, left pedal side, feeds the L-1 ASM and the metered pressure from the left DBCV, right pedal side, feeds the R-1 ASM while the metered pressure from the right DBCV, left pedal side, feeds the L-2 ASM and the metered pressure from the right DBCV, right pedal side, feeds the R-2 ASM. Inside each ASM are four antiskid valves, each ported/connected to 4 pistons of one brake. Each antiskid valve is independently and electrically controlled by the Antiskid Control Unit (ASCU), not shown, and, when commanded, reduces the DBCV metered pressure ported to the 4 pistons of the applicable brake. The ASCU takes information from the wheel speed transducers and automatically reduces the pressure applied to the brakes to prevent a skid. The ASCU also controls two protection functions at each wheel independently. The touchdown protection function releases pressure at all wheels to prevent accidental brake application at landing. The locked wheel protection function releases pressure at the locked wheel to allow it to begin turning again.

2.0 N391FE Brake System

FedEx worked with Boeing to develop a modified brake system for their MD-10 airplanes that would utilize the same wheel, brake, and tire used on their fleet of MD-11 airplanes. The MD-11 brake has carbon rotating (rotors) and stationary (stators) disks as opposed to the DC/MD-10 brake, which has steel rotors and stators. The brake system modification installed new antiskid components, MD-11 wheels, tires, and brakes, and modified MLG doors on the MD-10 airplanes under a Supplemental Type Certificate. On the MD-10-10F airplane, new MLG axles must be installed to accommodate the MD-11 wheels and brakes. This modification also re-identified the truck beam and strut assembly part numbers. Brake temperature indication was added to those MD-10 airplanes that did not already have this feature. The accident airplane, N391FE, was one of 15 MD-10-10F airplanes converted to the carbon brake system. The carbon brake system was installed on N391FE in July 2005. The carbon brake system did not change the basic operation of the system described above, although it did replace the wheel speed transducers, the ASM's, and the ASCU with newly designed components.

3.0 Carbon Brake System Issues

During the course of the investigation, the group was told that some of the 15 FedEx MD-10 airplanes (including the accident airplane) with the carbon brake system installed had occasional pilot reports of unacceptable brake grabbing, aircraft pulling left or right during braking, excessive pedal travel to obtain braking, and aircraft shuddering (shaking) during braking. Airplane N391FE had several of these brake system pilot reports prior to the accident, as summarized in Table 1. The pilot reports were causing costly delays, unproductive maintenance actions, and multiple brake system part removals, many with no fault found. Examination of the In-Service Evaluation[1] (ISE) data and information from the accident investigation led to three likely causes for the pilot reports.

1) With small brake pedal(s) application typical in normal landing and taxi operations, the time between initial brake pedal motion and the start of brake torque can be longer than expected. This delay frequently causes the flight crew to further advance the brake pedals, which results in a high initial brake pressure and torque. The high initial brake torque could be perceived as "brake grabbing" by the flight crew. Figures 2 and 3 show the DBCV lever position (connected to the brake pedals), hydraulic pressure out of the DBCV into the ASM, the hydraulic pressure out of the ASM into the brakes, and the strain measured on the forward side of the gear versus time for the right and left MLG, respectively. The data presented in Figure 2 is from Flight 1226 on March 3, 2007. The RH brake shows a delay of about 3 seconds from the time of first pedal movement until the brakes actuate and produce an increasing strain in the landing gear. Note the stepped characteristic of the pedal position that indicates application of more and more brakes. The data presented in Figure 3 is from flight 653 on March 9, 2007. The LH brake shows a delay of about 3 seconds from initial brake pedal movement to strain response at the landing gear. Again, there is a stepped characteristic to the pedal movement. For both pedals the hydraulic pressures into the ASM and into the brakes level off at about 150-200 psi for a period of time before rising closer to the level commanded by the pedal position. This is evidence of the delayed brake response due to a combination of factors that slow the hydraulic fill and stroke of the brake pistons necessary to engage the rotating and stationary disks in each brake. The carbon brakes have 40% larger piston displacements than the original steel brakes. This delayed response of the brakes can also be seen with the DBCV's and ASM's from the accident airplane[2].

2) After initiation of braking torque, the antiskid control software can command a near simultaneous pressure reduction in multiple brakes on one or both MLG. The resulting brake torque can then be reduced to near zero for a short period, interrupting the airplane deceleration braking force from one or both MLG, causing directional pulling and/or allowing the MLG to oscillate fore & aft. The pressure reduction occurs due to the antiskid

[1] See the Airworthiness Group Factual Report Addendum 4 – In-Service Evaluation.
[2] See the Airworthiness Group Factual Report Addendum 1.

