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

AIRWORTHINESS GROUP FACTUAL REPORT ADDENDUM 7
MAIN LANDING GEAR LOADS

July 21, 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

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C. DETAILS OF THE INVESTIGATION

1.0 Load Generation

The recorded raw data from each in-service evaluation (ISE) flight was stored in a unique Microsoft Excel spreadsheet with the date and time as the filename. The brake system pressures and strain values on the forward and aft sides of each main landing gear (MLG) below the air filler valve hole were copied to a stress worksheet to be manipulated and evaluated for each ISE flight. The zero offset strain value was subtracted from the recorded strain value at each time to produce an adjusted strain at the locations on the forward and aft side of the MLG strut about 3.60" below the air filler valve hole (RL5, RL6, LL5, and LL6). The data from flight 483 on April 10 (ID 10.27) and all subsequent flights indicated that strain gage RL6 was in error. For all subsequent flights the RL6 values were calculated using -1.22*RL5 based on several previous flights with good strain data on the RMLG. The drag in kips was calculated from the adjusted strain values using the following equations:

For the RMLG:

$$D_R(kips) = \frac{RL5 - RL6\left(\mu in / in\right)}{0.075414\left(\mu in / in \cdot lb\right)\left(1000\, lb / kips\right)}$$

For the LMLG:

$$D_L(kips) = \frac{LL5 - LL6\left(\mu in / in\right)}{0.073169\left(\mu in / in \cdot lb\right)\left(1000\, lb / kips\right)}$$

The constants in these equations were calculated based on the calibration runs performed after the instrumentation was installed. At the 90% N1 thrust level it was assumed that each MLG equally reacted the thrust yielding a drag load on each MLG of 31,000 lbs. The strains at the L5 and L6 locations on each MLG were recorded during the calibration runs and averaged over the entire run. Since the MLG material behaves in a linear fashion, the ratio of strain to drag load will remain constant for loading less than the yield stress and was calculated using the following:

$$k = \frac{\overline{XL5} - \overline{XL6}\left(\mu in / in\right)}{31{,}000(lbs)}$$

where X can be R or L depending on which MLG is being calculated. The drag load on the MLG was used only for plotting and examination and was not used in the fatigue analysis.

The principal hole stress at the 3 o'clock and 9 o'clock positions, in ksi, was then calculated using the adjusted strain below the hole as follows:

$$\sigma_{ISE} = CE\varepsilon = \frac{(2.6)(29\times10^{6}\ psi)XL6\left(\mu in/_{in}\right)}{1000\left(lb/_{kips}\right)}$$

where X can be R or L depending on which MLG is being calculated, C is the constant stress ratio between the L6 location and the principal hole stress, and E is Young's Modulus for 300M steel.

The above calculations were performed at each 0.005-second time increment for all of the ISE flights. The pressure and drag load data was plotted for each case and a dividing time between the touchdown and the initiation of braking was selected. A simple search routine provided the maximum and minimum drag load and stress values for the landing and braking portions of the data. This data was then collected in a loads worksheet for all of the ISE flights[1].

The maximum drag load due to braking on the RMLG was about 90 kips on flight 3857 (ID 8.19). The LMLG encountered a 96 kip drag load due to braking on flight 1205 (April 7, ID 10.23) and a 107 kip drag load due to braking on flight 842 (May 11, ID 12.52). The data from flight 1205 is presented in Figures 1 and 2. For all of the ISE data presented the x-axis represents elapsed time in seconds. The data shows erratic brake pedal applications on both the right and left pedals with the left being higher. The right hand (RH) pedal inputs also begin about 10 seconds before any left hand (LH) pedal inputs. The left pedal shows 6 abrupt applications that increase in stroke to the 5th application. It is on this 5th application of the left pedal where the 96 kip drag load occurs. The LMLG appears to deflect aft, deflect forward, and undergo a damped oscillation about the zero point. The data from flight 842 is presented in Figures 3 and 4. The data shows two sharp LH pedal inputs at the beginning of braking with one smoother and less severe RH pedal input beginning between the LH pedal inputs. Both LH pedal inputs are at about the same full deflection level yet they do not produce similar drag loads on the LMLG. The second LH pedal input produces a drag load of about 107 kips on the LMLG.

In order to examine the effects of the 100 kips drag load due to braking on the MLG, the Brake E condition with the drag set to 100 kips was run in the Finite Element Model (FEM)[2]. This condition produced a minimum principal stress (maximum compressive stress) of about -260 ksi at the 3 and 9 o'clock positions in the hole (Figure 5) and an equivalent plastic strain of about 0.0023. These results indicate the material has compressively yielded in the hole. The model was unloaded and revealed a residual tension stress of about 47 ksi at the 3 and 9 o'clock positions in the hole (Figure 6). The residual tension stress penetrated to a depth of about 0.025". This residual tension stress was assumed to be present in the air filler valve hole from the beginning of operation for the purposes of the fatigue analysis.

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[1] The loads worksheet for the ISE flights is presented in Attachment 1 to this report.
[2] See Airworthiness Group Factual Report Addendum 6 – MLG Finite Element Model for details.

Examination of the loads revealed an unusually high drag load due to braking on the LMLG of about 153 kips on flight 308 (April 4, ID 10.14). The magnitude of the drag load was about 50% larger than the next largest drag load calculated. The data from this flight is presented in Figures 7 and 8. There are three applications of the LH brake pedal with the last two close to the full deflection of the pedal. It is during the third pedal application that the drag load on the LMLG reaches its maximum value. The first LH pedal application does not produce a significant spike in the drag load on the landing gear but does result in a damped oscillation about the zero point. Without data for the LH brake pressure it is difficult to know what is happening with the brakes, but the appearance of the drag load is similar to activation of the anti-skid feature of the system for the first pedal application. The Brake E condition with a drag load of 153 kips was run in the FEM and produced a principal stress in the hole of about -295 ksi and an equivalent plastic strain of about 0.0075. Unloading of the model produced a residual tension stress in the hole of about 136 ksi. The group elected not to include this residual stress in the fatigue spectrum of a typical MD-10-10 for the following reasons, but did use the braking data in the fatigue analysis:

1. A residual tension stress of 136 ksi in the hole would have resulted in many more MLG cylinder failures similar to this one over the life of the DC/MD-10
2. Several drag loads in the vicinity of 100 kips were measured during the ISE but none were measured between 100 kips and 153 kips.
3. The special hard braking tests performed on March 29 produced drag loads less than 100 kips.
4. The 153 kips drag load indicates a coefficient of friction of approximately 1.0 based on the airplane gross landing weight. This exceeds the 0.8 limit load coefficient of friction per 14 CFR 25.493(b) and the 0.72 design limit load coefficient of friction.
5. The maximum hole stress due to braking is consistent with the other measured ISE flights and was, therefore, used in the braking spectrum.

