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Electrically Actuated Antiglare Rear-View Mirror Based on a Shape Memory Alloy Actuator

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This article focuses on the experience of Centro Ricerche FIAT (CRF) regarding the development of shape memory alloy (SMA) actuators, and addressed some new design approaches which have been defined. Specific characteristics of shape memory materials, such as the efficiency of the transformation, have oriented the design of actuators toward occasionally used devices. The antiglare manual mechanism, incorporated in the internal rear-view mirror of a car, fits this new approach well. An antiglare rear-view mirror is a system capable of detecting a glare situation during night-time driving in order to automatically switch the mirror plane so as not to distract the driver. The low forces required, together with the silent, bi-stable movement are suitable for the use of a SMA actuator in this application. In the first part of the paper, the conceptual design is illustrated and a preliminary overview of the working principle is provided together with a series of considerations regarding the kinematics and the layout of electronic sensors in order to realize a fully controlled mechatronic prototype. Before concluding, the description of the realization of a working prototype is presented. The prototype of the EAGLE (Electrically Actuated antiGLare rEar-view mirror) system has provided experimental confirmation that such a device can satisfy fatigue and functional test requirements, thus offering the opportunity to spread the use of SMA devices in the automotive field.

Keywords automotive antiglare mirrors, device re-engineering, shape memory alloy

1. Introduction

Exploiting compactness and silent operation of shape memory actuators, a new internal rear-view mirror with an automatic antiglare mechanism has been developed.

To date, automatic antiglare internal mirrors have been made of electro-chromic materials only. Electro-chromic rear-view mirrors produce a variation in the reflectance in case of a dazzling light. These materials have a response time of several seconds after the glare condition has occurred, meaning that the device is not very effective in terms of protecting against the disturbance to the eyes of the driver. On the other hand, relatively expensive materials are needed and the darkening produced on the mirror surface to eliminate the glare is often considered to be a negative aspect.

An improved solution from the ergonomic point of view therefore is offered by the mechanical movement of the reflecting prismatic surface. Traditionally, manufacturers have equipped vehicles with prismatic overhead rear-view mirrors which function by using a mirror backed triangular piece of glass attached to a mechanical pivot. During normal operation, collimated incident light from the rear windshield is reflected off the mirror. Upon angular adjustment, the prism reflects light off its frontal surface at night, creating a dimmer reflection (Ref 1).

The beneficial features of the manual actuator include low cost and silent operation, but consumers are generally averse to manual actuation in today's vehicles; as a consequence, most car drivers simply do not use such a function.

Furthermore, the need to re-engineer this component derives from the safety perspective since with the manual device drivers must take one hand off the driving wheel for a couple of seconds in order to rotate the mirror. Often car buyers are interested in technology features if offered at a relatively low price which also helps to distinguish the specific product. Following this reasoning, car designers work at continually developing at new technologies to perform a particular function but at lower cost, and potentially with a higher level of quality, functionality and reliability.

In recent years, mirror activation by electro-magnetic actuators have been attempted but these have not been particularly successful due to the size of the actuators and actuation noise which can distract the driver. Clearly inside a car every distraction to the driver is potentially dangerous. For this reason, the antiglare system exists and the manual or the electro-chromic technology is used.

The device with shape memory actuator overcomes these restrictions with a very fast actuation (from the normal to antiglare position in less than a second) that is also silent and gradual without mechanical jerking.

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This paper intends to demonstrate that shape memory alloys (SMAs) actuators represent an appropriate and feasible solution for providing a low cost and reliable automatic device.

The main features of shape memory actuators are the high density power and silent operation. The first feature is essential to enable a simple and low weight device, whereas low noise in the cabin of a car is fundamental to avoid driver distractions.

Previous experience in Centro Ricerche FIAT (CRF) gave rise to the realization of a prototype, the main aim of which was to produce a mirror rotation through the shape memory wire contraction during the glaring time. This system was composed of a direct connection between the SMA wire and mirror. Thus, during glare, the wire has to be heated continuously to maintain the required twisted position. As a consequence, a series of problems related to activation and deactivation time, power consuming and fatigue lifetime were encountered.

One aim of this paper is to describe the criteria adopted in the design of a new electrically actuated antiglare rear-view mirror.

2. Component Requirements

For the development of the device, the automotive specifications and the experience on mirrors of the development partner Ficosa International were taken into account.