initialization feature in the ASCU that is designed to quickly optimize brake pressures at the start of a rejected takeoff. Any abrupt deceleration of the MLG wheels causes this initialization to happen. Figures 4 and 5 show the same data parameters as above for the right and left MLG, respectively. Both plots were taken from flight 1201 on March 7, 2007. In Figure 4, the RH pedal position has a stepped characteristic as before and the ASM inlet and brake inlet pressures level off at about 150-200 psi while the brakes are filling. Once the brakes are filled the ASM inlet pressure spikes upward very abruptly. At the same time the strain on the forward side of the MLG begins a damped oscillation consistent with the MLG being pulled aft and then suddenly released causing it to oscillate at its natural frequency. In Figure 5, the LH MLG exhibits a similar response to that on the RH MLG. The one major exception is in the brake inlet pressure. The brake inlet pressure exhibits an abrupt spike at about the same time as the ASM inlet pressure but the brake inlet pressure drops quickly back to a low level. This is direct evidence of the ASCU commanding a significant reduction of the pressure input to one-half of the brake pistons on one wheel in response to the antiskid initialization on at least that LMLG wheel. The reason we don't see this type of spike in the brake inlet pressure on the RMLG is most likely because the brake where the pressure is measured was not completely filled at the time when the initialization was triggered by other brakes/wheels on the RMLG that had already completed their brake fill. Also, note that the application of brake pedals for both occurs between 6 and 7 seconds on the plot while the gear oscillations begin at about 8 and 10 seconds for the RH and LH MLG, respectively. The difference in the time of reduction in brake inlet pressures can result in pilot reports of aircraft pulling left or right during braking and aircraft shuddering during braking.

3) Hydraulic fluid contamination can result in internal damage and malfunction of brake system components. These malfunctions can increase the time to fill the brakes, and in some instances, block the flow of hydraulic fluid to a brake and/or interfere with the satisfactory operation of the antiskid function. FedEx began bleeding the brakes on all of their MD-10-10F airplanes and examining the fluid taken from the brake systems of these airplanes. Many fluid samples had contamination levels well above the recommended limits. The accident airplane, N391FE, also exhibited evidence of brake fluid contamination[3]. The ASM's have internal filters on the return lines that prevent contaminates from returning to the hydraulic system reservoir allowing build-up of contaminates over time. Several brake system components from other FedEx airplanes exhibited light to severe damage from contamination.

4.0 Brake System Changes

As a result of the data obtained from the in-service evaluation, the information uncovered during the accident investigation, and continued support from FedEx, several changes were made to the MD-10 carbon brake system to improve its performance. All of these improvements were installed first on N357FE, the in-service evaluation airplane, to substantiate their performance prior to installing them on the rest of the carbon brake equipped MD-10 aircraft.

To assure clean hydraulic fluid on the 14 FedEx aircraft with the carbon brake system, two main

[3] See the Airworthiness Group Factual Report Addendum 2.

modifications were performed. First, the antiskid manifold return line filters were removed in order to assure any debris in the brake system would flow to the hydraulic system reservoirs and the aircraft hydraulic system filters rather than remain in the ASM. Second, the brakes were replaced and the brake hydraulic systems were flushed to assure the removal of any contamination currently in the system.

The DBCV was modified to reduce both the initial dead band and the pressure gain versus the brake pedal position as illustrated in Figure 6. The black line is the original metered pressure schedule versus the input lever position for the DBCV and the dashed white line is the modified schedule. The modified schedule starts metered pressure output at a lower lever position (reduced dead band) and meters a lower pressure output for the first half of the lever travel. This modification reduces the delay between initial brake pedal advance and initial brake torque. In addition, other minor changes to the DBCV increased the fluid flow at small lever positions. The modifications make the MD-10 DBCV behave more like the MD-11 Integrated Brake Control Valve. Boeing Airplane Modification Letter (AML) MD-10-AML-32-103-A installs this improved DBCV on the FedEx airplanes.

The ASM was modified to change the brake inlet pressure response characteristic versus control signal from the ASCU and a separate 3000 psi hydraulic source was added to the brake system #2 ASM on each MLG. During brake pedal application typical in normal landing and taxi operations, the modified brake inlet pressure schedule (“unigain”) prevents any momentary pressure reduction commanded by the ASCU in one-half of each MLG brake (4 of 8 pistons). The modification does not affect brake system operation for brake pedal applications of more than about three-fourths of full travel. The modification eliminates the initialization software effect to brake system #2 preventing the pressure reduction at all wheels on each MLG. The brake torque reduction is changed from almost 100% to about 40% preventing the oscillations of the MLG seen in the ISE data. Boeing AML MD-10-AML-32-104-A installs the improved ASM and associated hydraulic lines on the FedEx airplanes.

After the two above noted AML’s were incorporated on N357FE, a series of tests was performed to gather in-service brake system data. Figures 7 and 8 show results for the RH and LH MLG, respectively. For both plots the aircraft was taxiing at 25 knots and the brakes were applied. In Figure 7, brake system 1 was active and brake system 2 was shut off. The data shows that the time between pedal application and MLG response is less than 1 second, significantly less than before. The data also shows the antiskid system significantly reduces the brake inlet pressure causing a gear oscillation since the system 2 was off. In Figure 8, brake system 1 was shut off and brake system 2 was active. The data again shows less than 1 second from application of the pedal to MLG response. The MLG response is smooth and does not show any oscillations. The data shows significantly less delay to initiate brake torque, minimal advancing of brake pedals before brake torque initiation, lowers the initial brake pressure and torque, prevents any significant reduction in multiple brake pressures, and minimizes any fore/aft movement of the main gears during braking. These two brake system improvements, along with the modified brake system described earlier, are being installed on all MD-10-10F aircraft.