2.0 Nickel Effect

During the NTSB materials laboratory investigation[3], a 0.008” layer of nickel was found in the air filler valve hole at the point of crack initiation. Examination of the outer cylinder manufacturing drawing and overhaul manuals revealed that this layer of nickel was not supposed to be present. The nickel did not completely cover the entire diameter of the hole, was of varying thickness, and had a somewhat splattered appearance. Research into the effect of nickel plating on 300M steel was conducted. According to the Metals Handbook[4], “Chromium, iron, and nickel plating generally contain high residual tensile stresses, which reduce the fatigue strength of the base metal of a shaft.” The detailed information and test data available for the effects of nickel plating on high strength steel involved either electroless nickel plating or nickel and chrome plating together on either 300M or 4340 steel rather than just electro-deposited nickel on steel. There is no nickel plating applied to the MLG outer cylinder during manufacture but the Component Maintenance Manual (CMM) allows for nickel plating of certain areas of the outer cylinder to build up worn areas of the seals or bearings. The allowed nickel is then plated with chrome.

[3] See the NTSB Materials Laboratory Factual Report 06-076 for details.
[4] American Society of Materials Metals Handbook, Volume 2, 8th Edition.

In the late 1970's Boeing performed a study on the effects of chromium and sulfamate nickel plating on the fatigue strength of 300M steel[5]. The test involved application of sinusoidal varying load on 300M steel coupons with groundout areas that had been filled with either soft or hard sulfamate nickel plating and subsequently plated with a 0.003" layer of chrome. The nickel was applied and tested in three different thicknesses, 0.030", 0.060", and 0.090". The coupons were tested to failure to develop the stress-life (S-N) curves. The total plating thickness versus stress factor was then plotted from the available data. The resulting curve reveals that with a nickel plating thickness of 0.008" a stress factor of 1.35 results. This factor will be applied to all MLG hole stresses for the purposes of the fatigue analysis.

3.0 ISE Fatigue Loads Analysis

The data from the ISE was used to develop fatigue spectra separately for the landing and braking components of the flights. A total of 266 flights had valid braking data and were used for the fatigue analysis. The minimum and maximum air filler valve stress was calculated for each valid flight as described in section 1.0. The calculations were performed for each case with the nickel effect in the hole and without the nickel effect. The residual tension stress of 47 ksi was included in all conditions. The maximum stress was calculated using:

$$\sigma_{\max} = \sigma_{\max ISE} + 47ksi \quad \text{(without nickel)}$$

$$\sigma_{\max} = 1.35\sigma_{\max ISE} + 47ksi \quad \text{(with nickel)}$$

Only those cases where the maximum ISE hole stress was positive (tension) had the nickel factor applied. The minimum stress was calculated using:

$$\sigma_{\min} = \sigma_{\min ISE} + 47ksi \quad \text{(with and without nickel)}$$

The stress ratio was calculated using:

$$R = \frac{\sigma_{\min}}{\sigma_{\max}}$$

The number of flights (n) was set to 1 for each case and the number of cycles to failure or life, N, was calculated using:

$$N = 10^{\left(14.8 - 5.38\log\left(S_{eq} - 63.8\right)\right)}$$

where:

$$S_{eq} = \frac{\sigma_{\max} - \sigma_{\min}}{2} + 0.48\frac{\sigma_{\max} + \sigma_{\min}}{2}$$

For the cases where N was calculated greater than 10,000,000 or where S_{eq} was less than 63.8 ksi, N was assigned a value of 10,000,000. The equation for N was derived from the Equivalent Stress Equation in MIL HDBK 5G, Figure 2.3.1.4.8(a) for unnotched 300M alloy forging. The note in the HDBK states that the Equivalent Stress Equation may provide unrealistic life estimates for stress ratios lower than R=-2.0 but the group decided that using it would give

[5] Reference Boeing document MDC-J3216, "Model DC-10 Fatigue Strength Effect of Chromium and Sulfamate Nickel Plate for Local Rework of 300M Steel"

conservative results. The accumulated damage (n/N) was calculated or was assigned a value of 0.0000001 if it was less than this value. The total accumulated damage for the RMLG and LMLG both with and without nickel was obtained by summing the individual damage values. The data for the RMLG is shown in Attachment 2 to this report and the LMLG data is shown in Attachment 3 to this report. The accumulated damage was normalized to 1000 landings.

Braking Damage	Damage per 266 Flights	Damage per 1000 Flights
RMLG without Nickel	0.00092955	0.00349455
RMLG with Nickel	0.00335479	0.01261200
LMLG without Nickel	0.00031077	0.00116832
LMLG with Nickel	0.00071503	0.00268808

The RMLG with Nickel has the greatest damage accumulation for the ISE braking data. There was no separate fatigue analysis due to braking at the hole location performed for certification of the airplane since the major loads are compressive in nature and the hole was not critical during the full-scale fatigue test.

A total of 237 ISE flights had valid landing data and were used for the fatigue analysis. A sample of typical hole stresses due to landing loads on the MLG from flight 1427 (February 13, ID 4.01) is shown in Figure 9. Each MLG deflects aft at touchdown producing a peak drag load (and minimum hole stress) then undergoes a damped oscillation back to its static position. The maximum hole stress values occur after the touchdown when the MLG swings forward after the aft deflection. The group elected to use the maximum hole stress and the successive two peaks for the fatigue analysis. The conservative assumptions were made that each of the three maximum peaks resulted in a fully reversed stress (R=-1), the second peak was 75% of the first, and the third peak was 50% of the first. The maximum landing hole stress measured during the ISE and corresponding to the first peak was grouped into 10 ksi stress bins and counted. The data was then normalized to 1000 landings. The ISE landing spectrums for the RMLG and LMLG are shown in Table 1.

The original certification of the MD-10-10 was performed based on sink speed and the assumed number of occurrences per 150,000 landings[6]. Examination of the ISE data revealed that the majority of the landings occurred with an angle of attack of about 6°. The certification conditions for spring back at 6° angle of attack and sink rates from 2.5 ft/sec to 8.5 ft/sec were input into the FEM to obtain the air filler valve bore principal stress. The bore principal stress for a sink rate of 9.5 ft/sec was linearly extrapolated from the values at 7.5 ft/sec and 8.5 ft/sec. The hole stress from the FEM was then factored up by 10%, placed into 10 ksi stress bins and normalized to 1000 landings. The hole stress at the 0.5 ft/sec and 1.5 ft/sec sink speeds was very small, essentially 0 ksi. Table 2 shows the certification landing spectrum. Table 3 provides a comparison of the certification and ISE spectra.

A fatigue evaluation of both the certification and ISE landing spectrums was then performed. For each certification condition or ISE stress bin, the fatigue damage at the 100% (A), 75% (B), and

[6] Reference Boeing Document DAC-67365 "DC-10 MLG Fatigue Criteria".

