Shape Memory Alloy Actuator Suitable for Use in Automatic Transmission Shift Systems

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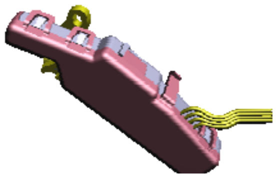

Abstract:
We review a shape memory alloy (SMA) actuator suitable to replace conventional brake transmission shift interlock (BTSI) electromagnetic solenoids in automotive applications for improvements to sound quality, weight reduction, and robustness against contamination. The design requires a power cutoff switch for the SMA wire as well as a strain relief mechanism to prevent damage to the wire when the shift lever is mechanically bound by the driver. The design couples an additional output from the actuator circuit. This output has practical use for signaling a shift lever Park position to any vehicle controller.

Keywords: shape memory alloy, SMA, solenoid, park switch, shifter, shift system, actuator, interlock

Introduction

In conventional automatic transmission shift systems, automobile manufacturers require that the shift lever be locked in the Park position until the user/operator applies the brake pedal. Designs traditionally accomplish this through the use of a shifter lever blocking mechanism coupled to an electromagnetic actuator such as a solenoid that responds to an electrical signal from the brake switch. The actuator pulls the blocker from the path of the gear select lever allowing access to other shift positions. The starting force required to pivot the blocking mechanism across all environmental conditions drives the actuator requirements.

Concerns of the State of the Art - Solenoids

Solenoids have been used in shift systems for over a decade successfully, yet there have been countless engineering hours devoted to improvements to these types of solenoids in haptic qualities such as sound and feel of the actuation event. Further, solenoid construction requires the use of ferrous materials and conductive coils to set up the magnetic flux paths used to create the force required to accomplish work. These materials add an undesirable mass presence in an automotive industry sensitive to weight in the product.

The shifter location in the vehicle is often alongside beverage cup holders, predisposing the solenoid to beverage spills. Spills ranging from carbonated soda to ice cream have found their way down the side of the shifter mechanism and into the solenoid resulting in solenoid binding.

Solenoids have a force-displacement curve such that the force increases at an exponential rate as the air gap is closed and inductance is maximized. Since in a pull-type solenoid, the air gap is largest at the beginning of the useful stroke, the useful force is also at the minimum at the beginning of the stroke. The high likelihood of beverage spills coupled with low starting pull forces account for a relatively high susceptibility of solenoid failure. A solenoid that will not or cannot respond to the electrical signal commanded to allow a shift from Park results in a vehicle locked in the Park position as the driver is unable to access any gear positions.

As green technologies drive the electrification of the modern automobile, use of lower electrical power devices in automotive subsystems is desired. A typical automotive shifter subsystem specification allows only 0.500 amps maximum to power a shifter solenoid coil at a nominal voltage of 12 VDC at 20°C. A solenoid coil has a designed nominal resistance under standard operating conditions, with a tolerance allowed for turn count differences, wire tensioning, and other process dependent variables. A solenoid coil resistance also increases and decreases with temperature with the copper constant.

$$R_2 = R_1 * (1+0.00393/T_2-T_1)$$

Higher temperatures at the copper coils result in higher electrical resistance, which for any $I = V/R$, reduces the current draw for a given voltage. Pull force in the solenoid coil is proportional to the magnetic flux and the magnetic flux to the current. From this relationship, high ambient temperatures and the thermal rise of the coil compromise the solenoid output efficiency. The solenoid design engineer is tasked to scale the solenoid design to provide the appropriate current to commence armature movement at the largest air gap with the highest saturated coil temperature and at the lowest voltage. This results in nominally inefficient power utilization under the standard operating conditions to meet full range functionality.

In summary, while solenoids have been the standby for mechatronics movement of shifter lever blockers, there are clear shortcomings where shape memory alloy technology has advantages.

Shape Memory Alloy Actuator Design

Figure 1 shows a typical force vs. displacement graph over a supply voltage range.