DATE	DESCRIPTION	CLOSE	ACTION	STA
27-Sep-05	Grabbing brakes, more on right side	27-Sep-05	Checked Temps, ASCU, Cycled, NFF	IND
19-Nov-05	Brakes grab at all speeds, bad at landing	19-Nov-05	NFF	MEM
11-Dec-05	Grabbing brakes when applied from FO side	11-Dec-05	Rig check, rigged right valve bottom drum	MEM
11-Jan-06	RTO high temped	11-Jan-06	Inspect, NDF	ORD
18-Feb-06	Grabbing at high speed, left side worse	18-Feb-06	Replaced ASCU	OAK
22-Feb-06	Right brakes grabbed	22-Feb-06	NFF, bled brakes	IND
24-Feb-06	Right brake grabs on landing	24-Feb-06	Air in Rsvr, bled brakes	IND
24-Feb-06	Brakes drag on taxi out	24-Feb-06	Return to gate, NFF	IND
24-Feb-06	Brakes drag on TO, RTO 90k	25-Feb-06	Brake pistons ok, temp 350 left, 160 right, replaced DBCV	IND
24-Feb-06	Tech Service Item opened	2-Mar-06	Multiple items	MOCC
24-Feb-06	Dragging on taxi, 350/165	25-Feb-06	Taxi and RTO test ok.	IND
13-Mar-06	Anti-skid fault	13-Mar-06	R&R ASCU	JAX
16-Mar-06	Anti-skid fault	16-Mar-06	Cycled CBs, NFF	AFW
17-Mar-06	Right brake grabs at 90k on rollout	28-Mar-06	Leaking in pucks, R&R brake ass'y	LAX
17-Mar-06	TSI Opened	28-Mar-06	Multiple/Above	MOCC
17-Mar-06	Both brakes grab on landing	17-Mar-06	NFF, maybe same landing as #22	AFW
18-Mar-06	Brake diff temps	19-Mar-06	NFF, note "brake just changed", I.e. line 24	LAX
22-Mar-06	Right brakes grab, temp diff	22-Mar-06	#4 brake hot, R&R brake ass'y	ORD
22-Mar-06	Anti-skid fault	23-Mar-06	Repair wire at transducer	ANC
22-Mar-06	Right brakes grabbing/temp diff	23-Mar-06	Bleed, check rig, R&R #7/8 ass'y	ANC
7-Apr-06	#3 Main brake leaking	7-Apr-06	R&R	MEM
14-Apr-06	Right side, right brake very sensitive	14-Apr-06	Rig right DBCV	MEM
14-Apr-06	TSI opened due to above	22-Apr-06	Multiple	MOCC
14-Apr-06	#6 brake high temp	14-Apr-06	Repair sensor	MEM
20-Apr-06	Brakes locked on rollout	22-Apr-06	NFF, work with TSI	MEM
20-Apr-06	TSI opened	28-Apr-06	Multiple	MOCC
14-Jul-06	Both grab on rollout	14-Jul-06	#3 leaking, R&R	MEM

NFF – No Fault Found
NDF – No Discrepancies Found
R & R – Remove and Replace
TSI – Trouble Shooting Instructions from Maintenance Operations Control Center (MOCC)