50% (C) stress levels was calculated with the nickel effect in the hole and without the nickel effect. The residual tension stress of 47 ksi was included in all cases. As noted before, the certification stresses from the FEM were factored up by 10%. The maximum stress was calculated using:

$$\sigma_{\max} = \sigma + 47ksi \text{ (without Nickel)}$$

$$\sigma_{\max} = 1.35\sigma + 47ksi \text{ (with Nickel)}$$

The minimum stress was calculated using:

$$\sigma_{\min} = -\sigma + 47ksi \text{ (with and without Nickel)}$$

The stress ratio, R, was calculated using the same equation as in the braking analysis. The number of cycles to failure (fatigue life) was taken from the Boeing certification S-N curves for 300M[7]. The original Boeing data had stress-life (S-N) curves for R=0, -0.2, -0.4, -0.6, and -1.0. A linear interpolation of the given data was performed to produce S-N data at R=-0.1, -0.3, -0.5, -0.7, -0.8, and -0.9. The calculated stress ratio and maximum stress were compared to the certification data and the number of cycles to failure, N, was chosen from the tabulated values at the highest stress ratio less than or equal to the calculated value and the highest stress less than or equal to the calculated value.

The fatigue damage, n/N, was calculated for each condition and summed to provide the total accumulated damage per 1000 landings. ISE stress levels below 40 ksi do not produce any fatigue damage so these conditions do not contribute to the accumulated damage in the analysis. Sink speeds of 0.5 ft/sec and 1.5 ft/sec produce very little stress in the hole, minimal spin up, and minimal spring back so the damage for these conditions was assumed to be zero. The ISE and certification fatigue data for both the RMLG and LMLG is presented in Attachment 4 to this report. The accumulated damage for the ISE and certification conditions per 1000 landings is shown below. The certification data assumes equivalent damage on the RMLG and LMLG.

Per 1000 flights	Damage (ISE)
RMLG without Nickel	0.00706329
RMLG with Nickel	0.10499639
LMLG without Nickel	0.00102536
LMLG with Nickel	0.01404425

Per 1000 flights	Damage (Certification)
MLG without Nickel	0.00035924
MLG with Nickel	0.00530493

The fatigue life in cycles was determined by calculating the number of cycles required for a damage accumulation of 1.0. For the certification data a scatter factor of 3.0 was used and for the ISE data a scatter factor of 1.0 was used.

[7] Reference Boeing Document MDC-J8386, "300M and Hy-Tuf Steel Fatigue Properties Comparison"

FedEx MD-10-10 Certification Damage & Fatigue Life		
Condition	No Nickel	0.008" Nickel
Landing - Per 1000 Flights	0.00035924	0.00530493
Braking - Per 1000 Flights	0	0
Total - Per 1000 Flights	0.00035924	0.00530493
Fatigue Life (cycles, scatter factor of 3)	927874	62835

FedEx MD-10-10 ISE RMLG Damage & Fatigue Life		
Condition	No Nickel	0.008" Nickel
Landing - Per 1000 Flights	0.00706329	0.10499639
Braking - Per 1000 Flights	0.00349455	0.01261200
Total - Per 1000 Flights	0.01055784	0.11760839
Fatigue Life (cycles)	94716	8503

FedEx MD-10-10 ISE LMLG Damage & Fatigue Life		
Condition	No Nickel	0.008" Nickel
Landing - Per 1000 Flights	0.00102536	0.01404425
Braking - Per 1000 Flights	0.00116832	0.00268808
Total - Per 1000 Flights	0.00219368	0.01673233
Fatigue Life (cycles)	455855	59765

The MD-10-10 MLG outer cylinder was certificated for a safe life of 46,800 cycles based on the forward trunnion lug failure during the full-scale fatigue test. The fatigue analysis indicates a fatigue life of 8,503 cycles based on the RMLG with nickel present in the air filler valve hole, a residual stress of 47 ksi in the hole and using the ISE spectrum. The analysis indicates a safe life of 62,835 cycles (scatter factor of 3) based on either MLG with nickel present in the air filler valve hole, a residual stress of 47 ksi in the hole and using the certification spectrum.

FedEx MD-10-10 In-Service Evaluation RMLG Air Filler Valve Stresses Landing Spectrum				
Stress Range (ksi)	Stress Bin (ksi)	ISE Frequency (Occurrences)	Cumulative %	Frequency per 1000 landings
5-15	10	82	34.60	345.99
16-25	20	45	53.59	189.87
26-35	30	46	73.00	194.09
36-45	40	27	84.39	113.92
46-55	50	7	87.34	29.54
56-65	60	9	91.14	37.97
66-75	70	5	93.25	21.10
76-85	80	2	94.09	8.44
86-95	90	2	94.94	8.44
96-105	100	4	96.62	16.88
106-115	110	2	97.47	8.44
116-125	120	3	98.73	12.66
126-135	130	1	99.16	4.22
136-145	140	0	99.16	0.00
146-155	150	1	99.58	4.22
156-165	160	1	100.00	4.22

FedEx MD-10-10 In-Service Evaluation LMLG Air Filler Valve Stresses Landing Spectrum				
Stress Range (ksi)	Stress Bin (ksi)	ISE Frequency (Occurrences)	Cumulative %	Frequency per 1000 landings
5-15	10	131	55.27	552.74
16-25	20	42	73.00	177.22
26-35	30	24	83.12	101.27
36-45	40	14	89.03	59.07
46-55	50	3	90.30	12.66
56-65	60	7	93.25	29.54
66-75	70	2	94.09	8.44
76-85	80	7	97.05	29.54
86-95	90	3	98.31	12.66
96-105	100	2	99.16	8.44
106-115	110	1	99.58	4.22
116-125	120	0	99.58	0.00
126-135	130	0	99.58	0.00
136-145	140	1	100.00	4.22
146-155	150	0	100.00	0.00
156-165	160	0	100.00	0.00

Table 1 – MLG ISE Landing Spectrums for RMLG and LMLG

Sink Speed (ft/sec)	Stress (ksi)	FEM Factor 1.10*Stress (ksi)	Stress Bin (ksi)
0.5	0.0	0.0	0
1.5	0.0	0.0	0
2.5	1.9	2.1	0
3.5	56.0	61.7	60
4.5	84.2	92.6	90
5.5	101.1	111.2	110
6.5	97.3	107.0	110
7.5	117.9	129.7	130
8.5	144.8	159.3	160
9.5	171.7	188.9	190

Table 2 – Certification MLG Landing Spectrum[8]

FedEx MD-10 MLG Air Filler Valve Stresses Comparison of Certification and In-Service Data			
Stress Bin (ksi)	Occurrences Certification	Occurrences ISE RMLG	Occurrences ISE LMLG
0	840	0.00	0.00
10	0	345.99	552.74
20	0	189.87	177.22
30	0	194.09	101.27
40	0	113.92	59.07
50	0	29.54	12.66
60	122	37.97	29.54
70	0	21.10	8.44
80	0	8.44	29.54
90	29	8.44	12.66
100	0	16.88	8.44
110	8.63333	8.44	4.22
120	0	12.66	0.00
130	0.3	4.22	0.00
140	0	0.00	4.22
150	0	4.22	0.00
160	0.06	4.22	0.00
170	0	0.00	0.00
180	0	0.00	0.00
190	0.00667	0.00	0.00

Table 3 – Comparison of ISE and Certification Landing Spectra

[8] Reference Boeing Document DAC-67365 "DC-10 MLG Fatigue Criteria" for the number of occurrences at each sink speed.

