Study of Out-of-Plane (OOP) Forces in the Super-conducting Toroidal Magnet of CLAS

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Introduction

Oxford Instruments built and commissioned the super-conducting toroidal magnet for CLAS (Cebaf's Large Acceptance Spectrometer). During commissioning, in 1995, the magnet was ramped up to maximum current (3861 A) and over several weeks the performance of the magnet was checked. No OOP- force warnings were observed.

Recently, coil B (see Fig. 1) has started to show a *net OOP-force* warning-signal at 3380A. Since the CLAS collaboration would like to run the magnet at least at 92% of full field (3560 A), the cause for the generation of the OOP-force warning-signal has been investigated. This note presents the results of the study.

Warning and Slow-rundown limits

To measure OOP-forces, each side of a coil is instrumented with six OOP-force sensors (12 sensors per coil). The *total OOP-force*, which is the sum of the OOP-forces of a side, top or bottom, of a coil is measured. And from the values of the total OOP-force of a coil the *net OOP-force* (total OOP-force on topside minus total OOP-force on bottom side minus the weight of coil) is calculated.

Slow rundown trip levels and thresholds for warning signals ensure that the magnet is not damaged by large OOP-forces. Slow rundown trip levels are set at various stages. A slow rundown is started:

1. If the OOP-force registered by any one of the sensors on coils A or D, *vertical-coils,* is equal to or greater than 400 Kg, or if the OOP-force registered by any one of the sensors of coils B, C, E or F, *side-coils,* is equal to or greater than 600 Kg.
2. If any two sensors on the same side of a *vertical-coil* register 300 Kg or more, or if any two sensors on the same side of a *side-coil* register 500 Kg or more.

3. If the total OOP-force of a *vertical-coil* is equal to or greater than 1000 Kg or if the total OOP-force of a *side-coils* is 1800 Kg or more.
4. If the net OOP-force is equal to or greater than750 Kg.

A warning signal is shown on the power-supply screen when the net OOP-force is greater than 200 Kg. If the net OOP-force exceeds 500 Kg a warning signal is generated on the main display (TACL) screen.

Analysis

Recent data-logged OOP-forces have been graphed and analyzed in four categories. These are:

1. <u>Individual OOP-force Sensors</u>

These plots of the OOP-forces registered by individual sensors as a function of the current indicate that the largest forces occur in the forward regions and that coil B sensors in the forward region show by far the largest OOP-force.

2. <u>Total OOP-forces</u>

These graphs show, for a particular coil, the total OOP-forces as a function of the current. The plots indicate that the total OOP-force for the topside of coil B increases rapidly and that if this trend were to continue, as indicated by the sixth order polynomial fit, slow run-down would occur at 3750 A.

3. <u>Net OOP-force</u>

The plots of the net OOP-force versus current show that above 1000 A, coil B has the greatest increase in net OOP-force per ampere. The warning-signal is generated at 3380A and if this trend were to continue a slow rundown would occur at approximately 3800 A.

Overall, coils B and C show a greater increase in net OOP-force per ampere than coils E or F. The vertical coils, A and D, show the least increase in net OOP-force per ampere.

Random instantaneous fluctuations, spikes, such as the one which can be seen in the "Net Force Coil B & F" plot are a concern. Such spikes seem to have a magnitude of roughly 50 Kg. The cause and implication of these spikes at present are unknown.

4. Net OOP-force differences

Absolute differences of the net OOP-forces between symmetrically equivalent coils, such as A&D, B&F and C&E were calculated and plotted as a function of the applied current. The graphs indicate that the *side-coils* have more stress than the *vertical coils*. Further, the coils to the right of the beam-line are subject to more stress than the coils to the left of the beam-line. The most dramatic increase in the net OOP-force difference as a function of current is exhibited between coils B and F.

Conclusion

The above analysis clearly indicates that:

1. The magnet cannot be ramped up to full field.
2. Since operating the magnet in the warning-zone could damage the magnet irrevocably, the maximum current should not exceed 3380 A. At present coil B is the cause of the warning, however it is not known how the overall stresses of the entire coil array will affect the magnet. Operation of the magnet in the warning area maybe feasible if it is concluded that the engineering design can withstand, long-term, such stresses.
3. Coils to the right of the beam-line (B and C) are subject to higher OOP-forces. The only reason at present attributable for this behavior of the OOP-forces is that after full field commissioning, the Region 3 Sector 4 drift chamber has been extracted and inserted a number of times. The extraction/insertion procedure may have affected the alignment of the coils B and C and thereby increased OOP-forces.