Table 1 – Brake Write-Ups, N391FE

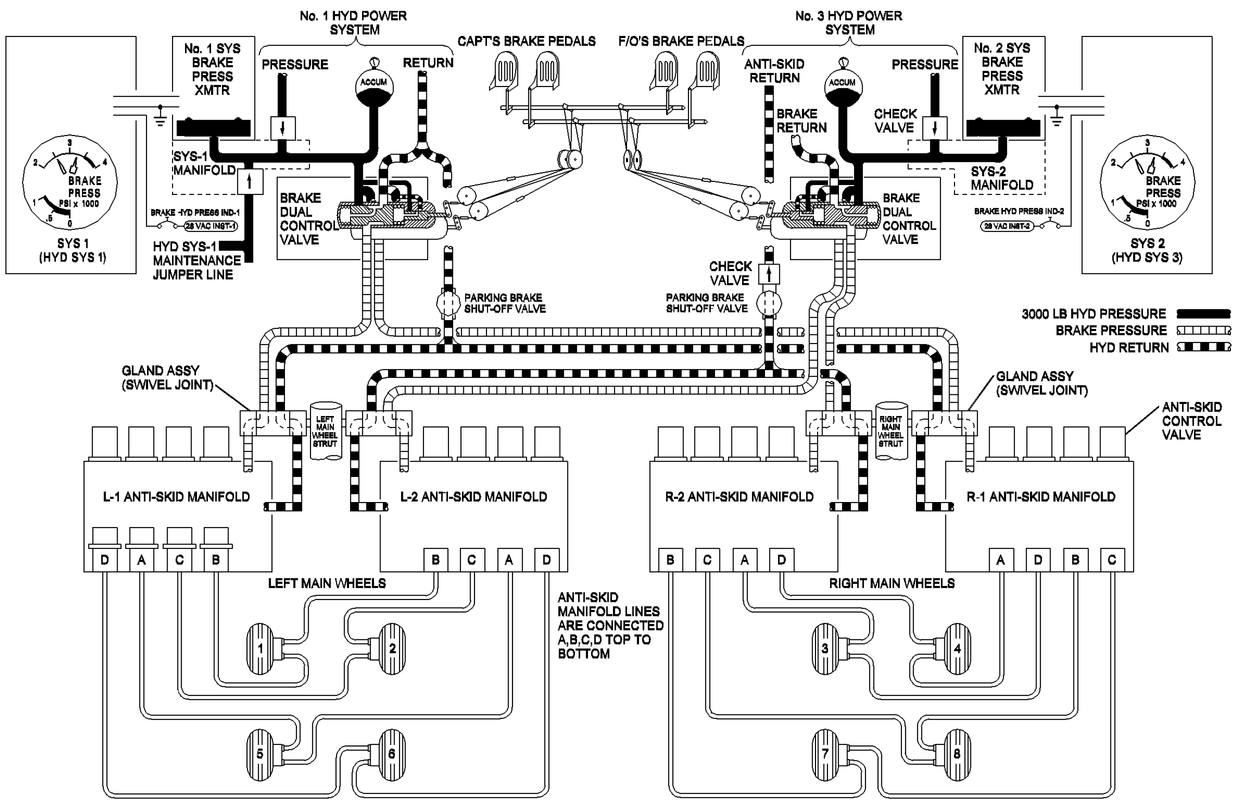

Figure 1 – MD-10 Brake System Schematic

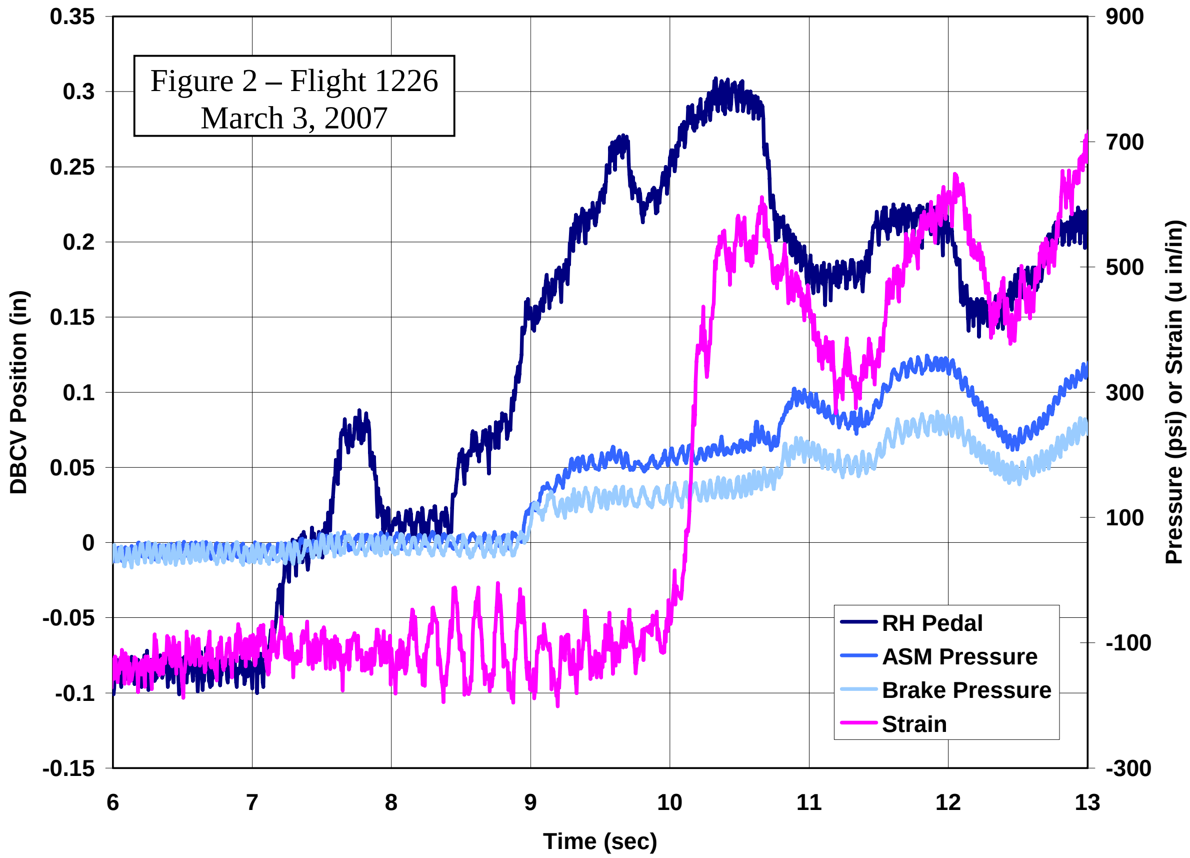

Figure 2 – Flight 1226
March 3, 2007

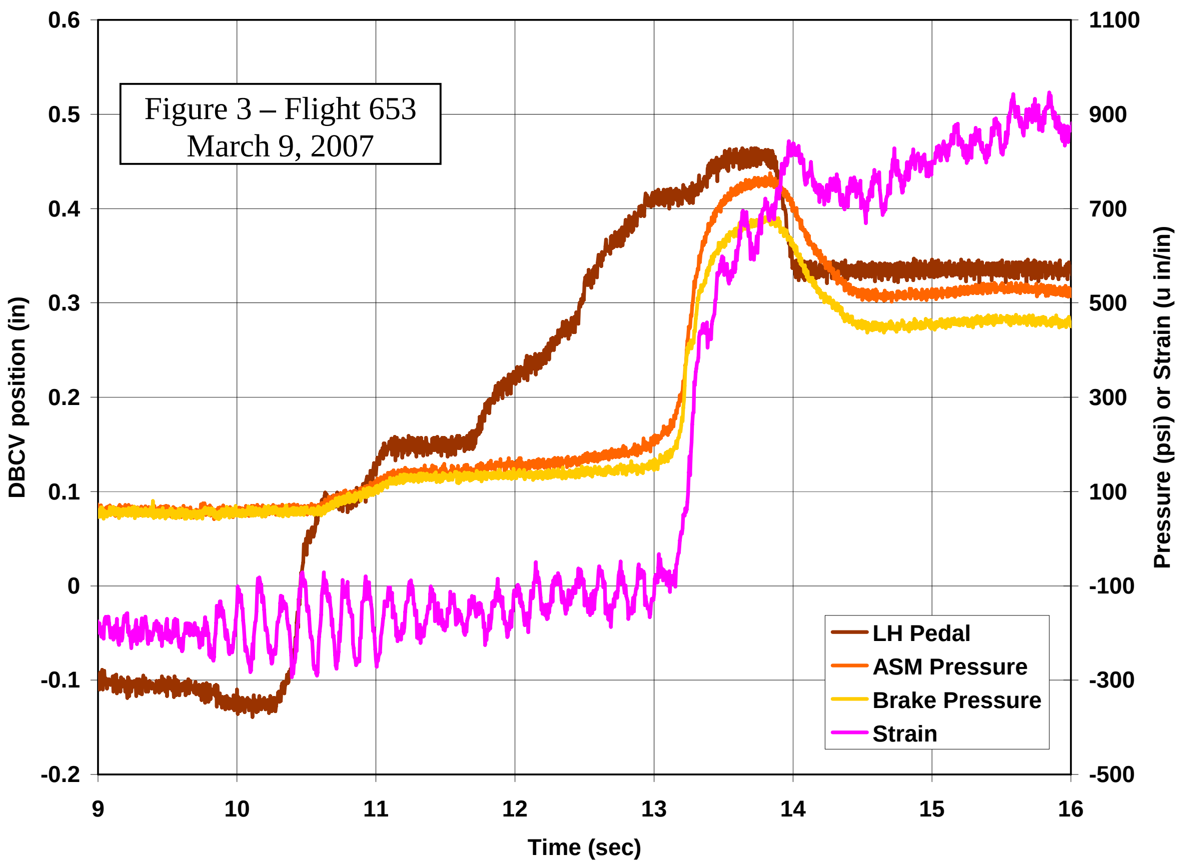

Figure 3 – Flight 653
March 9, 2007