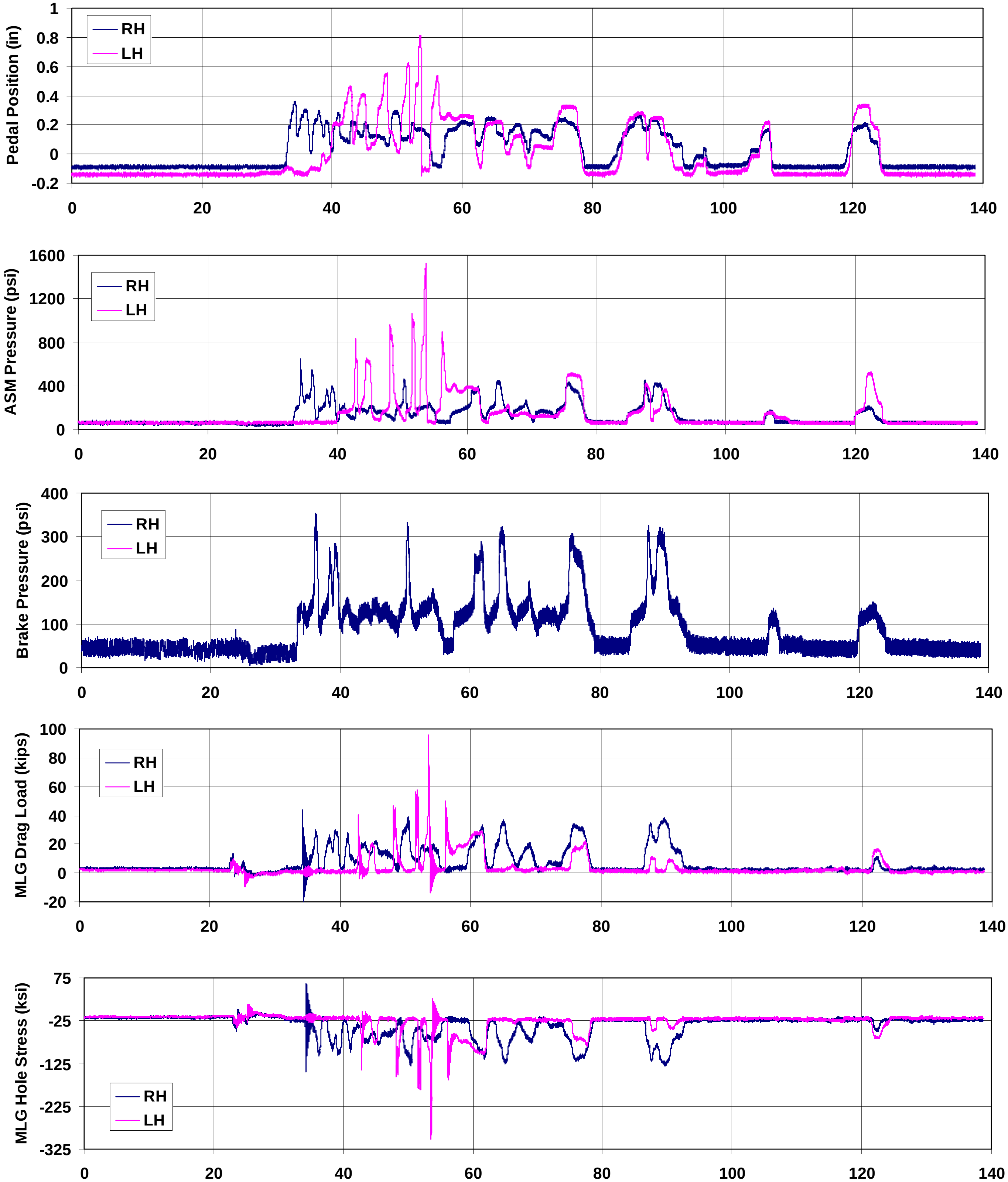

Figure 1 – ISE Data, Flight 1205, April 7, 2007, ID 10.23

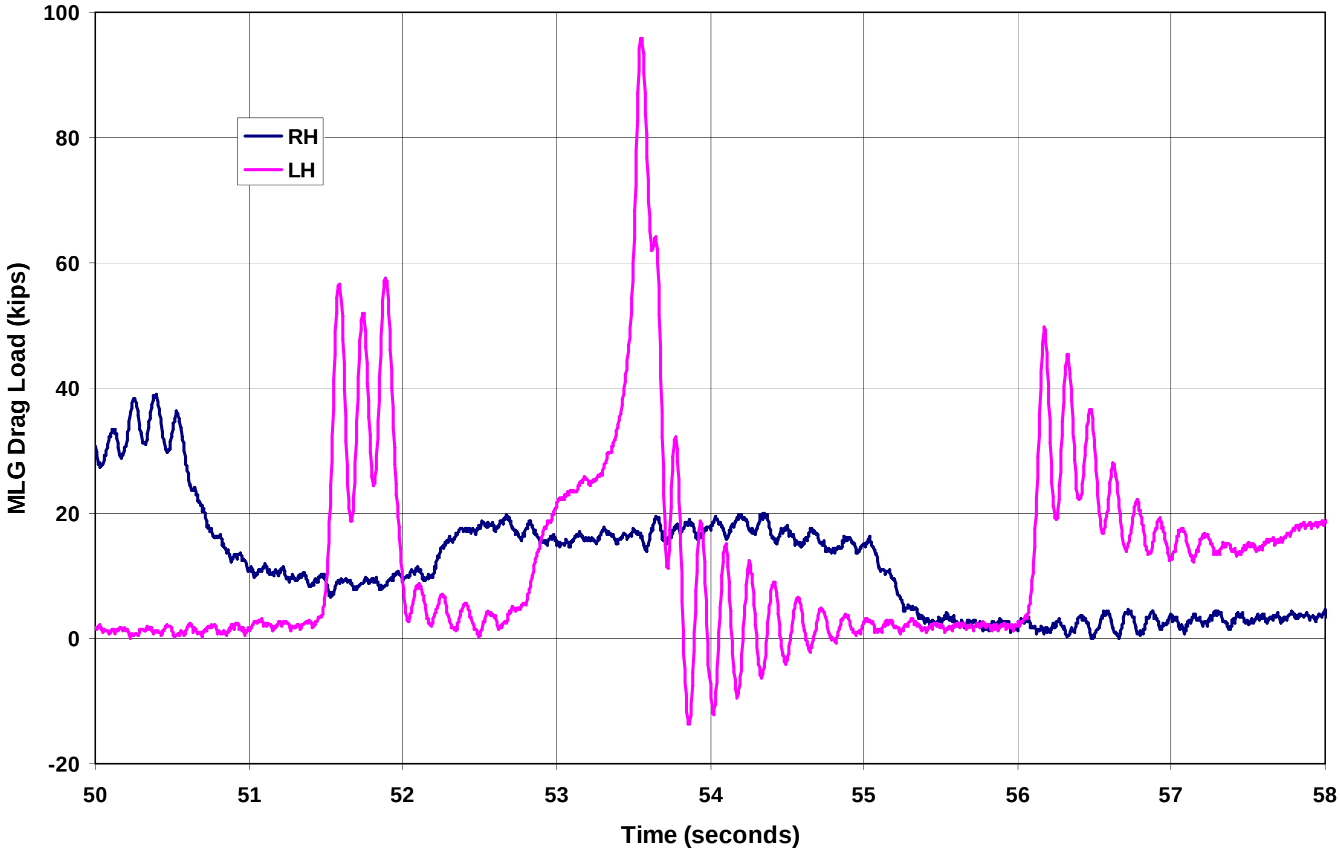

Figure 2 – MLG Drag Load, Flight 1205, April 7, 2007, ID 10.23