The typical requirements of automotive components are very demanding both in terms of performance and reliability (Ref 2). Each automotive component maker must ensure these specifications are respected before supplying the component to the car maker. The component checking process is very stringent and often makes the introduction of new devices in the car difficult, particularly in the case of new, emerging technologies. However, it also stimulates development of new materials capable of meeting the specifications required.

Figure 1 shows the main specifications that an automotive component must comply with. The most critical points for development of new actuators based on shape memory materials are as follows:

- operating temperatures,
- fatigue and number of cycles, and
- long-term stability of mechanical characteristics.

As for the SMA's operating temperature, it must be stressed that the SMAs on the market based on Ni-Ti are characterized by martensite-austenite transition temperatures (A_s—austenite start) of up to 99 °C. However, due to the high-level hysteresis involved (usually above 20 °C), the austenite-martensite transformation temperature (M_f—martensite finish) is below 78 °C (Ref 3). These materials can be used in actuators that normally operate below 78 °C, such as those that operate only during the night or those located in points of the body where the temperature does not rise above M_f. Evidently it is necessary to ensure that the actuator is not damaged at higher temperatures and, at the same time, is not actuated automatically due to a high ambient temperature. This problem is related to the transformation temperatures and restricts the potential field of application of SMA alloys in the car. Over recent years considerable effort has been dedicated to resolve these issues; nevertheless, it is still appropriate to shift the entire shape memory transformation cycle to above 100 °C.

In order to exploit the characteristics of SMA devices and their miniaturization potential, there is a tendency to integrate the actuator within the mechanics or even inside the structure of the component. Therefore, the component can be considered to become "smart", meaning also that the functional performance must be assessed at a system level. In some cases, this prevents the use of standard tests, thus requiring the development of "ad hoc" procedures in order to characterize the "smart components" (Ref 4).

Activation time	< 1 s
Operating voltage	10 ÷ 16 VDC
Operating temperature	-40 ÷ +85°C
Numbers of cycles	60000
Work in harsh environment	\
Low cost	\
Vibration	50 ÷ 2000 Hz, up to 10g

Fig. 1 Typical requirements of automotive components

3. Conceptual Design

The technical specification of the device are

- bi-stable mechanism,
- silent operation,
- approximately 8° mirror rotation,
- fatigue life up to 60,000 cycles, and
- low cost.

The design process started with the study of kinematics. Attempting to merge compactness with simplicity, a bi-stable mechanism similar to those present in pens was designed, the idea being to use a SMA wire to push a mechanism that forces the mirror to assume alternately the normal position and the rotated position. This movement allows the prismatic mirror to reflect the undesired light on to the headliner and consequently perform the antiglare function.

The new device comprises three main components:

- a SMA wire,
- a piston, and
- a bracket to support the mirror.

The SMA wire forces the piston to move vertically; on the piston, a pin connected to a hinged bracket slides within a slot into the piston. The bracket is rigidly connected to the prismatic mirror. Each wire contraction causes the piston to move and forces the bracket to rotate alternately following the slot path. The shape of the slot is designed with two engaging points corresponding to the stable positions of minimum potential: one of these positions is reached and maintained during the glare phase, while the other is maintained during normal operation. The mechanism is designed to provide a separation between the wire position and the mirror position, allowing the wire to cool down to be ready for the successive actuation. Figure 2 shows the first sketches made to visualize the mechanism working principle.