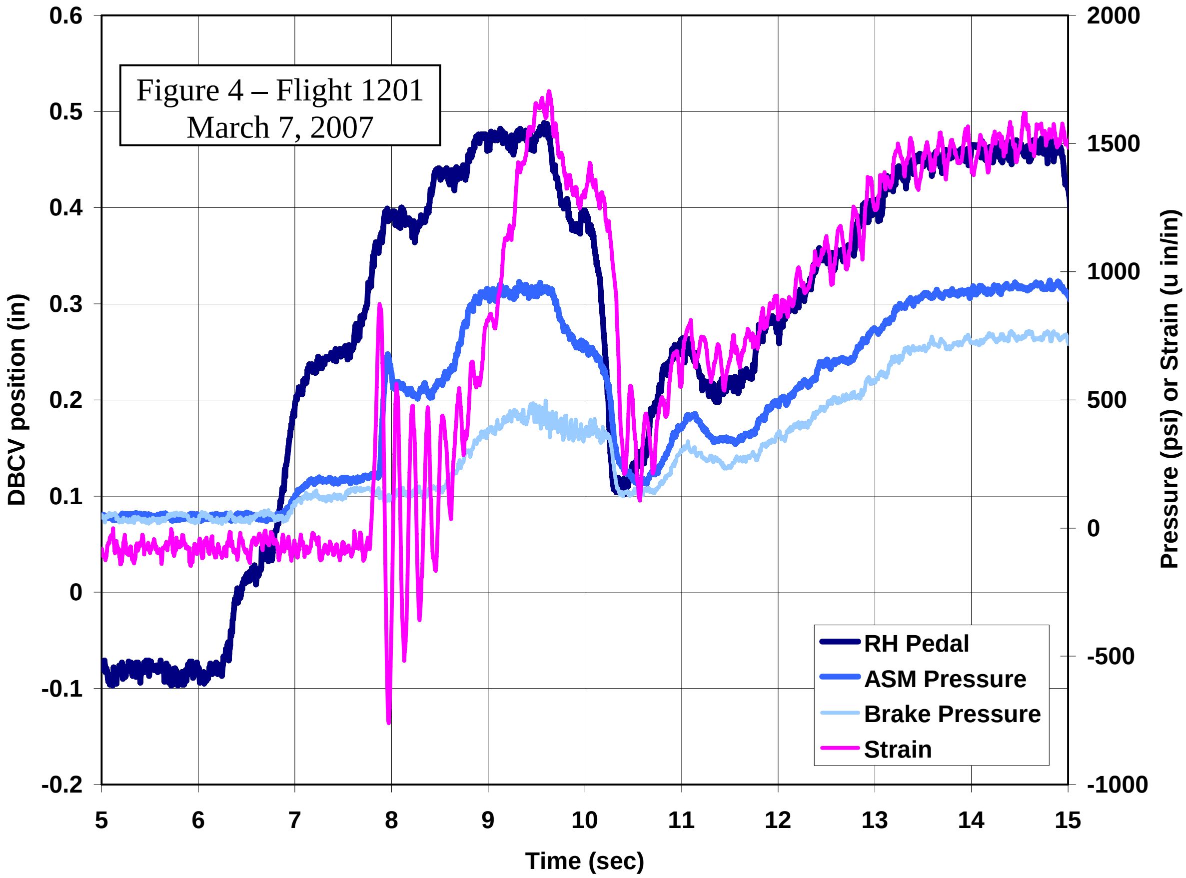
Figure 4 – Flight 1201
March 7, 2007
DBCV position (in)
Pressure (psi) or Strain (u in/in)
Time (sec)
RH Pedal
ASM Pressure
Brake Pressure
Strain
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
2000
1500
1000
500
0
-500
-1000
5
6
7
8
9
10
11
12
13
14
15