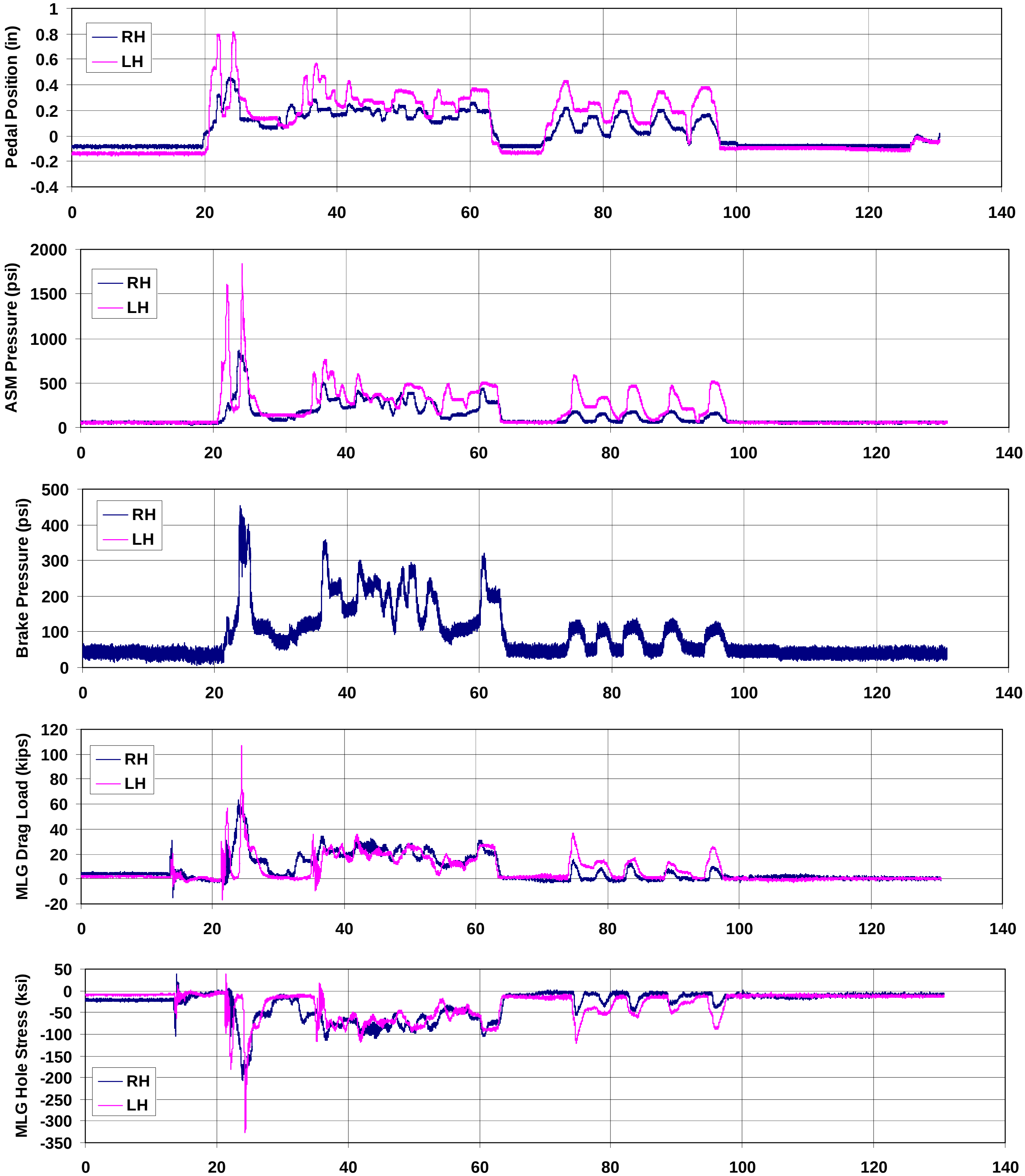

Figure 3 – ISE Data, Flight 842, May 11, 2007, ID 12.52

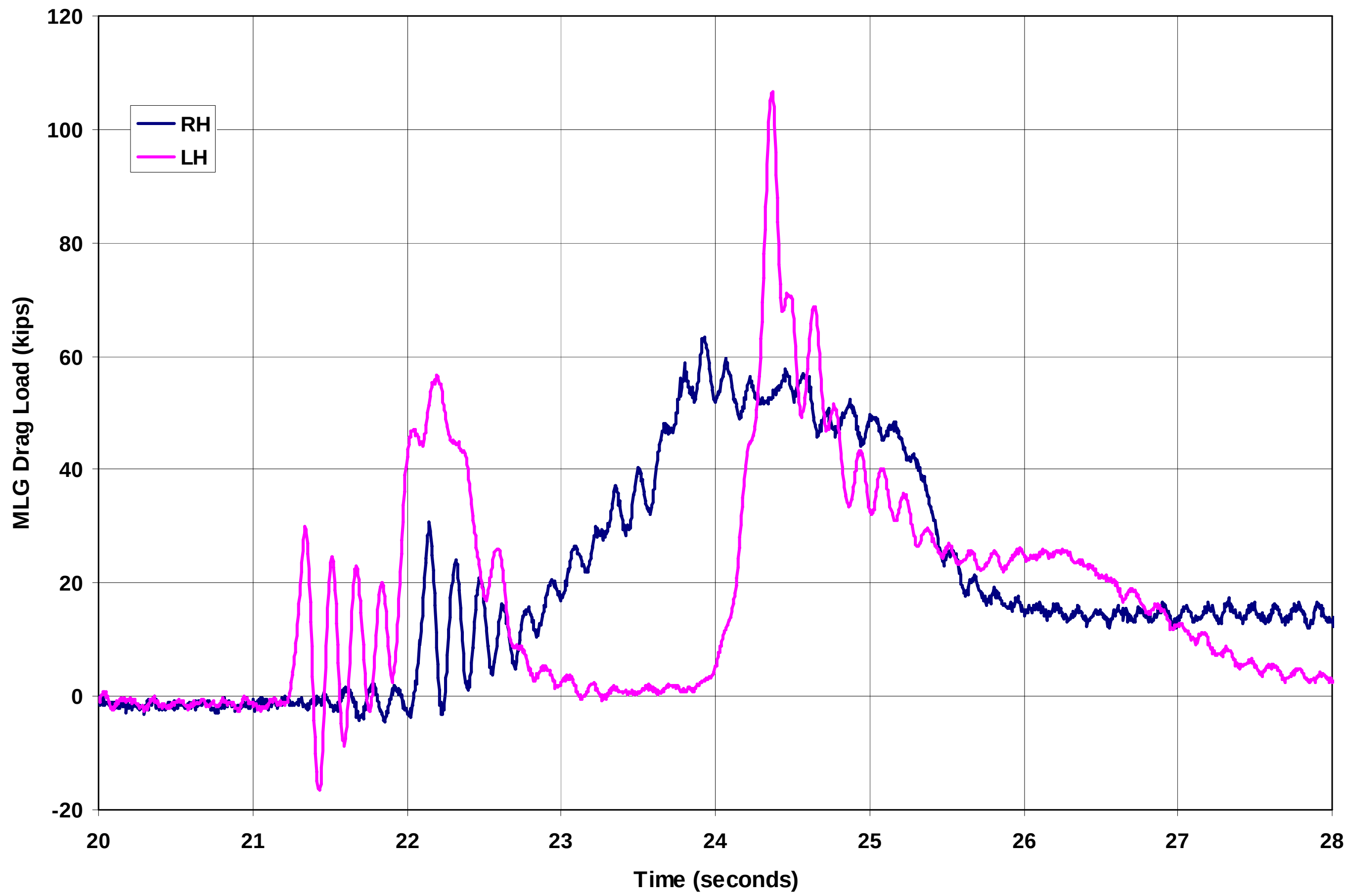

Figure 4 – MLG Drag Load, Flight 842, May 11, 2007, ID 12.52

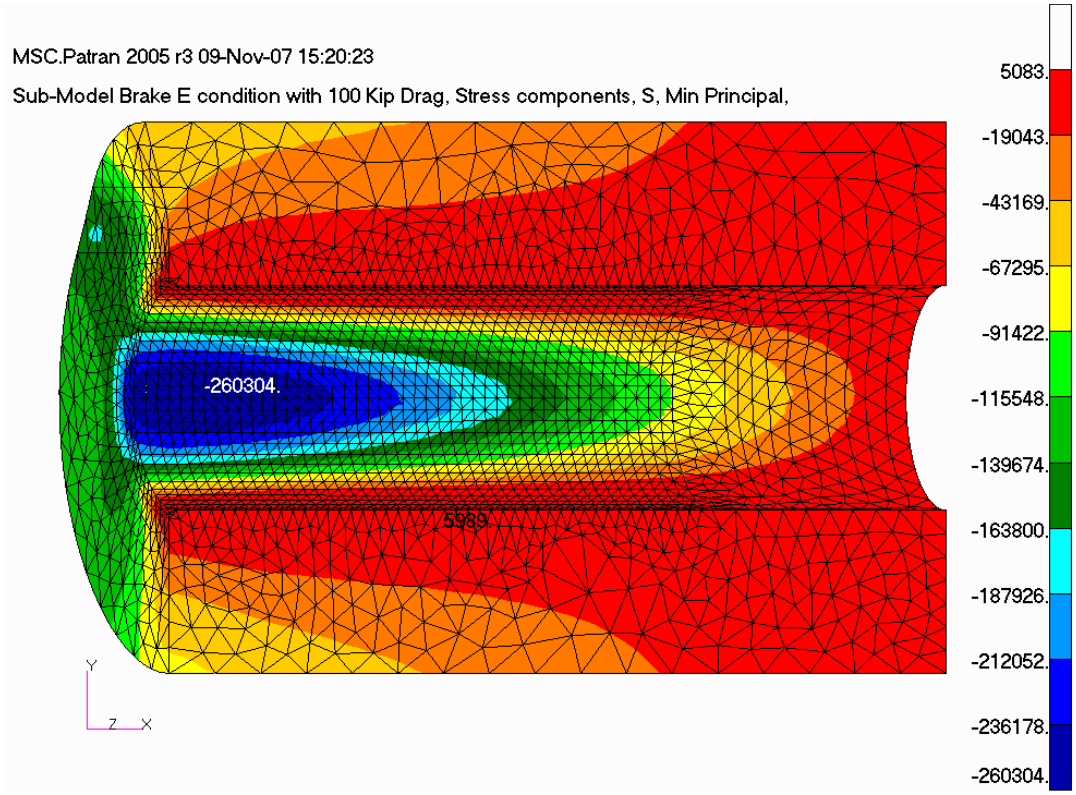