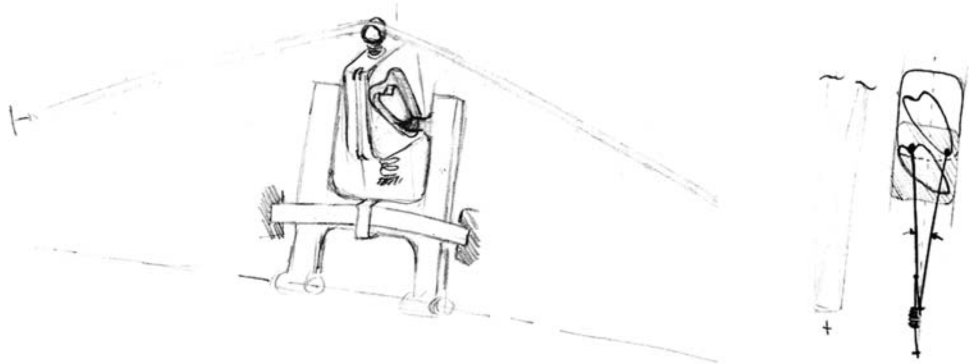

Fig. 2 First draft of the mechanism showing the main working principle

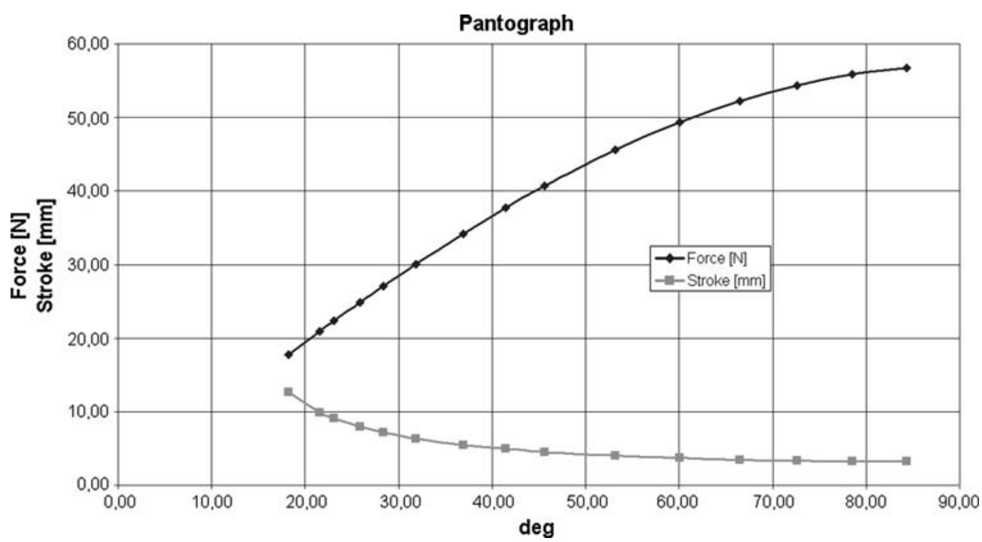

Fig. 3 Wire response simulation; vertical stroke and force vs. 0.5 mm diameter SMA wire starting position angle

The mechanism has been designed in order to ensure no error possibility during actuation, to guarantee the stability of the mirror from vibration and to be silent during activation and deactivation. The result is a simple, thin, wire-integrated component that provides designers with styling freedom.

4. Wire Engineering

At the heart of the system is the interaction between the wire and the slot profile, and a significant proportion of the design effort focused on minimizing the stress over the wire during actuation.

The objective here is to ensure a predetermined displacement so as to guarantee the appropriate relative movement between the slot and the pin (which is rigidly connected to the bracket); a two-way shape memory effect stabilized wire was used to perform this task (Ref 5).

Experimental data provided an indication of the nominal load to which the wire could be stressed, in order to achieve a fatigue life of over 500,000 cycles: this value is about 150 MPa. Correspondingly, it is appropriate not to exceed this value systematically since the hysteresis curve switches to a higher temperature if the load is increased (Ref 6). With the increase of the transformation temperatures, various drawbacks can arise such as the increase of necessary actuation energy, the increase of final temperature and, as a consequence, the increase of required heating and cooling times.

Additionally, the wire was positioned like a pantograph to enhance the stroke available, causing the axial stress to increase. Therefore, one aim of the design process was to arrange the device in such a way as to make the wire work in the range in which the shape memory wire is safe.

Tensile force and available stroke depend on the angle that the wire forms when mounted in the device (pantograph angle); using the diagram shown in Fig. 3, it is possible to choose the pantograph angle that enables the right balance between stroke and force needed. The diagram illustrates the force and stroke values at different angles of the pantograph placed wire. The values are calculated assuming a 150 MPa tensile strength on a 0.5-mm-diameter wire. The angle chosen is 24° and the wire length is 200 mm. The wire contracts 8 mm linearly and the available useful displacement for the actuation is 10 mm (2 mm over the nominal 4% contraction). That range provides a safety margin during actuation. At the same time, the theoretical force the wire can exert is 23 N (@ 150 MPa).

The wire shown in Fig. 4 has a silicone covering (Ref 7). Since the transformation is completely controlled by temperature, the wire section is affected by high thermal gradients. Besides the interface between the crimp and the wire with the free air is a breaking affected point, therefore the wire covering uniforms the conductivity coefficient on the heat exchanging surface and reduces the thermal stress on the material itself.