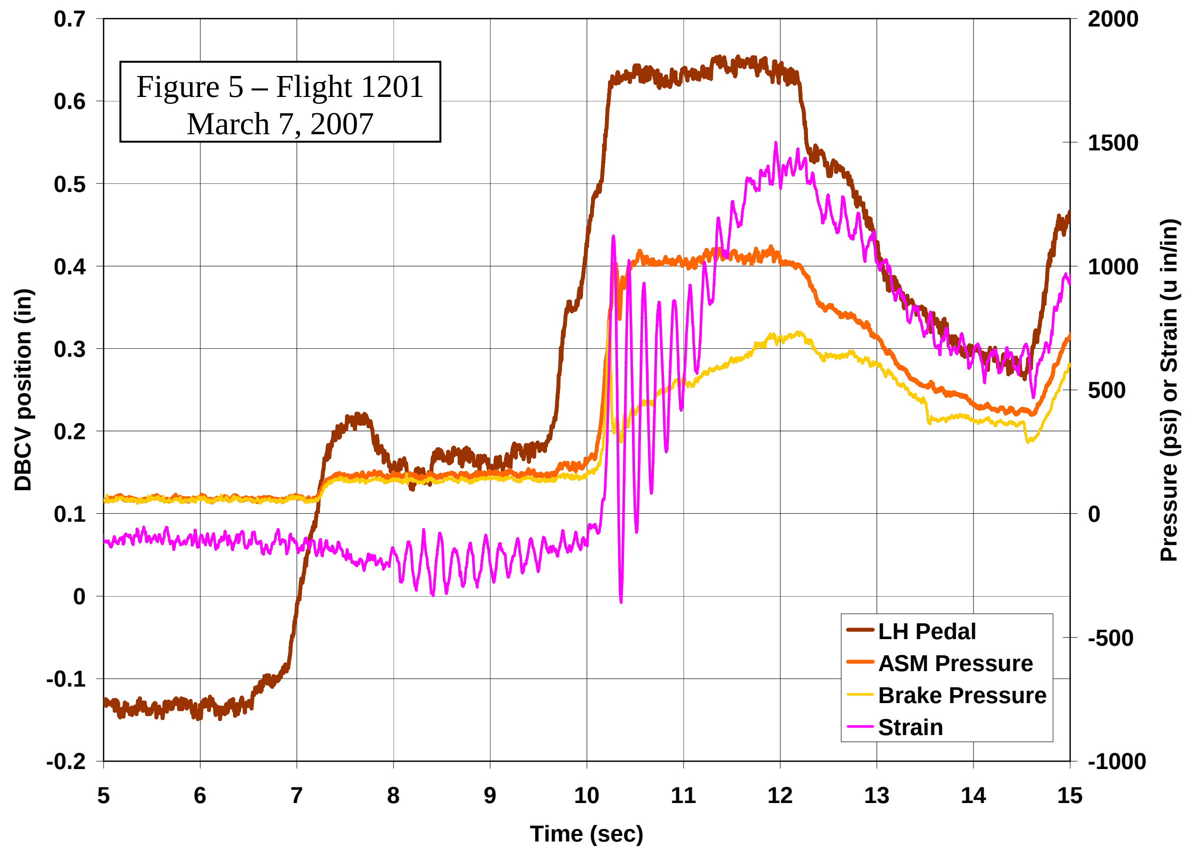
Figure 5 – Flight 1201
March 7, 2007
DBCV position (in)
Pressure (psi) or Strain (u in/in)
Time (sec)
LH Pedal
ASM Pressure
Brake Pressure
Strain
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
2000
1500
1000
500
0
-500
-1000
5
6
7
8
9
10
11
12
13
14
15