Figure 5 – FEM Results for Brake E Condition with 100 kips Drag Load

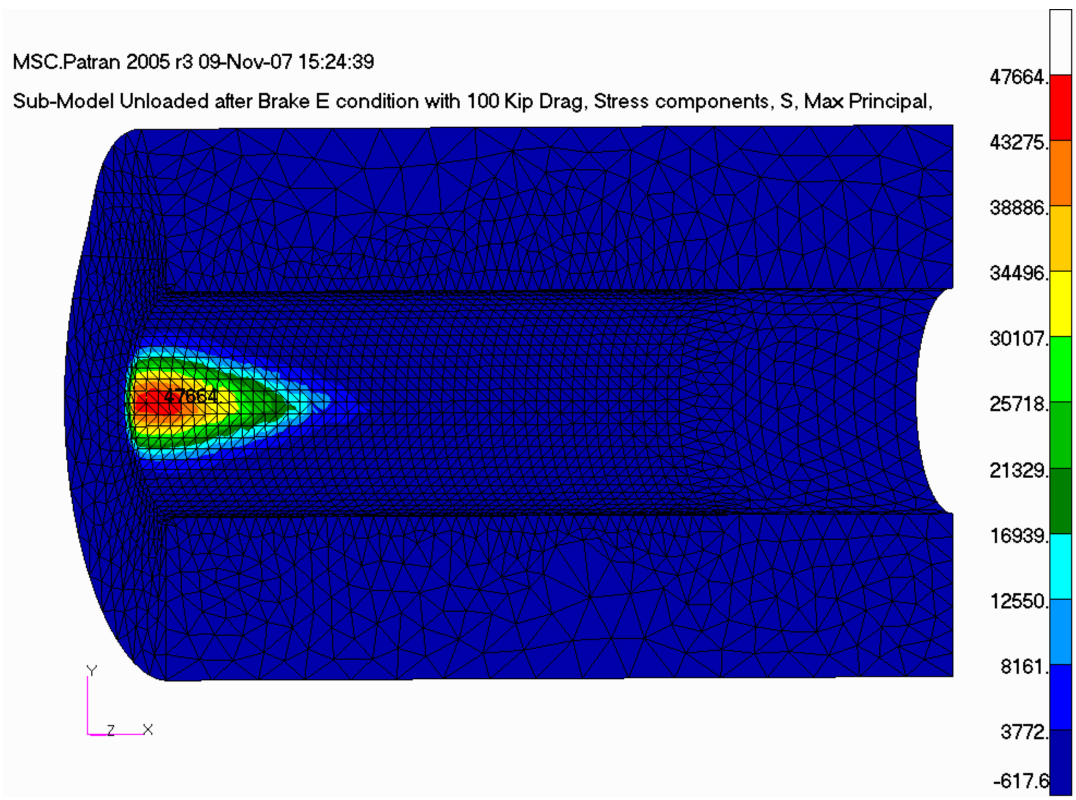

Figure 6 – FEM Results for Residual Stress due to Brake E Condition with 100kips Drag Load