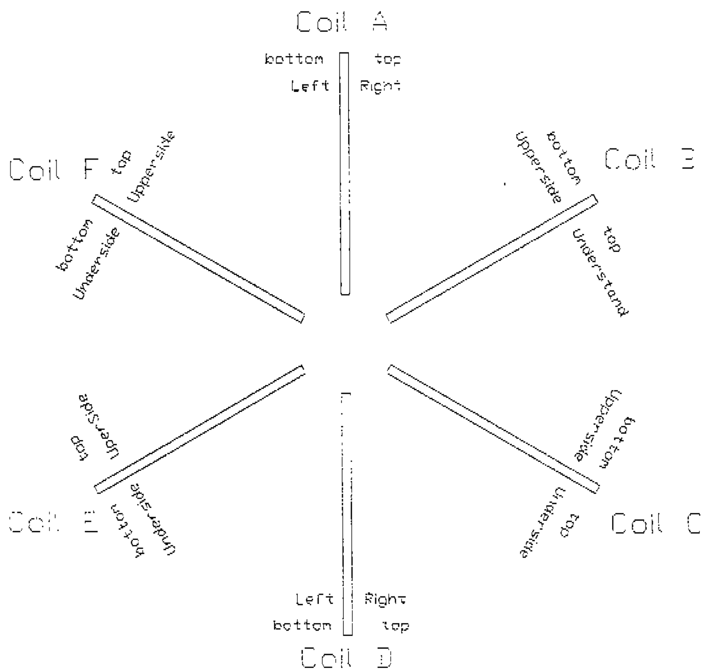
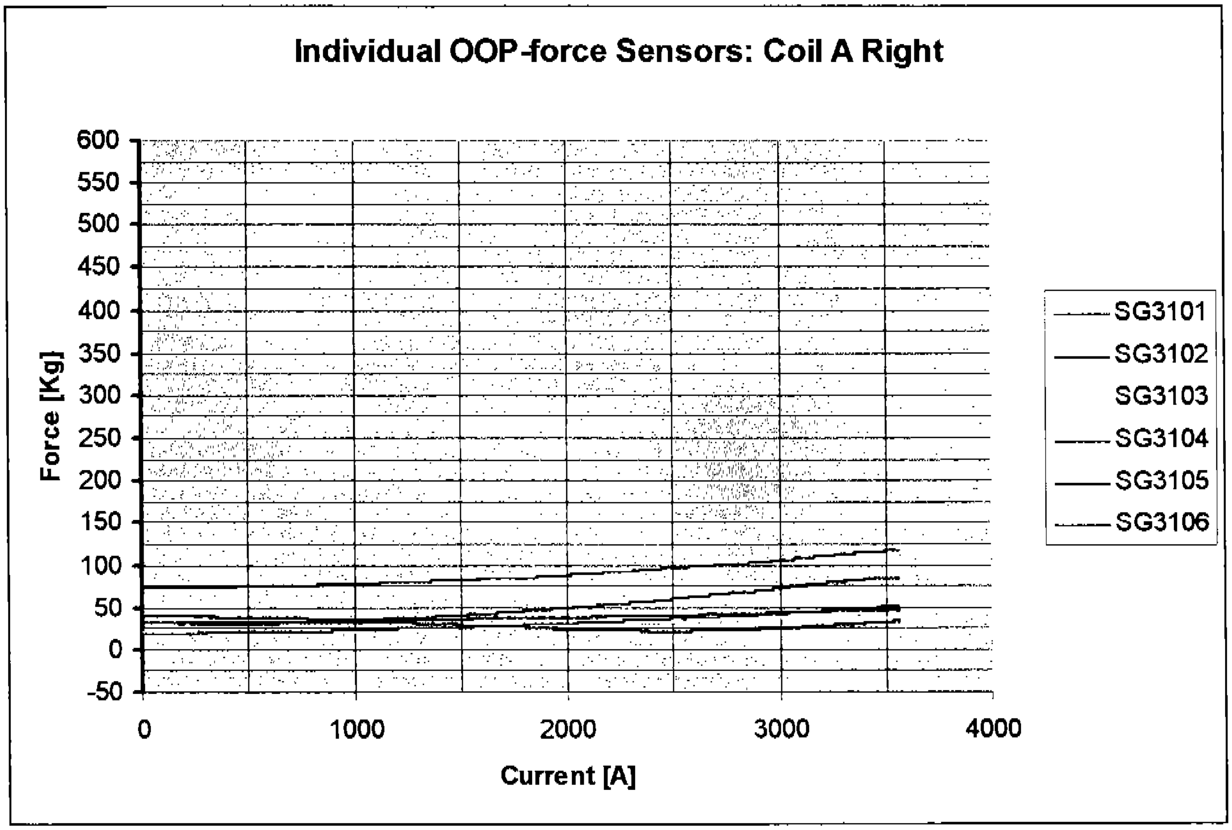
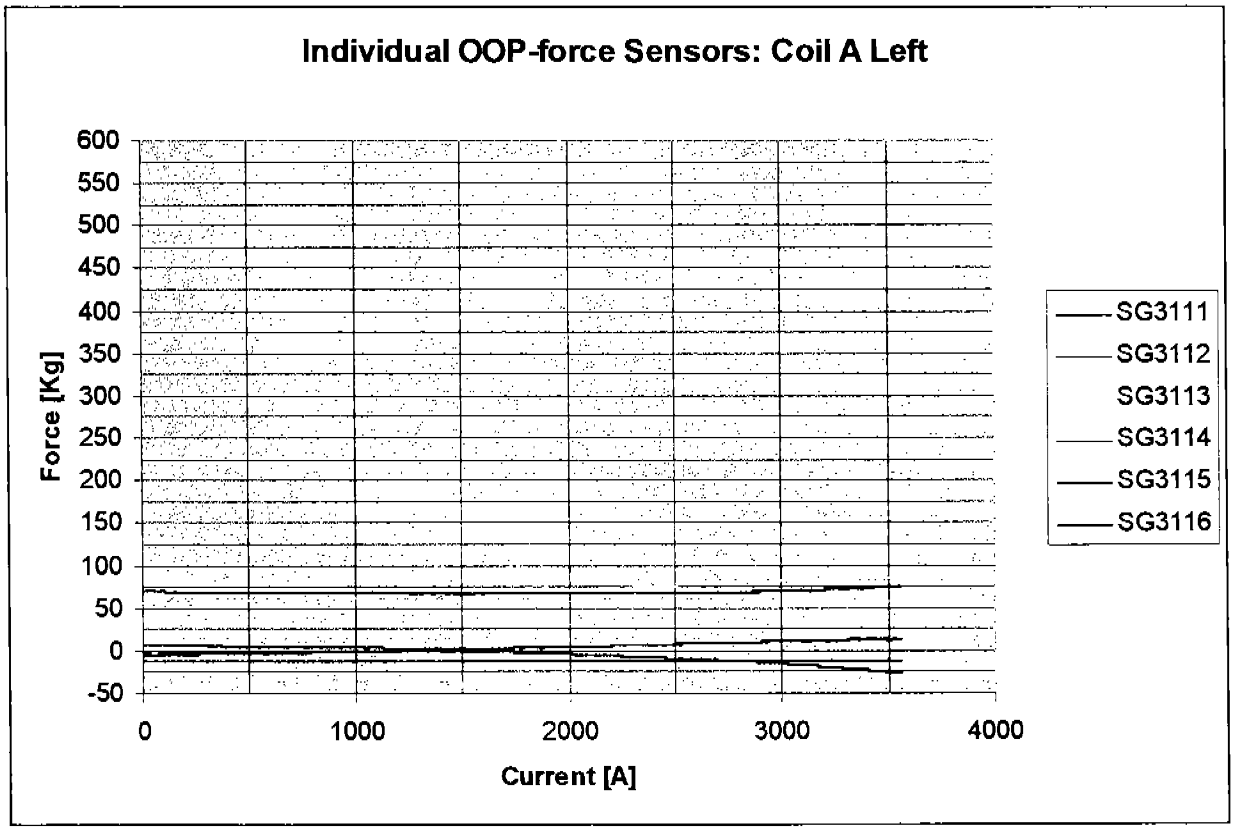
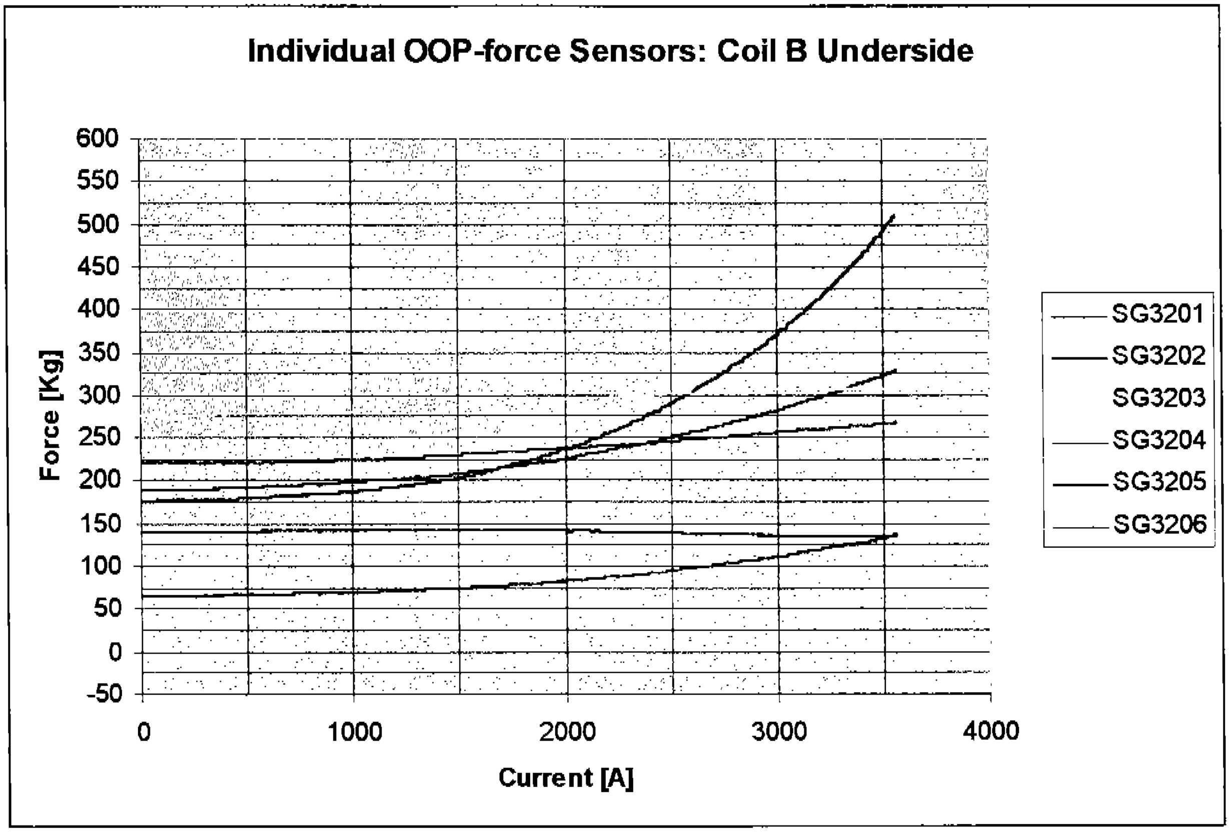
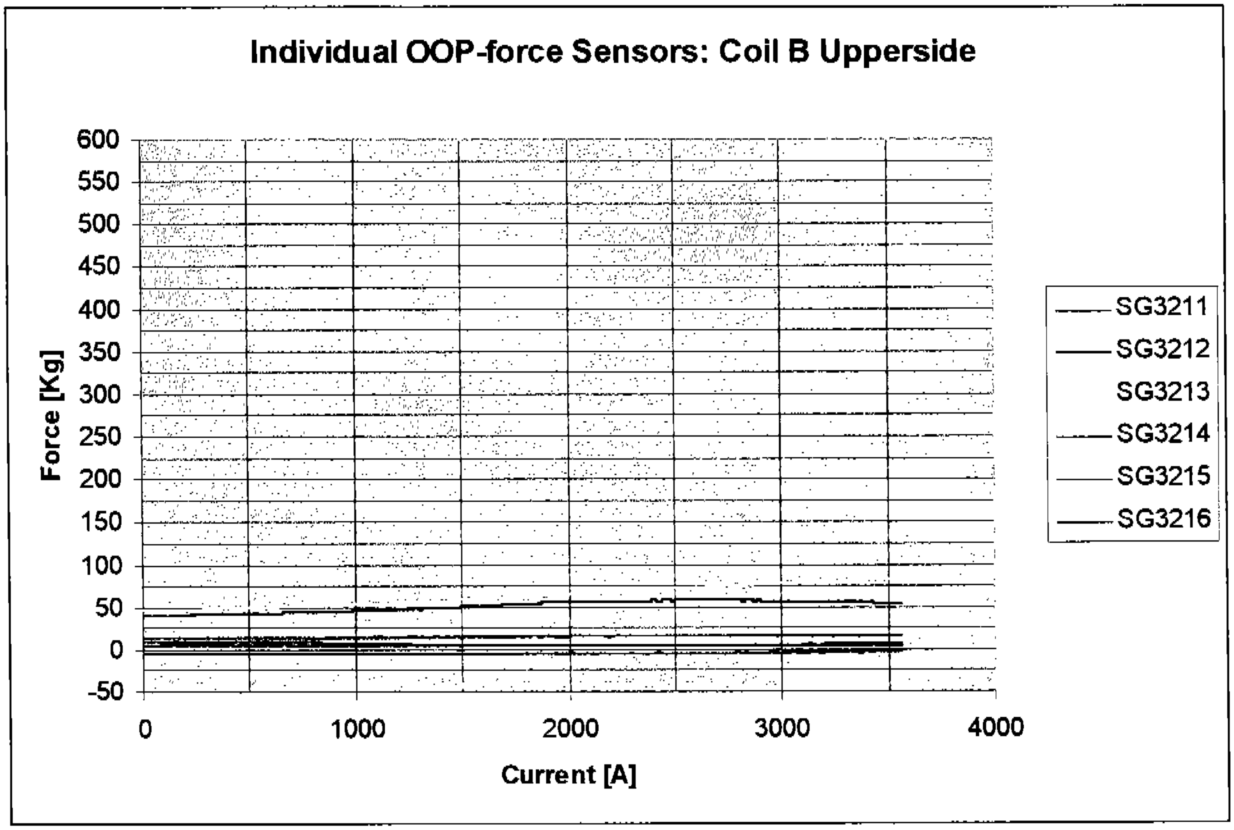