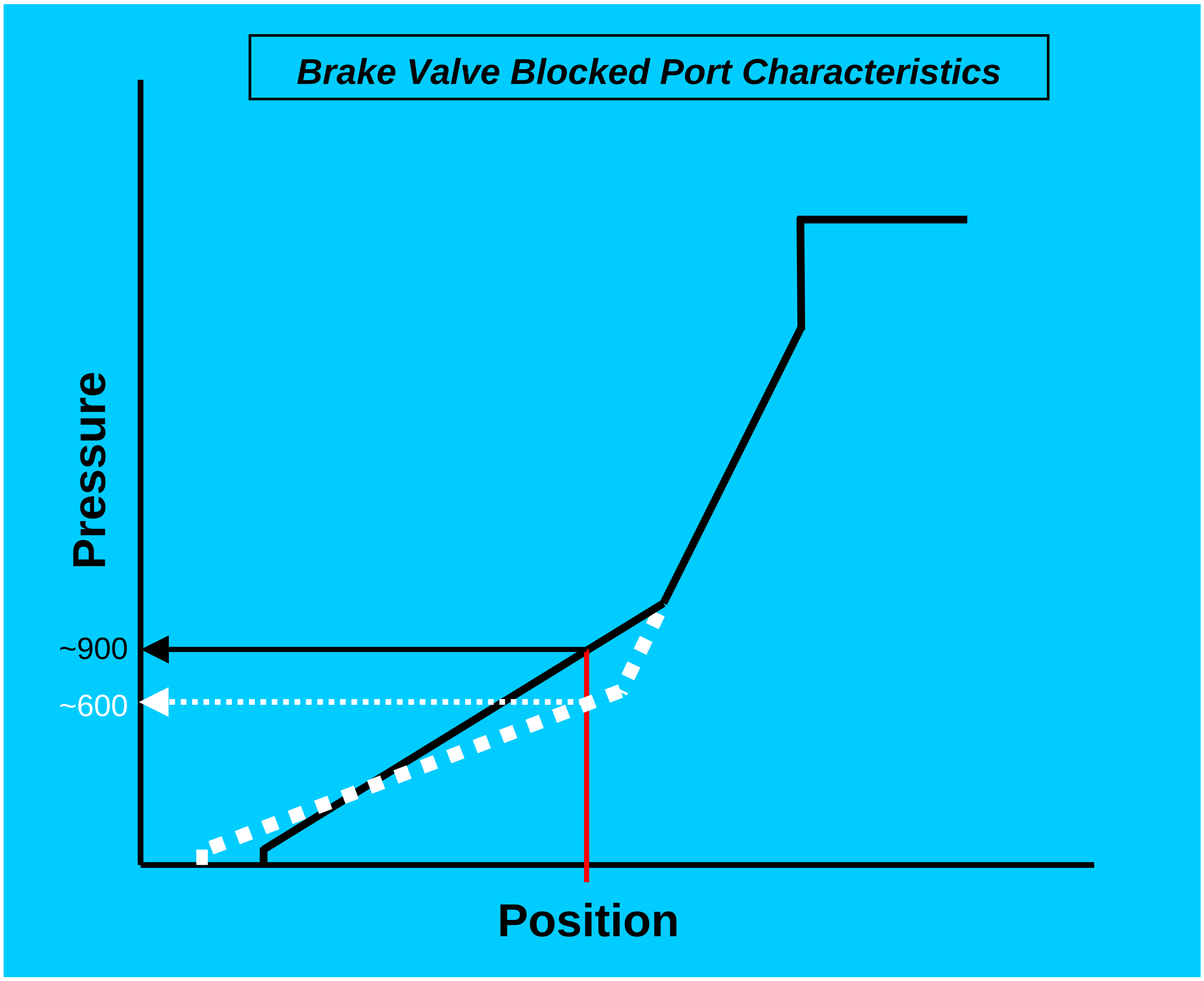

Figure 6 – DBCV Modifications (Post ISE)

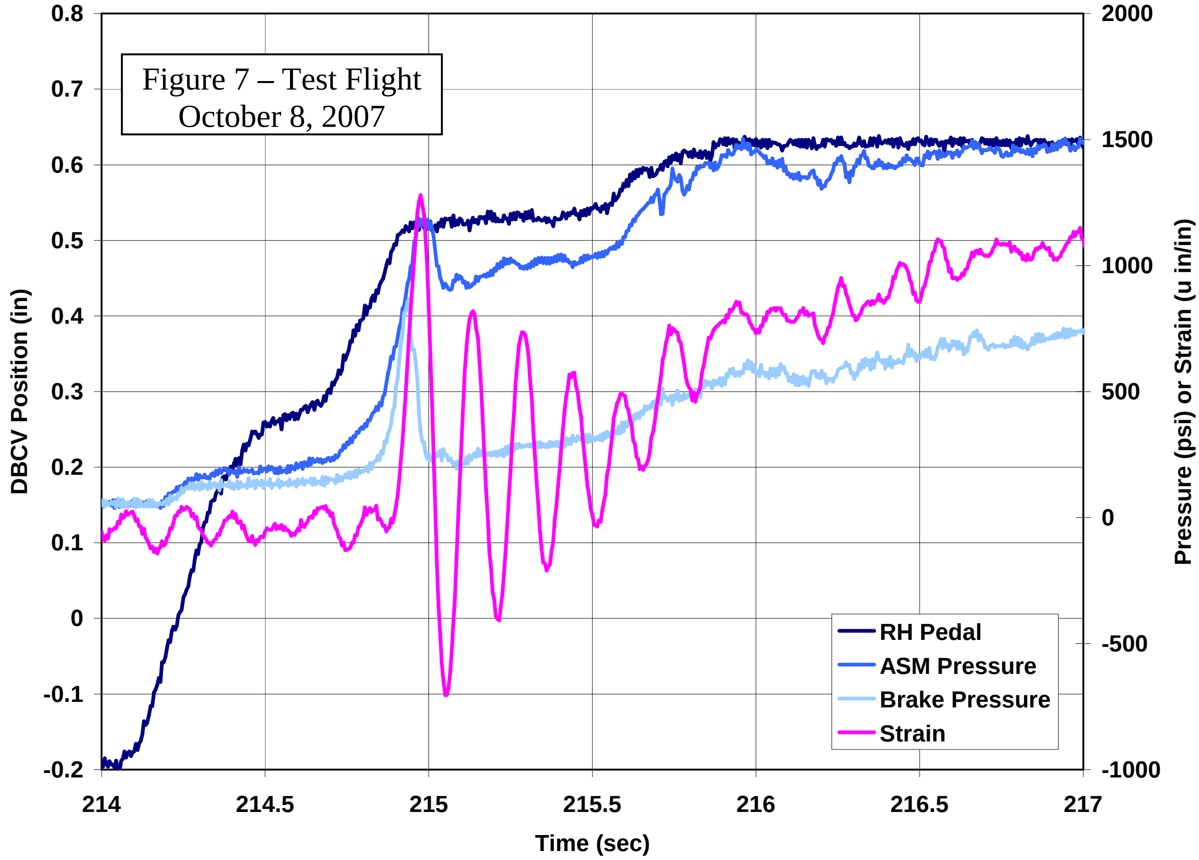
Figure 7 – Test Flight
October 8, 2007
DBCV Position (in)
Pressure (psi) or Strain (u in/in)
Time (sec)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
2000
1500
1000
500
0
-500
-1000
214
214.5
215
215.5
216
216.5
217
RH Pedal
ASM Pressure
Brake Pressure
Strain