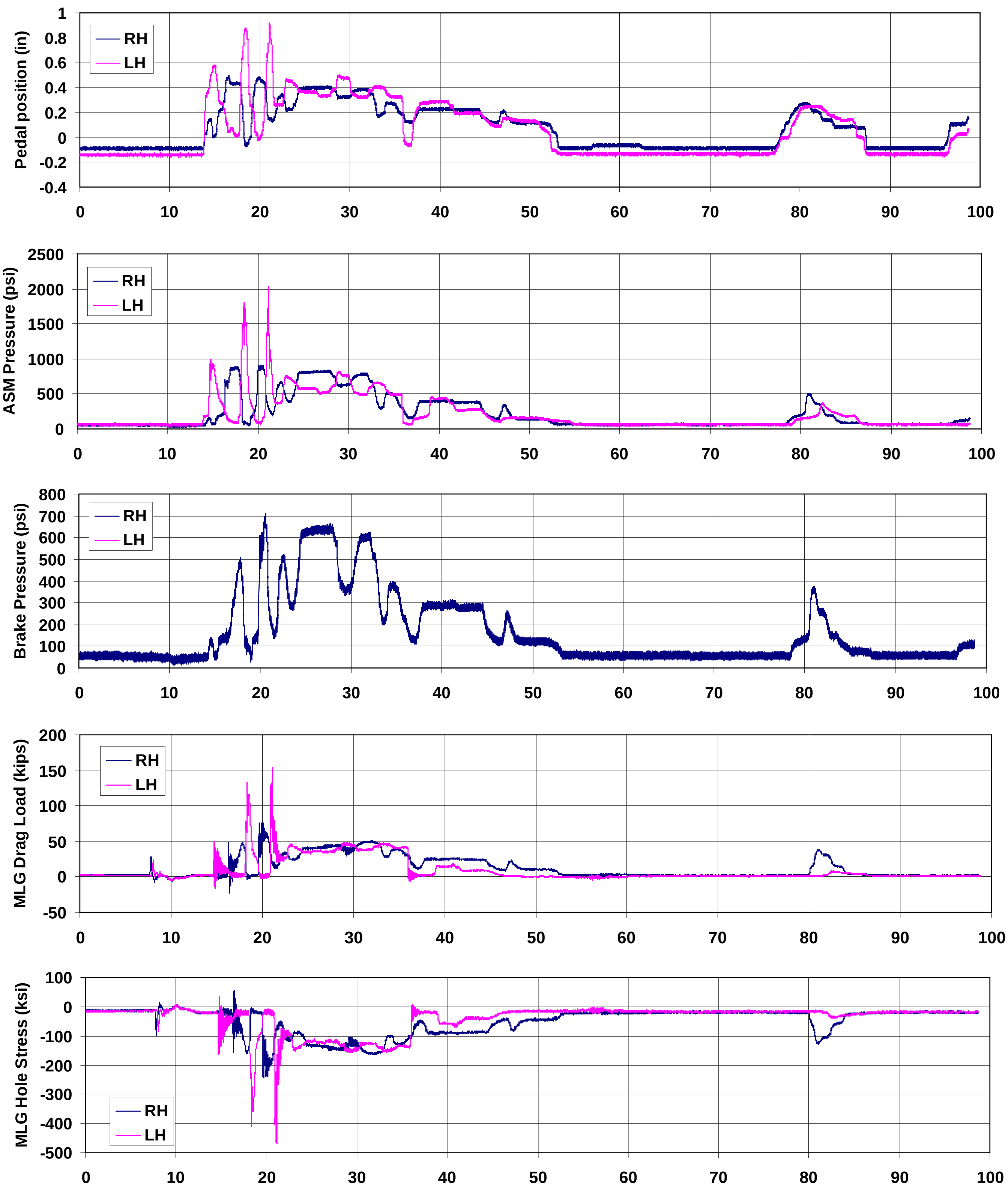

Figure 7 – ISE Data, Flight 308, April 4. 2007, ID 10.14

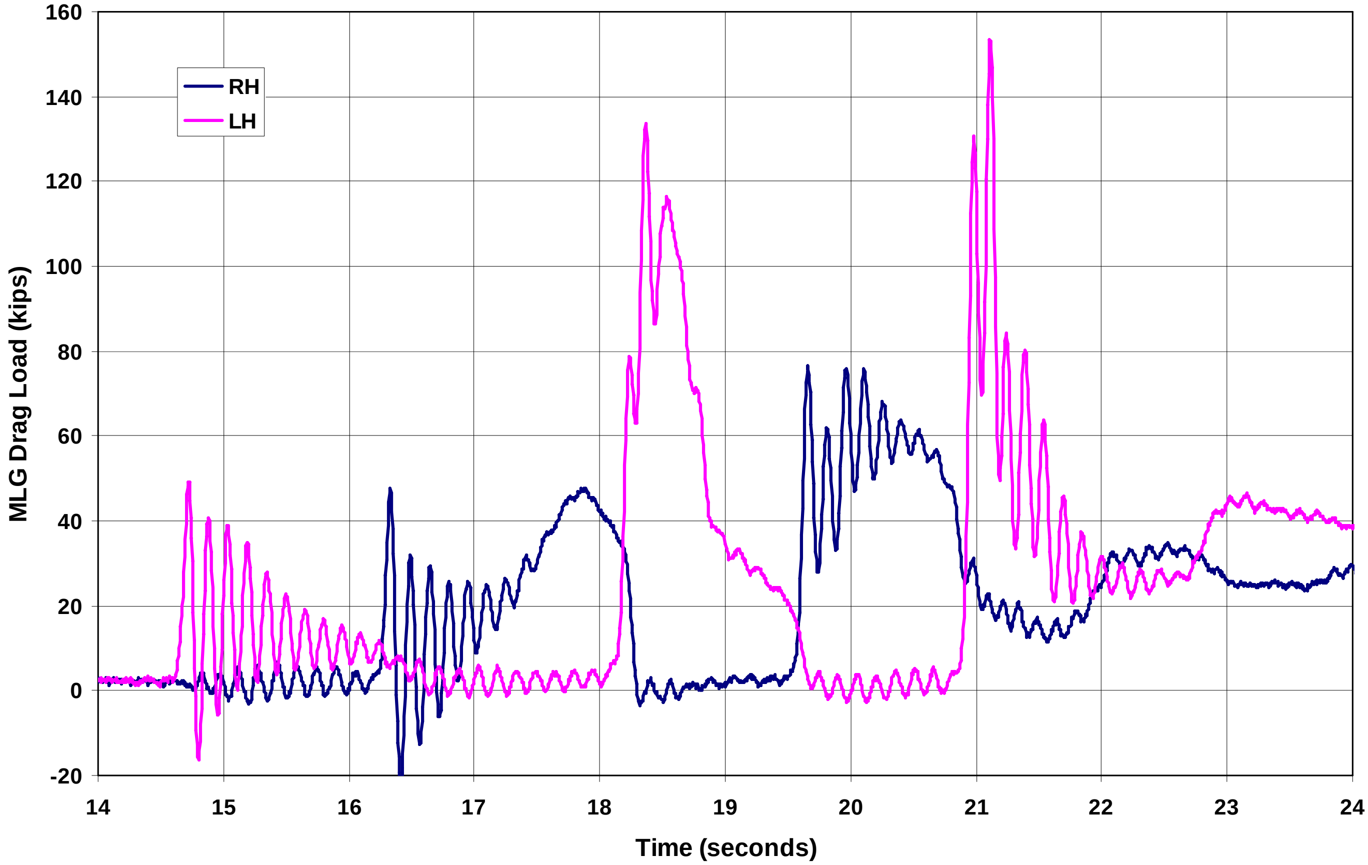