Furthermore, the silicone cover causes the thermal conductivity to increase and the wire cooling time to decrease. This means that the whole antiglare movement can be very fast and the activation frequency can be raised.

5. Mechanism Engineering

One of the first aspects investigated regarding the mechanism was the layout of the components incorporated in the device.

For reasons of symmetry the piston was placed in the middle of the mirror, the 200 mm SMA wire was laid behind the mirror plane as presented in Fig. 5 and 6.

The SMA actuator moves the piston and simultaneously compresses the two reaction springs which have a dual role:

- To bring the system always to a minimum-potential engaged position in order to keep the bracket (mirror) blocked.

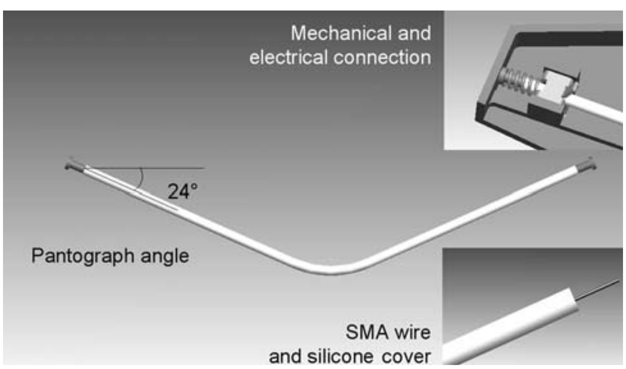

Fig. 4 Shape memory wire final layout with mechanical crimps and silicone covering

- To stress the wire during the cooling time in order to accelerate the shape recovery.

Two constant load springs were mounted to transfer a constant load on the SMA wire during the actuation. Correspondingly, considering force losses due to friction to be a nominally constant value, it was possible to forecast the loads acting on wire section and consequently simplify the device design.

During normal operation of the device, accidents may occur such as mechanism blockage or poor stroke end alignment. The system is protected from misuse by the insertion of a compression spring mounted axially and in series with the wire. In this way, the connection between the wire and the main structure collapses when the wire tension exceeds a predetermined value of about 33 N, the aim being to lengthen the life of the wire loading mechanism by preventing it from breaking prematurely.

A large part of the work conducted was dedicated to the design of the slot path in order to convert wire work (in terms of forces and stroke) into an ergonomic movement which minimizing friction losses. In the design of the slot profile, it is important to imagine how the bracket needed to move. When glare occurs, the mirror should rotate 8° from the starting position and then must be blocked in that position. The releasing actuation should disengage the mirror and bring it to the original position.

The question was how to make this rotation starting from the SMA wire contraction, enabling smooth movement of the mirror and consequently an "ergonomic" behavior of the device. Indeed, the asymmetric "heart" shape and the slot slope are the results of kinematic and ergonomic considerations, considerable time having been spent on its design.

To better understand the reasons behind arriving at this particular shape, it is useful to note that

- the vertical extension is 8 mm which corresponds to the available stroke provided by the wire,
- the width is defined by the 8° mirror rotation, and
- a mechanical stroke end-stop is useful to limit piston stroke and relax the wire in both stable positions.

The diameter of the pin was selected by considering the force acting on it and so as to avoid the second stable position

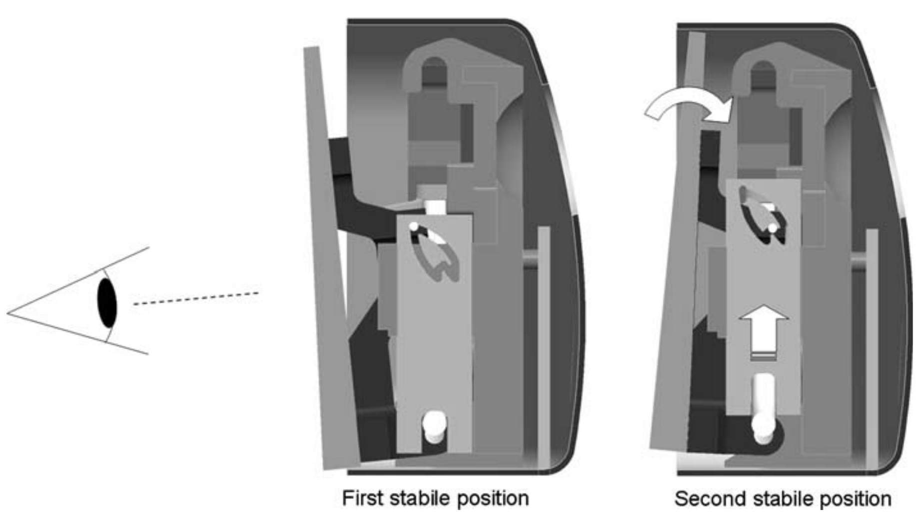

Fig. 5 Cross section showing the sloth path and the pin connected with the handle

bypass. At the same time, the slope of the ramp determines the loads that the wire has to sustain during actuation.