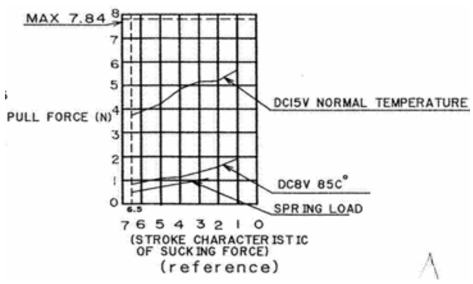

Figure 1: Solenoid Force-Displacement vs. Supply Voltage

Since the shape memory alloy wire transition is a physical change, the force it produces is only dependent on the transformation temperature to perform its work. It is independent of output force variations with temperature and voltage. In selecting a suitable construction for the actuator, a shape memory wire selection considers the percent strain required to achieve a reasonable stroke in a diameter of wire that could support the pull force. A suitable Flexinol® grade of wire is a strand of 0.076 mm (0.003") Flexinol® wire at the 90°C transition temperature. This transition temperature needs to be above the maximum cockpit temperature of 85°C. The shape memory alloy wire acts like a simple resistor with its resistance increasing with its length and with temperature up to its phase change. The wire resistance decreases as it moves through its phase change as the wire length decreases and its diameter increases. This decrease in resistance is limited to completion of the phase change, as thereafter resistance increases with temperature again like a simple resistor. According to the Flexinol® data table [2], the wire requires approximately 0.100 amps of current to heat to the transition temperature in the lengths sufficient to achieve the required travel. Approximately 140 mm of wire is used in a looped configuration (70 mm length) to achieve a wire travel target of 2.0-3.0 mm of travel at the sliding member with a pull force of approximately 0.80 N. Since the wire is looped, it provides double its load carrying capacity. So the design is capable to 1.60 N simply by looping. Further, in the right angle configuration the force applied to the sliding member by symmetry is doubled again.

Sound electrical connection requires the wire be in a looped construction to assure a static electrical contact. The wire terminates at one end of the actuator, wraps around a radius on the opposite side, and returns to its starting point using a right angle pull as in Figure 2.

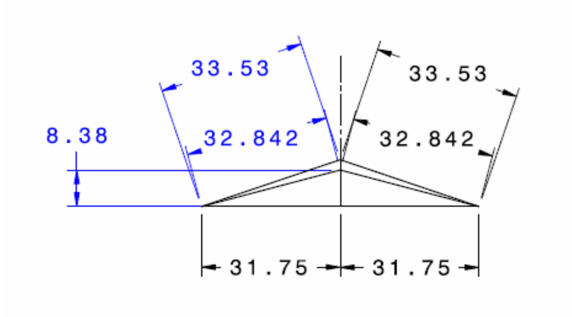

Figure 2: SMA Wire Actuation Design Profile (mm)

In automatic transmission console shift systems, it is common for operators to bind the action of the shift lever blocker by pressing the shift knob button or pulling the shift lever before stepping on the brake. To protect the SMA from overstress, it is necessary to use an indirect pull and include a mechanical strain relief shown in Figure 3.


Figure 3: Strain Relief Spring

Protecting the SMA wire from overcurrent, a circuit cuts power to the wire once a predetermined slide position had been reached. This is accomplished through use of a phototransistor. Once voltage is applied to the device, the wire quickly changes phase thereby contracting and accomplishing the desired work. Once the phototransistor detects the presence of the slide, it cuts power to the wire. The wire then dithers between energized and de-energized states at the phototransistor state change. This dithering offers a sustained hold current that is less than that of the heating current, thereby having more efficient power utilization and maintaining the wire right at its transition temperature – effectively optimizing the cooling time by limiting any thermal overshoot. The slide and phototransistor are shown in Figure 4.

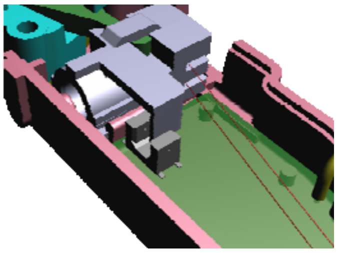

Figure 4: Phototransistor and Slide

The slide is a nylon component with a glossy finish to glide smoothly across the guide channels in the housing to create a low friction surface. The arm feature on the slide responsible for cutting power to the wire needs to be non-reflective for proper phototransistor function. To accomplish this function, the arm interrupting the source on the transistor is molded with a sandblast texture on the surface to provide a locally opaque finish.

Terminations of the wire to brass terminals are accomplished via mechanical crimp and electrically to the PC board with through-hole solder connections with discrete wire conductors shown in Figure 5. The brass terminal support assures proper location and mechanical retention of the wire.

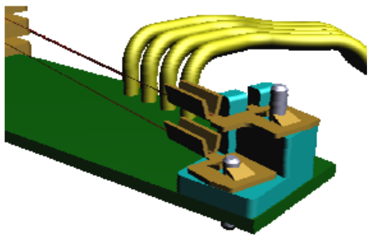

Figure 5: Prototype Electrical Termination

Commonly, console shifters contain a lever switch to indicate the shift lever is in the Park. This requires a discrete lever-type switch as a separate electrical contacting element of the shift subsystem, equally deposed in the architecture so as to be subject to contamination and fluid spills. An innovative step in this actuator design considers that the phototransistor is required for turning off the SMA wire when the desired position is achieved. One uses a mechanical means to maintain the SMA slide in the blocked position when the shift lever is moved from the Park position; and only allows the SMA slide to return to its home position when the shift lever is returned to the Park position. The output from the phototransistor doubles then as the switch to the key lock actuator. In this way, a common functionality is achieved integrally with a feature that is already required for proper SMA function. This eliminates a separate switch and wire harness in the overall shifter subsystem architecture.

Results

The actuator assembly is qualified on its merits in comparison to an active production automotive solenoid assembly on the basis of mass, noise quality, pull force, beverage spill, cyclic durability and response time.

