Thermal Saturation, Current Degradation and Mechanical Load Analysis in Electromagnetic Diverter Gates

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***Abstract*—Electromagnetic diverter gates in high-speed mail sorting systems frequently exhibit "Past Gate" errors and jams under heavy ZIP-code concentration. Field measurements show that excessive duty cycle causes the solenoid coil to thermally saturate, increasing resistance from $13.9\,\Omega$ (cold) to as high as $19\,\Omega$ (hot), resulting in a $26\,\%$ current drop and nearly $45\,\%$ loss of pulling force. This paper combines electrical measurements, mechanical spring-force analysis, high-speed video motion analysis, and thermal characterization to demonstrate that the root cause of gate malfunction is thermal overload, not component failure.**

I. Introduction

Diverter gates route mail into output bins via solenoid actuation against a return spring. Under balanced distribution, each gate operates with a moderate duty cycle. However, ZIP-code concentration causes certain bins to receive a disproportionately large volume of mail, forcing their gates to operate continuously. This sustained activation results in coil heating, electrical degradation, slowed mechanical response, and ultimately incomplete gate motion.

II. System Overview

The diverter mechanism includes:

- $42\,\text{V}$ PWM driver,
- Electromagnetic solenoid coil,
- Extension return spring (normally-closed force),
- Gate arm that actuates into the mail path.

III. Electrical Measurements

A. Coil Resistance Profiling

Initial cold resistance measured:

$$R_0 = 13.9\,\Omega$$

Hot-state resistance after continuous operation:

$$R(T) = 18.5\,\Omega \text{ to } 19\,\Omega$$

Jam event (warm-state):

$$R_{\text{jam}} \approx 16\,\Omega$$

B. Temperature Estimation

Using copper TCR:

$$R(T) = R_0[1 + \alpha(T - T_0)]$$

$$\alpha = 0.0022/^\circ\text{F}, \quad T_0 = 77\,^\circ\text{F}$$

Fig. 1: Front view of the diverter gate and return spring.

C. Current and Force Reduction

At $42\,\text{V}$:

$$I_{\text{cold}} \approx 3.0\,\text{A}$$

$$I_{\text{hot}} \approx 2.2\,\text{A}$$

Force is approximately proportional to current squared:

$$\frac{F_{\text{hot}}}{F_{\text{cold}}} \approx \left(\frac{I_{\text{hot}}}{I_{\text{cold}}}\right)^2 \approx 0.55$$

IV. Field Evidence and Failure Observation

During normal operation, a large jam occurred. The diverter gate was extremely hot to the touch and exhibited delayed motion. Immediately after stopping the machine, the coil resistance initially exceeded $16\,\Omega$, consistent with severe thermal saturation. However, because the coil cools relatively quickly once de-energized, the measured value had already dropped to $15.4\,\Omega$ by the time the multimeter was connected. This rapid resistance decay further confirms that the coil was operating in an overheated state compared to its baseline cold value of $13.9\,\Omega$. The jam event therefore, provides direct field evidence of the thermal overload failure mode.

Fig. 2: Large jam event associated with a thermally saturated gate.

Fig. 3: Coil measured at $16\,\Omega$ immediately after the jam.

V. Spring Force Measurement and Analysis

A. Method

A controlled comparison was performed using two return springs of identical geometry: one worn spring removed from service and one new replacement spring. To reduce endpoint ambiguity, total end-to-end spring length was measured in all cases. Both springs were suspended from a fixed point and loaded with the same reference mass (water bottle with fixed fill volume), ensuring identical applied force during testing.

B. Reference Load Comparison

The measured free length for both springs was approximately $L_0 = 17\,\mathrm{mm}$. Under the same applied reference load, the worn spring extended to $44\,\mathrm{mm}$, while the new spring extended to $39\,\mathrm{mm}$. These correspond to extensions of $x_{\text{old}} = 27\,\mathrm{mm}$ and $x_{\text{new}} = 22\,\mathrm{mm}$, respectively.

Because the applied force was identical in both tests and the spring force follows $F = kx$, the effective stiffness ratio is given by

$$\frac{k_{\text{new}}}{k_{\text{old}}} = \frac{x_{\text{old}}}{x_{\text{new}}} = \frac{27}{22} \approx 1.23.$$

This indicates that the new spring is approximately 23% stiffer than the worn spring under the same reference load.