During actuation, an appropriate level of force must act to ensure proper operation of the bi-stable mechanism in every condition of use. This force must act in a direction during the engaging run, and in the reverse sense during the disengaging phase. This is obtained by a plastic flexure inspired by the conventional solution of the manual actuated rear-view mirror connected to a handle.

The flexure upper hinge, the bracket lower hinge and pin axis had to be aligned in the vertical plane. That plane defines the bracket instability position (Fig. 6). When the pin axis crosses that plane, the pin is pushed toward the opposite arm of the heart-shaped slot. The force produced by the flexure forces the pin to follow the right ramp. Consequently, the alternation of the engaging states is guaranteed since there is no possibility for the pin to come back on the same side again. The instability zone is relatively wide due to friction, and so the theoretic slot was modified respectively.

Kinematics and dynamics were simulated in Pro/Engineering Mechanism application, the results enabling appropriate operation of the system to be predicted.

6. System Logic and Electronic Board Layout

To understand the logic behind the development of the system, lets consider driving on a highway at night during a relatively long journey—the driver is already feeling tired and eyes are starting to be overstressed. A car behind approaches with incorrect projector lights leveling resulting in glare.

The system has been designed to detect such situation using two photodiodes mounted on the electronic drive board; these sensors trigger the start of the actuation sequence. The SMA wire is then heated and the mirror rotates.

A hall-effect position sensor detects the moment when the system has reached the point at which the bi-stable device changes its stable equilibrium reference; then the wire is de-energized but the mirror is maintained mechanically in this position. When glare stops (e.g. the car behind overtakes), the system activates the wire a second time, so the mechanism becomes unclamped and the mirror rotates back to the starting position.

The anti-glare mirror movement is silent, rapid (taking less than 400 ms) and does not distract or interfere in any way with the attention of the driver (Fig. 7). In order to avoid continual