Coil A
bottom
top
Left
Right
Coil F
top
Upperside
bottom
Underside
Coil B
bottom
Upperside
top
Understand
Upperside
top
Coil E
bottom
Underside
Upperside
bottom
top
Underside
Coil C
Left
Right
bottom
top
Coil D

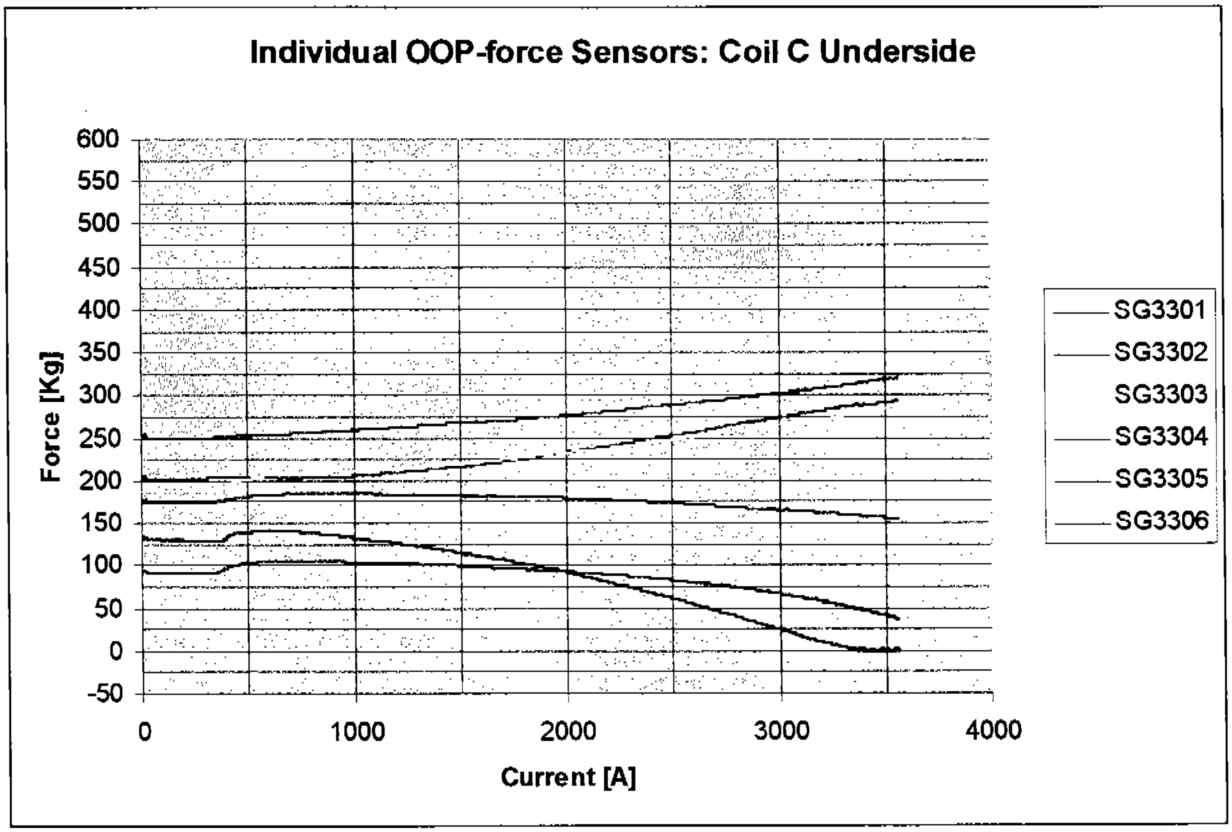
Fig. 1

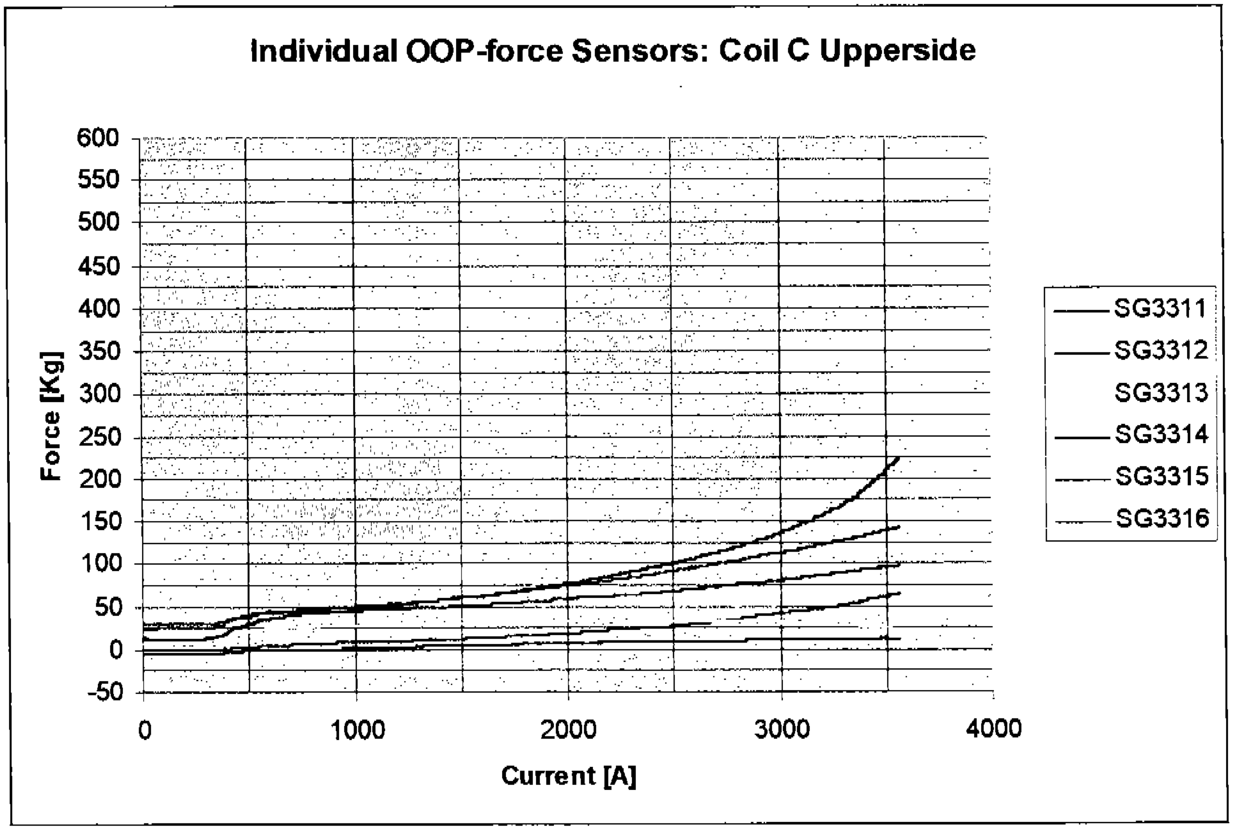

Individual OOP-force Sensors: Coil A Right
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
Force [Kg]
0
1000
2000
3000
4000
Current [A]
SG3101
SG3102
SG3103
SG3104
SG3105
SG3106