TABLE I: Reference Load Spring Comparison

Spring	Extension (mm)	Relative Stiffness
Worn	27	1.00
New	22	1.23

C. Effect on Gate Motion

The increased stiffness of the new spring raises the mechanical load that must be overcome by the solenoid during gate actuation. Under cold conditions, the solenoid provides sufficient force margin to overcome this load. However, as shown in Section III, thermal saturation reduces solenoid force by nearly 45%. When combined with a stiffer return spring, the available net force becomes marginal, increasing the likelihood of delayed, incomplete, or intermittent gate opening during sustained high-duty operation.

VI. Combined Model and Discussion

This section will integrate:

- Measured coil electrical degradation,
- Temperature rise,
- Current and force drop,
- Spring force load,
- High-speed motion reduction.

A diagram will illustrate the interaction:

High Duty Cycle $\rightarrow$ Heat Rise $\rightarrow$ Resistance Increase $\rightarrow$ Force Loss $\rightarrow$ F

VII. Conclusion

Preliminary findings indicate that diverter gate malfunctions arise from thermal overload due to uneven ZIP-code distribution, not component failure. As the solenoid heats above $220\,^\circ\mathrm{F}$, its force drops nearly in half, becoming insufficient to overcome even a standard return spring—much less a worn one. Future work will complete high-speed analysis, validate thermal data, and produce a predictive model for maintenance scheduling.

Appendix

Raw measurements, photos, and formulas will be included here.

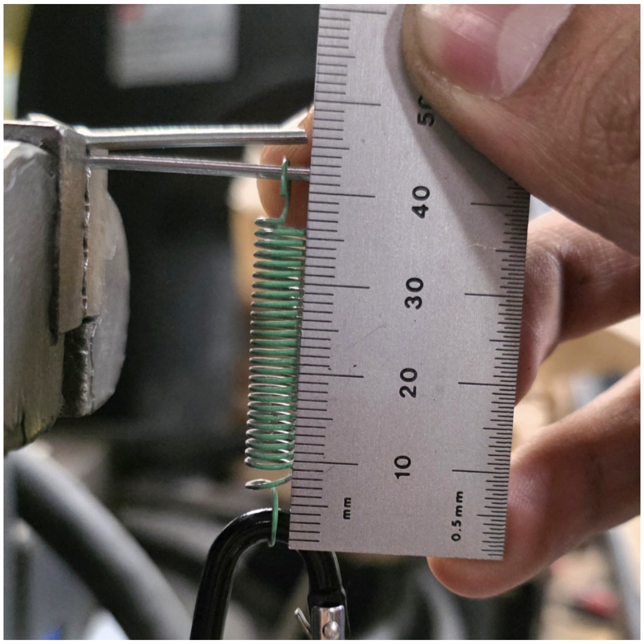

Fig. 4: Worn Spring.

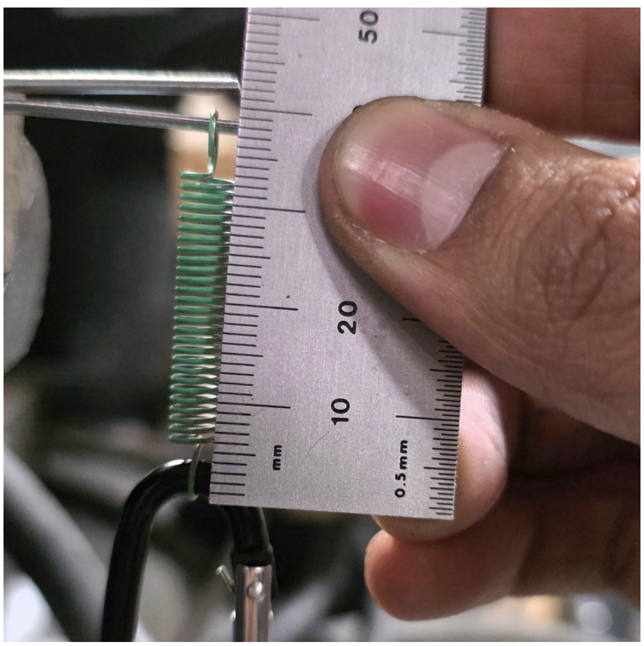

Fig. 5: New Spring.

References

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