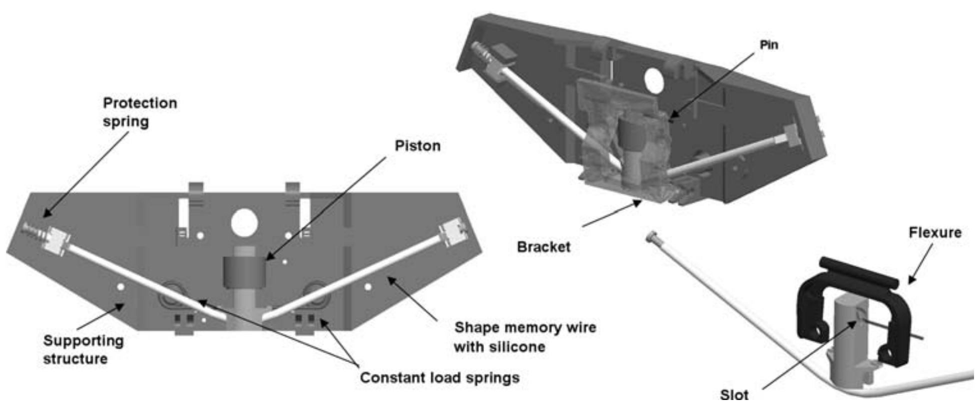

Fig. 6 CAD of the device and description of the components

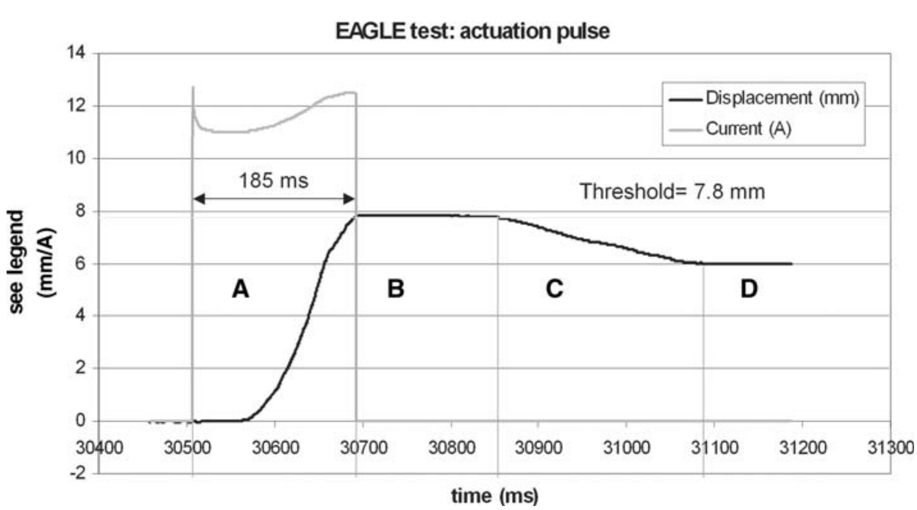

Fig. 7 Typical activation pulse and wire activation response time

operations of the system, which may cause an annoying flickering effect, a filtering time between a wire activation and the following is enforced (i.e. no actuations are allowed for a determined time after an actuation has occurred). In the current prototype, it was decided to pause the actuations for 20 s (Fig. 8).

The wire current absorption is regulated by means of a PWM controlled switch to optimize the behavior of the wire. The PWM frequency is about 100 Hz, sufficiently far from the typical acoustic spectrum. Any kind of current control can be used as well.

The heating time cannot be predetermined since it depends on the starting temperature of the wire, and the cabin of a car is a highly variable environment. For this reason, it is not possible to operate with a constant duration pulse and thus effective heating duration is defined by a position sensor that cuts the power supply. A hall sensor was chosen as position sensor in order to be noncontact, being placed onto the electronic board and allowing an easy mounting process.

Three different uniquely identifiable voltage values occur for the three different positions of the piston.

- Saturation for 1st stable position.
- <1 V for stroke end position.
- 3.2 V for 2nd stable position.

7. Testing the Wire

An initial fatigue test was performed on the sole actuating wire in the same geometrical configuration of the whole device. According to specifications, 60,000 actuations must be guaranteed. The wire was set up on the base with 24° angle and loaded with 2.34 kg (corresponding to 150 MPa). A potentiometer is mounted on the testing device to enable control similar to the expected one. A blocking device was mounted in order the simulate the behavior of the definitive