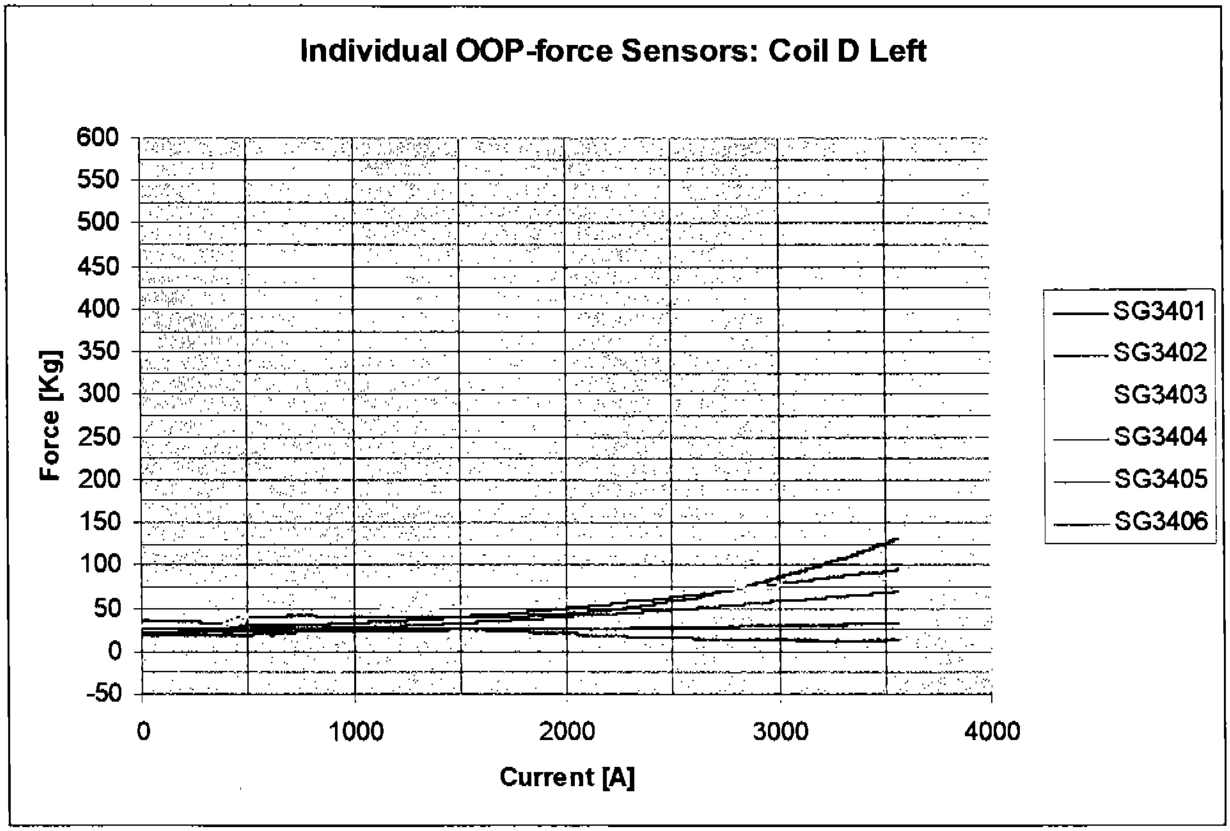

Individual OOP-force Sensors: Coil A Left
Force [Kg]
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
0
1000
2000
3000
4000
Current [A]
SG3111
SG3112
SG3113
SG3114
SG3115
SG3116

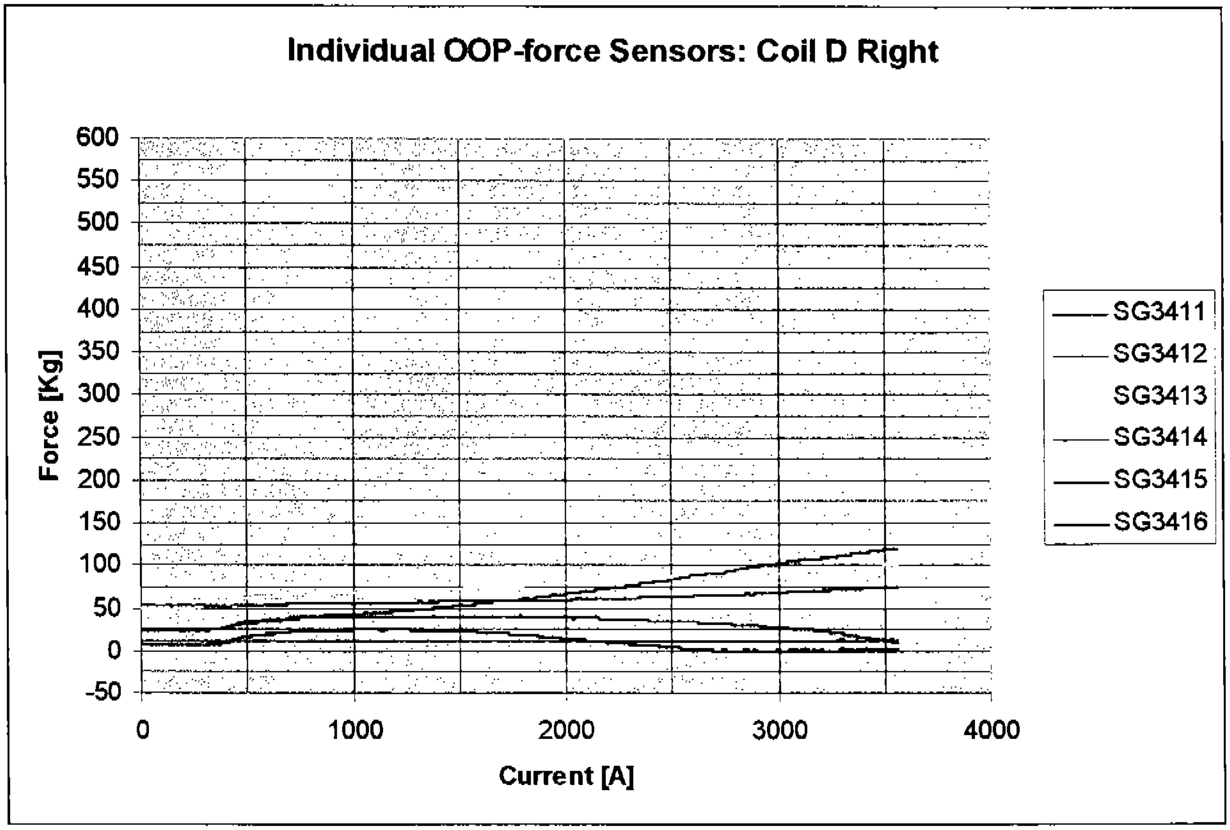

Individual OOP-force Sensors: Coil B Underside
Force [Kg]
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
0
1000
2000
3000
4000
Current [A]
SG3201
SG3202
SG3203
SG3204
SG3205
SG3206

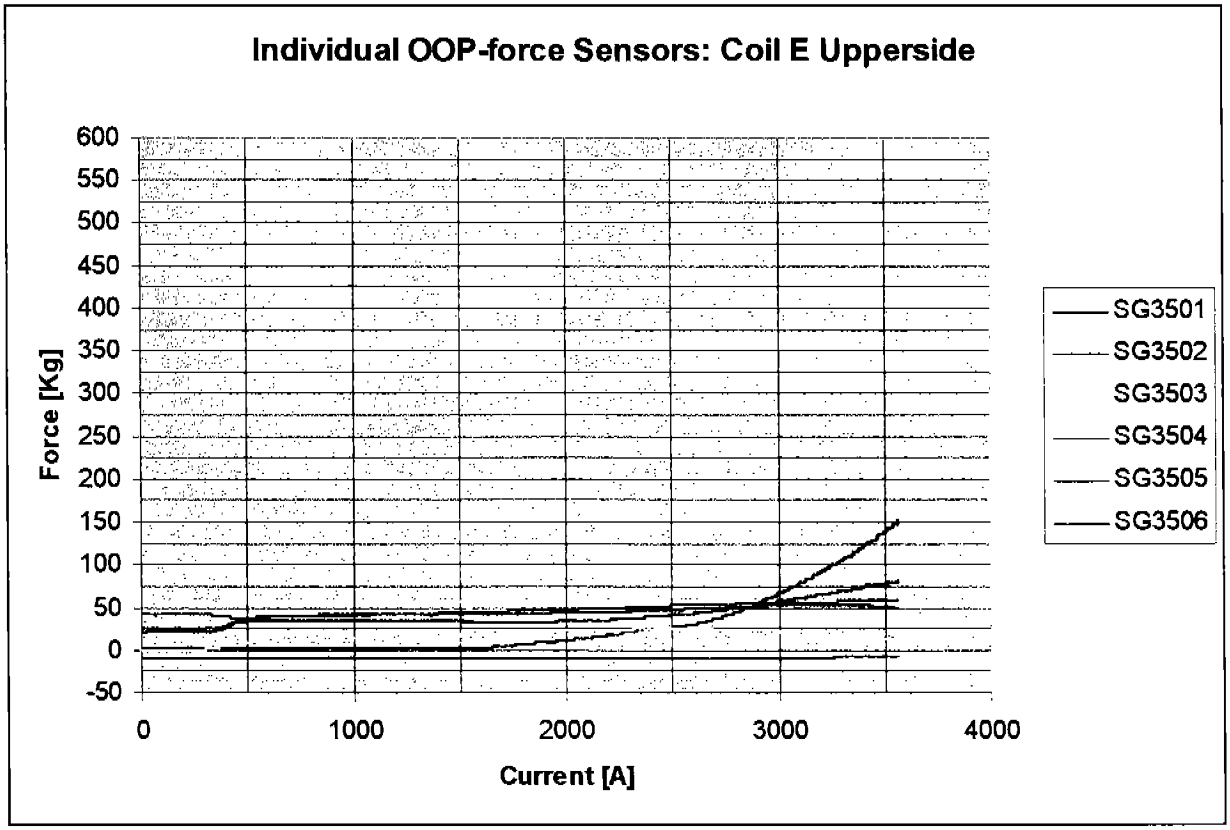

Individual OOP-force Sensors: Coil B Upperside
Force [Kg]
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
0
1000
2000
3000
4000
Current [A]
SG3211
SG3212
SG3213
SG3214
SG3215
SG3216