Figure 8 – MLG Drag Load, Flight 308, April 4, 2007, ID 10.14

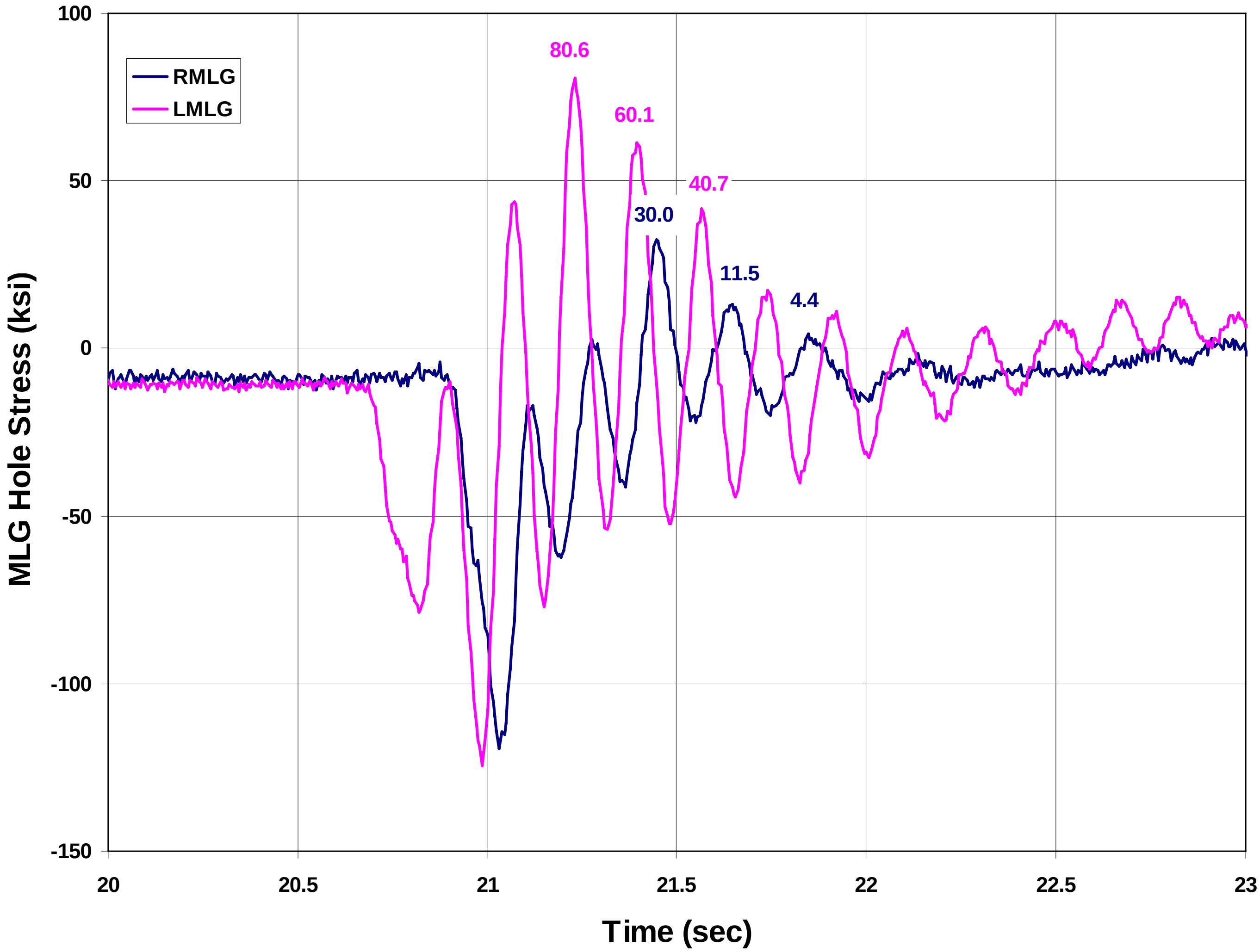

Figure 9 – MLG Hole Stress, Flight 842, February 13, 2007, ID 12.52