Mass

The solenoid weighs 0.100 kg, and the SMA Actuator weighs 0.020 kg for a realized reduction of 0.080 kg. As the entire benchmark shifter weight is 1.13 kg, changing the actuator from the existing solenoid to the SMA embodiment results in a 7% reduction in the target shifter subsystem mass.

Pull Force

The SMA actuator betters the conventional pull-type solenoid in that it provides its greatest force at the beginning of its pull stroke. The pull force of the SMA actuator does not vary with ambient temperature changes or voltage input changes. The instantaneous current required to cycle the SMA actuator is 145 mA, and the current required to hold it at the phototransistor state change is approximately 50 mA. This compares to a 24 ohm solenoid coil, given 12.0 VDC applied, will draw 490 mA at room temperature. The variation in current draw for a solenoid coil at different voltages and temperatures, negating self-heating effects, appear in Table 1. Any current that is drawn above that required to perform the required work, less than 270 mA in this example, is wasted.

	Temp (°C)	Voltage (VDC) 8V	12V	16V
SMA	20		0.145	
24 W	-40			**0.870**
Solenoid	20	0.400	0.490	0.650
(calculated)	85	**0.270**		

Table 1: SMA vs. Solenoid Current Draw (Amps)

Noise Quality

There is emphasis in the automotive industry to continue the reduction of noises in the vehicle cabin. Many of the console shifters on the market today have solenoid activation noise in the 60 dBa range. This noise is evident in the vehicle when the shift lever is in Park and the brake pedal is pressed. With background noise levels in an anechoic chamber at

26 dBa, the prototype SMA actuator achieves noise levels in the 30 dBa range.

Beverage Spill / Contamination

An underappreciated failure mode in console shift systems is the presence of soda and other beverages in and around the center console of the modern automobile. This location is also the prime location of coveted cup holders, which bring substantially sticky and otherwise deplorable conditions for mechatronic elements. The requirement in console shifters is for the assembly to be subjected to up to two (2) liters of Coca-Cola® poured onto the shifter assembly and cycled, then allowed to set for 24 hours and then cycled again. Provided the shifter is allowed to shift from Park, then the test is considered to have passed. Several solenoids and the shape memory alloy actuator successfully pass this test; however, a boundary test to show an improvement is desired. An additional proof test on one sample each submerges an SMA actuator and a solenoid in the PepsiCo product Mountain Dew® and energizes the assemblies several cycles. The assemblies are allowed to set and the beverage evaporates over 48 hours leaving the sticky sugary residue in the housing. The SMA actuator successfully cycles without damage, but the solenoid does not function after the 48 hours.

Cyclic Durability

The durability requirement of the modern console shifter is 500k cycles. Six (6) prototype SMA actuators cycle for over 1 million cycles (2X life) without incident.

Response Time

The important characteristic for fast response times in a console shifter is ‘on’ or ‘energize’ time. This is the time required from the moment the brake pedal is depressed to the point at which the shift lever is not inhibited from moving from the Park position, and this requirement is typically 100 ms maximum. The on response times for the SMA actuator appear in Table 2. The off response times do not vary with voltage since the temperature of the wire was maintained right at the transition temperature due to dithering at the phototransistor. The off response times are instead dependent on the cooling rate of the wire and are longer with higher ambient temperatures.

Temp ºC	VDC	On Time (ms)	Off Time (ms)
-40	8	400	80
-40	12	100	100
-40	14	60	100
22	8	180	150
22	12	70	145
22	14	50	140
75	8	70	400
75	12	30	400
75	14	20	470

Table 2: SMA Response Times vs. Voltage and Temperature

Summary

The prototype SMA actuator offers functional improvements over solenoids in the area of mass, audible noise, and contamination resistance. The actuator demonstrates functional reliability over a million cycles at no load. The response time shows consistent and acceptable results in the energized direction, and the ability to turn off at acceptable intervals across the -40°C to 85°C thermal requirement.

Acknowledgements

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References

[1] Brown, J. (n.d.), Technical Characteristics of Flexinol Actuator Wires TCF1140RevD. [Electronic Version], Retrieved from http://www.dynalloy.com/pdfs/TCF1140RevD.pdf

[2] Tech Data (n.d.), Retrieved from http://www.dynalloy.com/TechData.html

[3] Mitteer, D.M. (2008) Shifter with Shape Memory Alloy and Safety Circuit, USPTO Application 20090025501.

[4] Odesser-Torpey, M. (2006), “Cars and Quick-Service”, *QSR Magazine*, Oct 2006 [Electronic Version], https://www.qsrmagazine.com/articles/features/94/car_design-1.phtml

[5] Butera, F. (2008), Shape Memory Actuators, *Advanced Materials & Processes*, March 2008 [Electronic Version], http://www.shape-memory-alloys.com/documents/Advanced Materials_March 2008.pdf