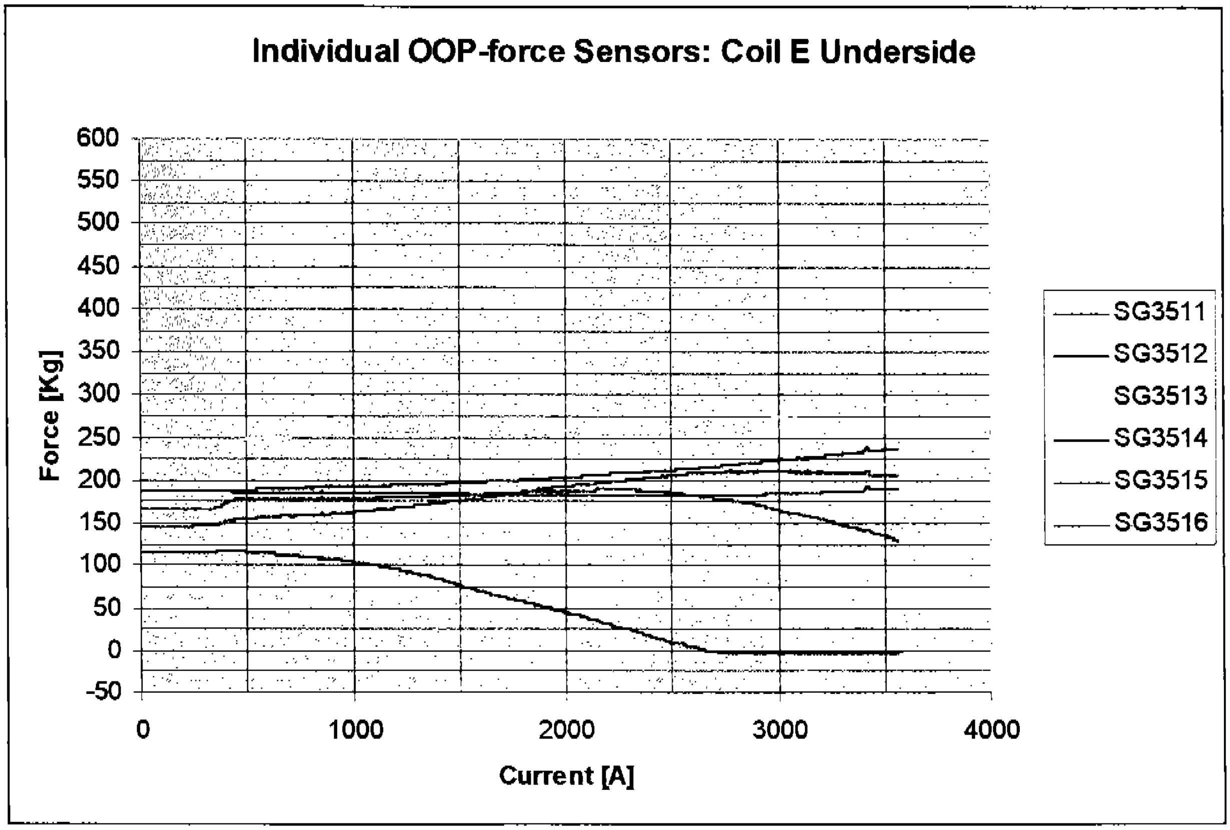

Individual OOP-force Sensors: Coil C Underside
Force [Kg]
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
0
1000
2000
3000
4000
Current [A]
SG3301
SG3302
SG3303
SG3304
SG3305
SG3306

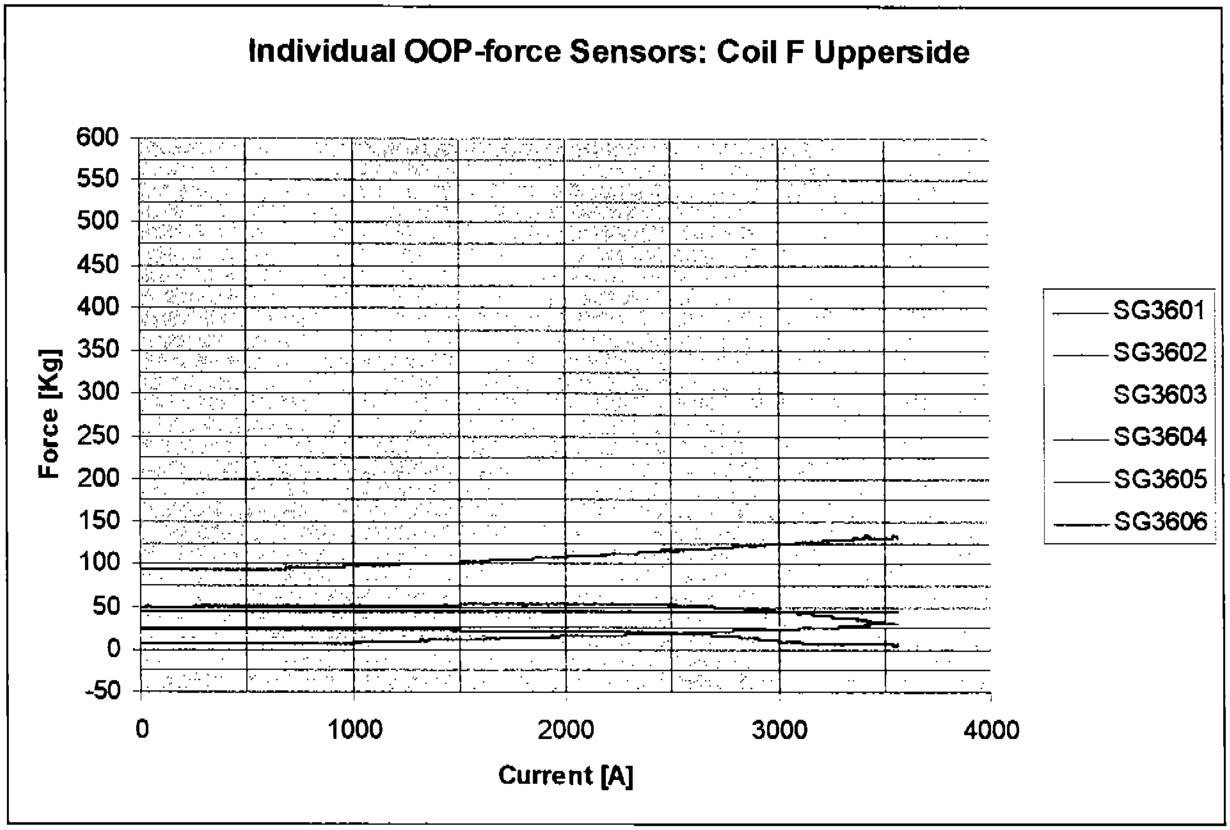

Individual OOP-force Sensors: Coil C Upperside
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
Force [Kg]
0
1000
2000
3000
4000
Current [A]
SG3311
SG3312
SG3313
SG3314
SG3315
SG3316