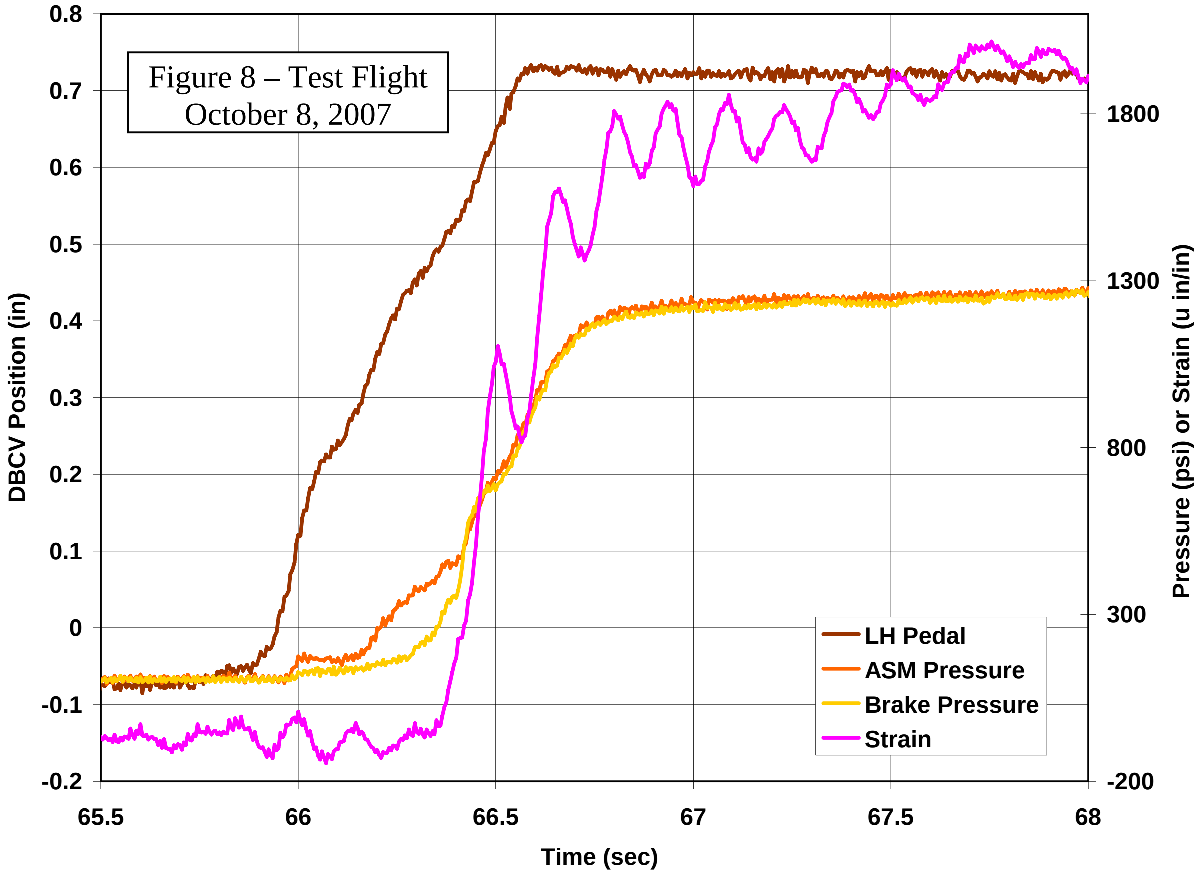
Figure 8 – Test Flight
October 8, 2007
DBCV Position (in)
Pressure (psi) or Strain (u in/in)
Time (sec)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
1800
1300
800
300
-200
65.5
66
66.5
67
67.5
68
LH Pedal
ASM Pressure
Brake Pressure
Strain