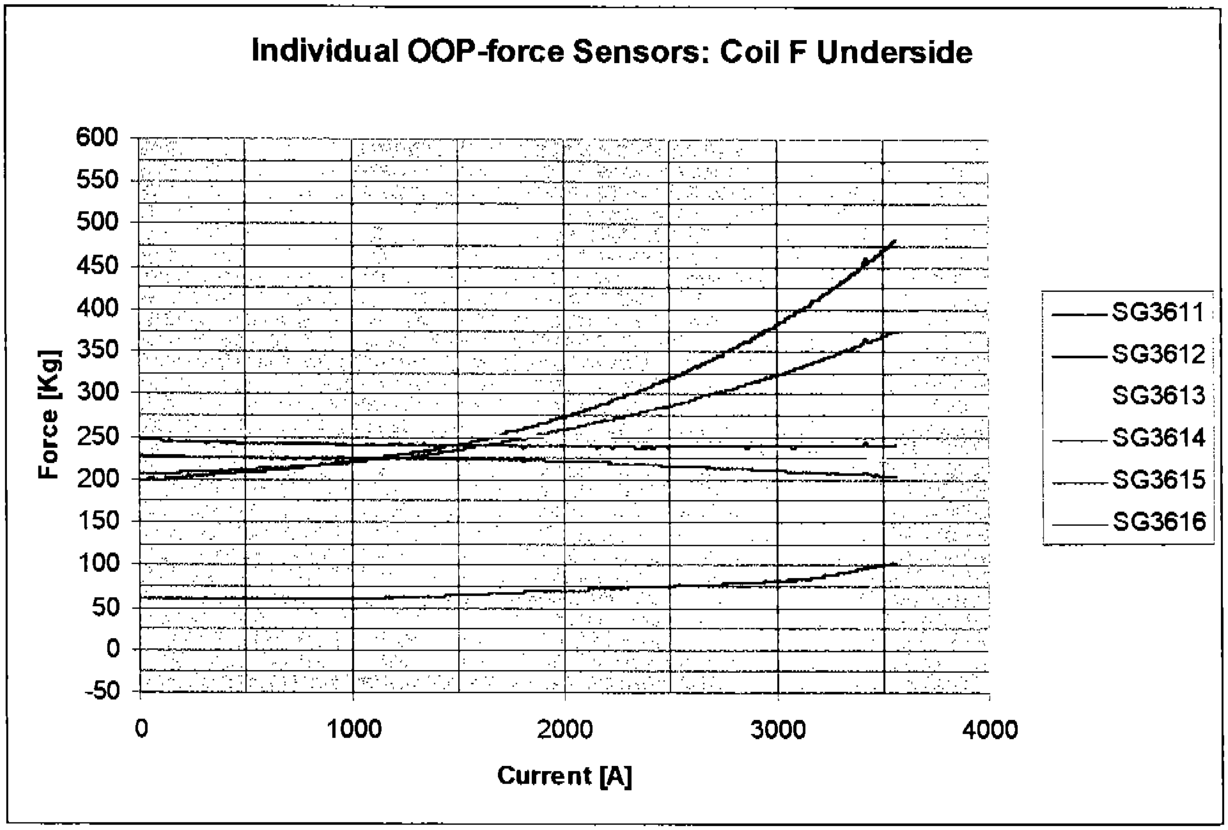

Individual OOP-force Sensors: Coil D Left
Force [Kg]
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
0
1000
2000
3000
4000
Current [A]
SG3401
SG3402
SG3403
SG3404
SG3405
SG3406

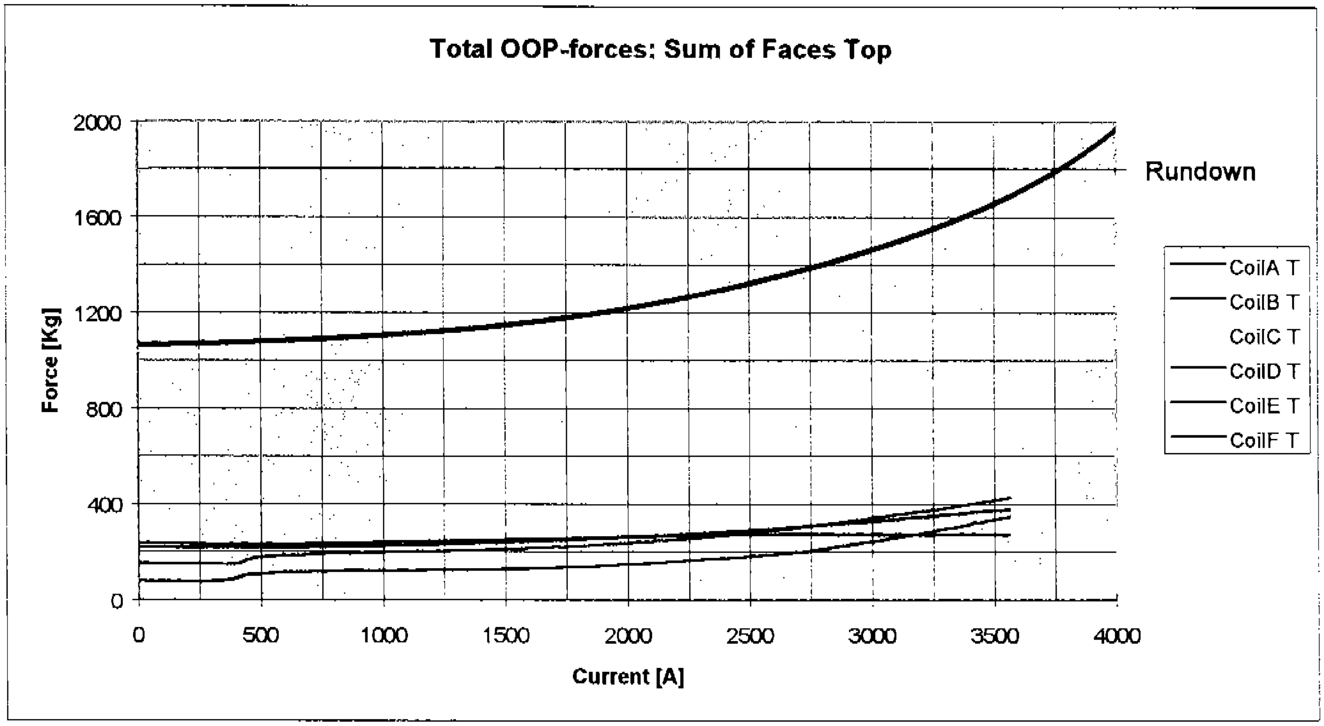

Individual OOP-force Sensors: Coil D Right
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
Force [Kg]
0
1000
2000
3000
4000
Current [A]
SG3411
SG3412
SG3413
SG3414
SG3415
SG3416

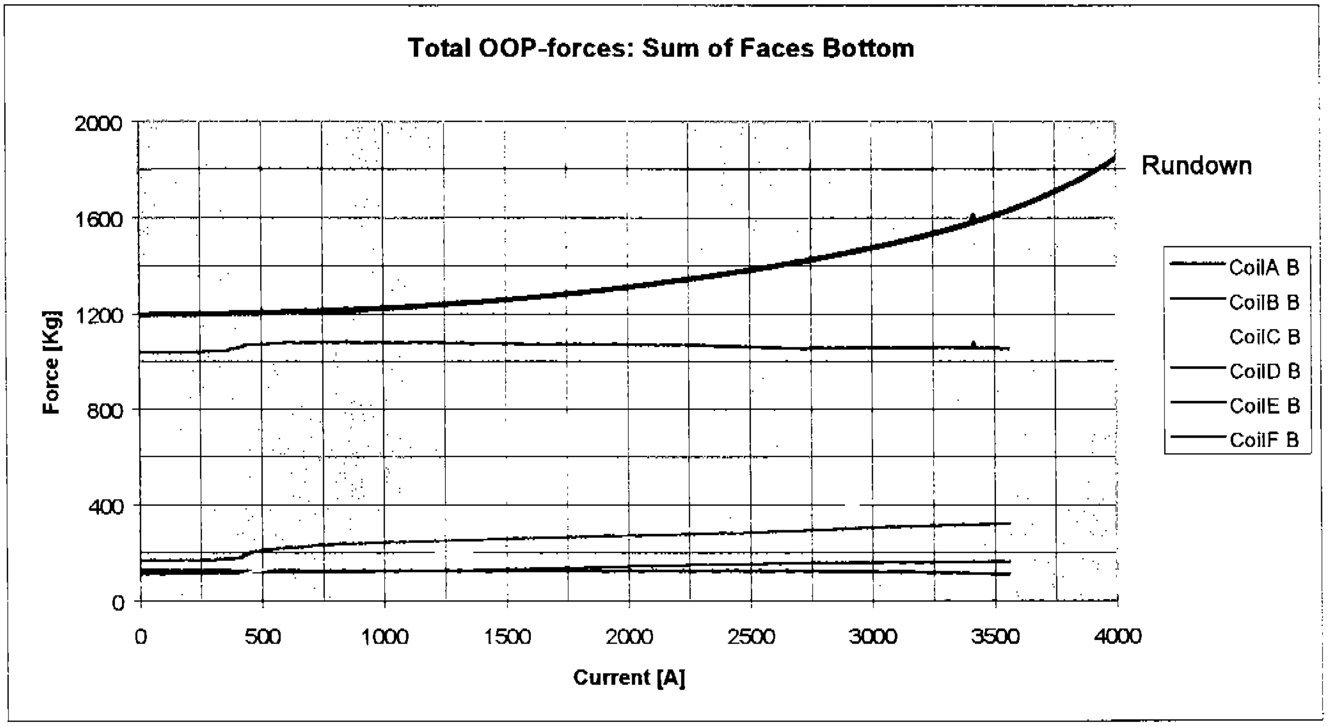

Individual OOP-force Sensors: Coil E Upperside
Force [Kg]
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
0
1000
2000
3000
4000
Current [A]
SG3501
SG3502
SG3503
SG3504
SG3505
SG3506

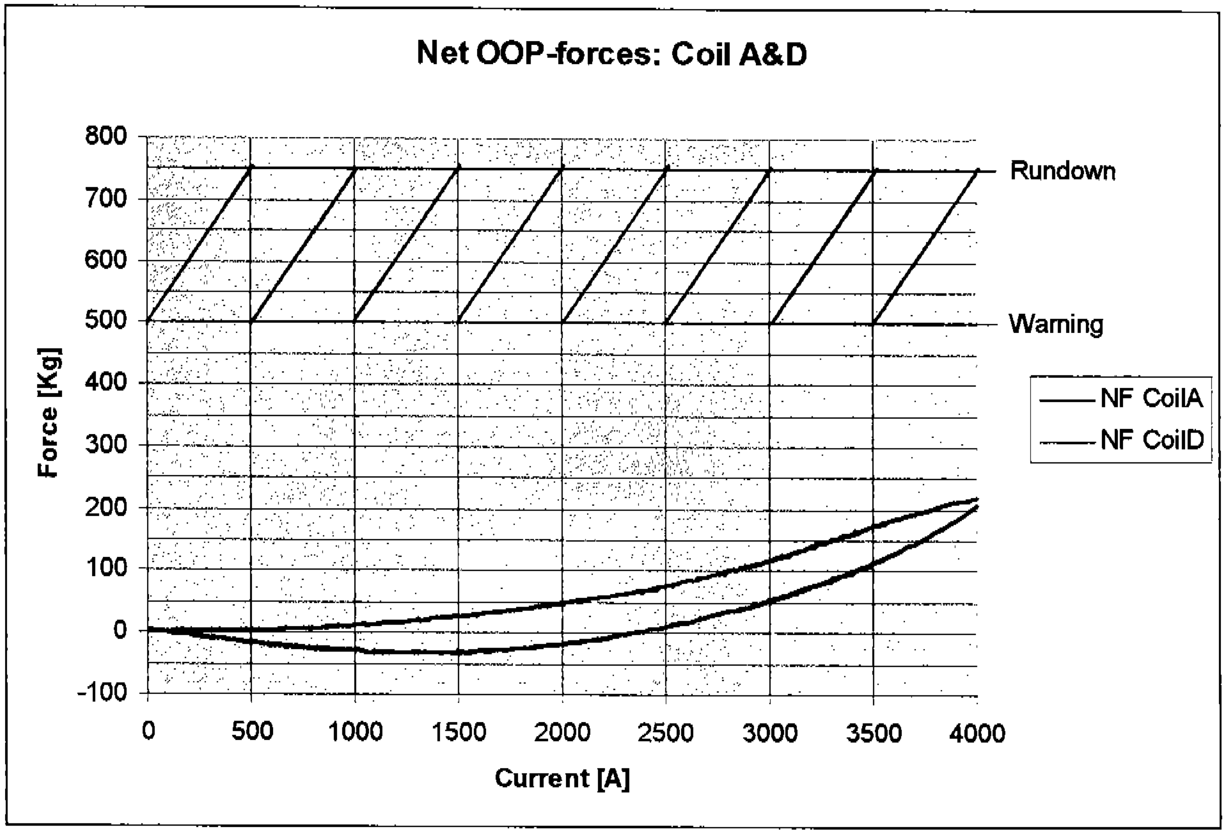

Individual OOP-force Sensors: Coil E Underside
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
Force [Kg]
0
1000
2000
3000
4000
Current [A]
SG3511
SG3512
SG3513
SG3514
SG3515
SG3516

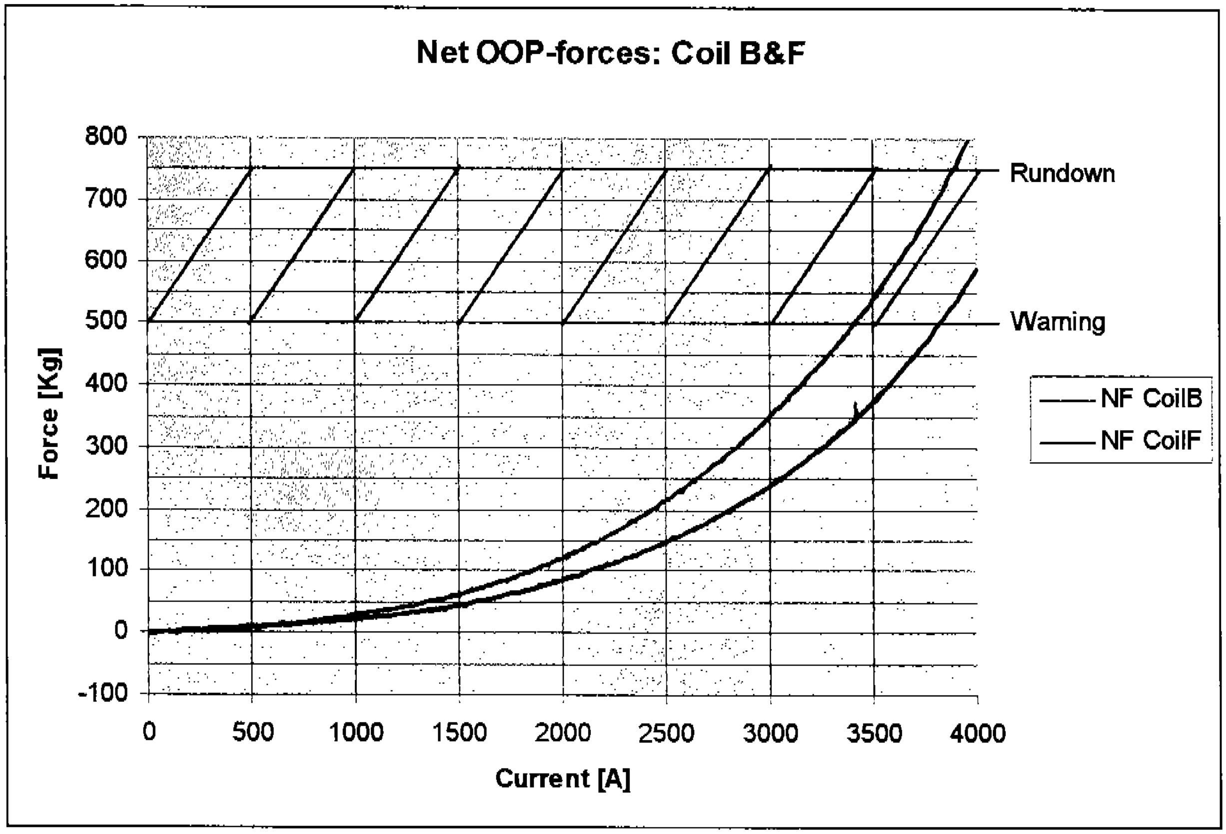

Individual OOP-force Sensors: Coil F Upperside
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
Force [Kg]
0
1000
2000
3000
4000
Current [A]
SG3601
SG3602
SG3603
SG3604
SG3605
SG3606

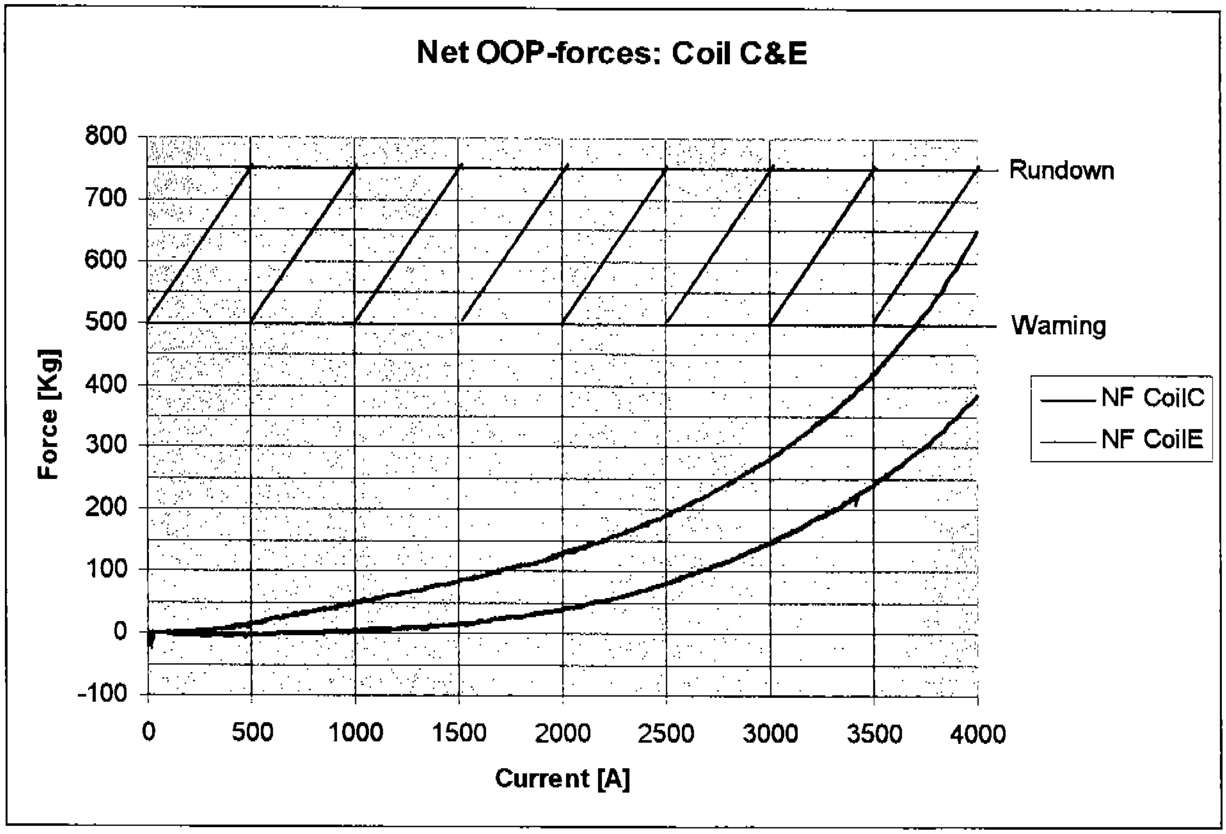

Individual OOP-force Sensors: Coil F Underside
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
Force [Kg]
0
1000
2000
3000
4000
Current [A]
SG3611
SG3612
SG3613
SG3614
SG3615
SG3616

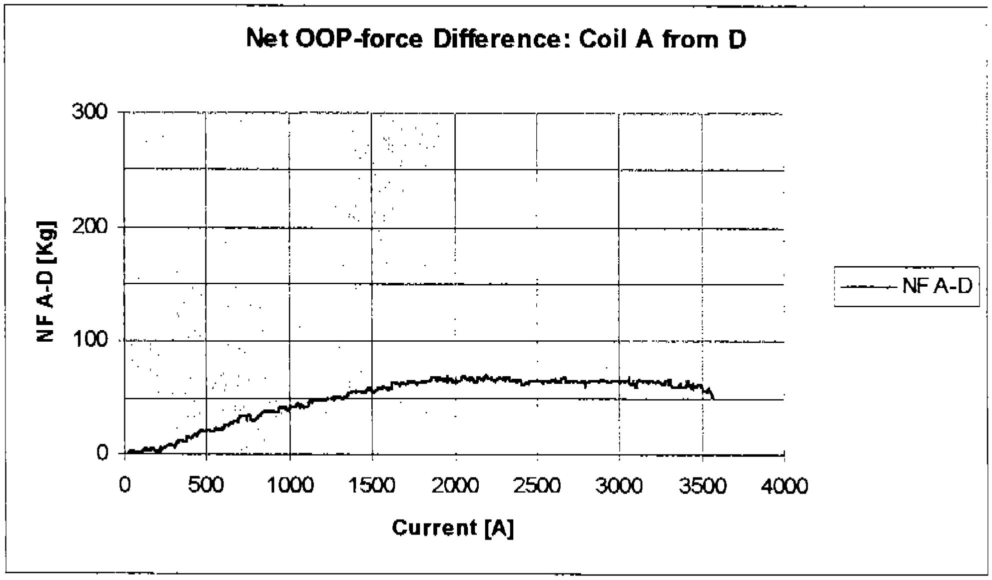

Total OOP-forces: Sum of Faces Top
2000
1600
1200
800
400
0
Force [Kg]
0
500
1000
1500
2000
2500
3000
3500
4000
Current [A]
Rundown
CoilA T
CoilB T
CoilC T
CoilD T
CoilE T
CoilF T

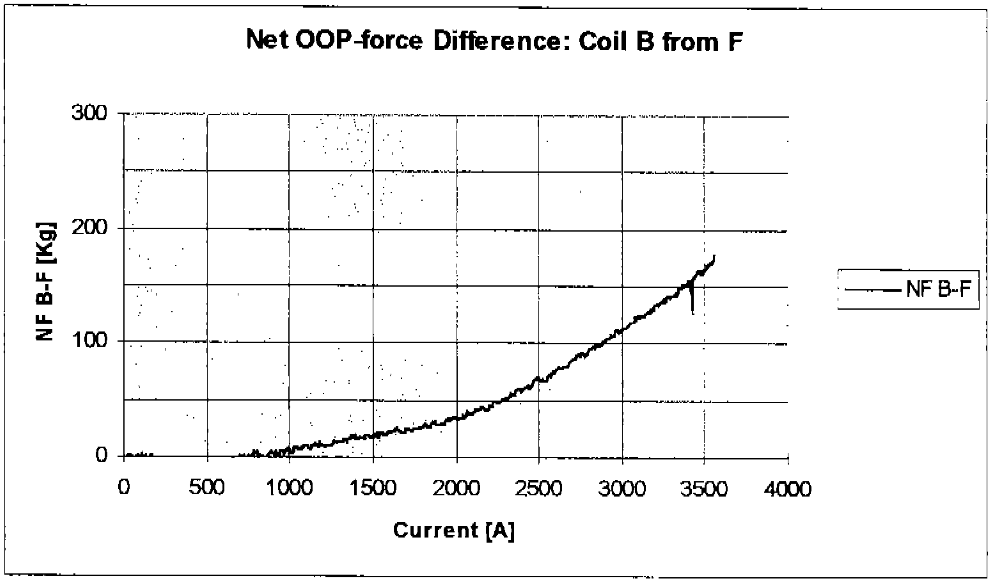

Total OOP-forces: Sum of Faces Bottom
Force [Kg]
2000
1600
1200
800
400
0
0
500
1000
1500
2000
2500
3000
3500
4000
Current [A]
Rundown
CoilA B
CoilB B
CoilC B
CoilD B
CoilE B
CoilF B

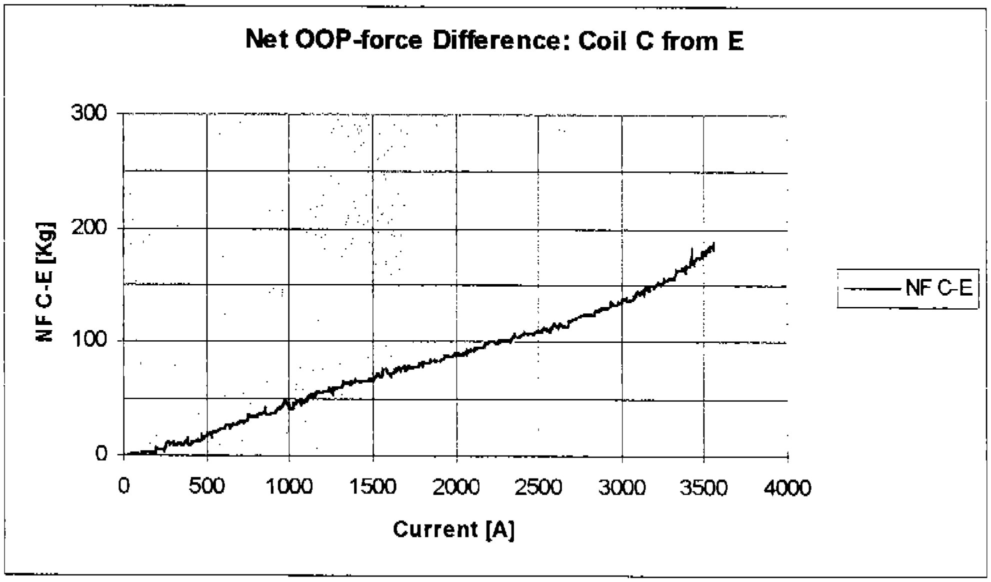

Net OOP-forces: Coil A&D
800
700
600
500
400
300
200
100
0
-100
Force [Kg]
0
500
1000
1500
2000
2500
3000
3500
4000
Current [A]
Rundown
Warning
NF CoilA
NF CoilD


Net OOP-forces: Coil B&F
800
700
600
500
400
300
200
100
0
-100
Force [Kg]
0
500
1000
1500
2000
2500
3000
3500
4000
Current [A]
Rundown
Warning
NF CoilB
NF CoilF


Net OOP-forces: Coil C&E
Force [Kg]
Current [A]
800
700
600
500
400
300
200
100
0
-100
0
500
1000
1500
2000
2500
3000
3500
4000
Rundown
Warning
NF CoilC
NF CoilE


Net OOP-force Difference: Coil A from D
NF A-D [Kg]
300
200
100
0
0
500
1000
1500
2000
2500
3000
3500
4000
Current [A]
NF A-D


Net OOP-force Difference: Coil B from F
NF B-F [Kg]
300
200
100
0
0
500
1000
1500
2000
2500
3000
3500
4000
Current [A]
NF B-F


Net OOP-force Difference: Coil C from E
300
200
100
0
NF C-E [Kg]
0
500
1000
1500
2000
2500
3000
3500
4000
Current [A]
NF C-E