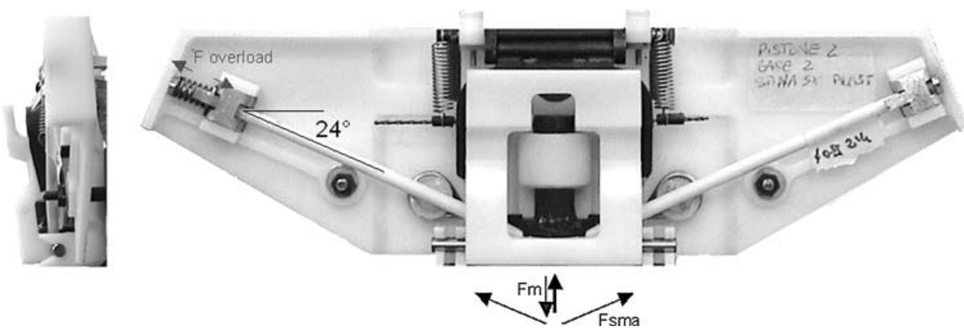

Fig. 8 Final prototype

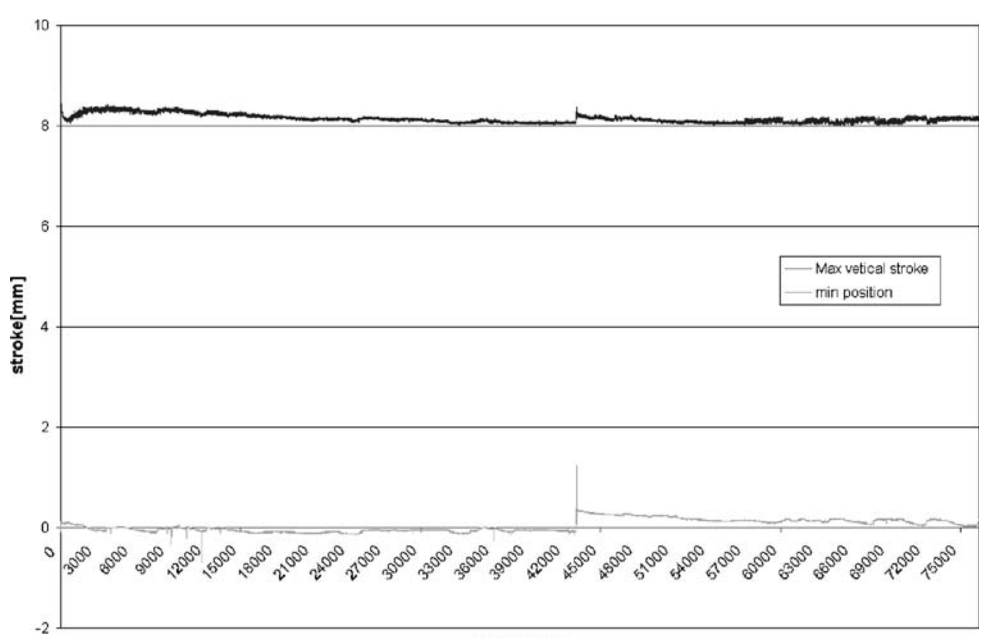

Fig. 9 Fatigue test on Dynalloy SMA wire mounted in the same geometrical configuration of the whole device (pantograph angle: 24°, wire loaded with 2.34 kg, wire diameter: 0.5 mm)

mechanism. During heating and cooling, maximum and minimum position, maximum current, applied voltage and heating time were recorded. The system cuts the power as soon as the stroke reaches 8 mm; the recorded overshoot can be attributed to inertial "bouncing" of the system which is not constrained. The electrical power is applied by a voltage generator at 10 V. The voltage in this case is lower than the automotive reference (used in the test of the whole system) since the absence of mechanical frictions would make the actuation too fast. A constant cooling time between subsequent pulses was applied.

A first test has been performed on the Dynalloy SMA wire (0.5 mm diameter). The results are shown in the graph below, and are positive with more than 75.000 actuations (Fig. 9).

Results demonstrate that the wire can withstand the fatigue requirements under the specified working conditions.

A second fatigue test has then been performed on the SAES Getters SmartFlex wire (0.5 mm diameter), with the same set of parameters. Again results demonstrate high fatigue resistance of the wire under the specified working conditions.

8. Complete Device Testing

The EAGLE (Electrically Actuated antiGLare rEar-view mirror) prototype was produced and assembled in order to perform a complete experimental activity. A fatigue test was performed on the prototype provided with a SMA wire controlled externally.

F_m min	18.2 N	Minimum Piston load
F_m max	25.2 N	Maximum Piston load
F_{sma} min	22.4 N	SMA wire load
F_{sma} max	38.7 N	SMA wire load
σ_{min}	114 Mpa	On wire section
σ_{max}	197 Mpa	On wire section
$F_{protection}$	33.4 N	Protection spring in action

Fig. 10 The table summarizes the forces and the stresses acting on the wire and on the piston

The forces acting on the piston and on the wire are summarized in the table shown in Fig. 10.

The device was mounted in standard working configuration without the mirror, and a potentiometer was installed and maintained in contact with the piston by a weak spring. The potentiometer was used to simulate the hall sensor and identify the position of the piston. All the tests were performed at room temperature (between 20 and 26 °C).

The target for the tests was to exceed 60.000 cycles (30,000 complete cycles of activation and deactivation).

A fatigue test was performed on the EAGLE mechanism mounted with a SMA wire controlled externally. The control was such that the current was interrupted as soon as a certain threshold was exceeded. The current itself was applied by a short circuit on 13 V power supply. As a further protection a "maximum duration time" was defined after which the current was interrupted even if the mechanical threshold had not been reached.

The diagram shown in Fig. 11 represents the overall behavior of the characteristic parameters during the fatigue test. The system achieved 73,455 actuations before the test was been interrupted before failure having already exceeded expectations.

9. Conclusions

This paper demonstrates that SMAs represent a good solution to create automatic devices inside vehicles. Typical automotive specifications have been presented and commented with reference to the main features of shape memory materials.

The example of an innovative design of an internal antiglare rear view mirror has been presented starting with the state-of-the-art of antiglare rear-view mirrors and continuing with shape memory wire characteristics and the target device function. The wire was used as a pantograph to enhance stroke output and was covered by a silicone cover to accelerate cooling. Electronic control ensures an adaptive power input according to the environment conditions, resulting in a long fatigue life for the device.

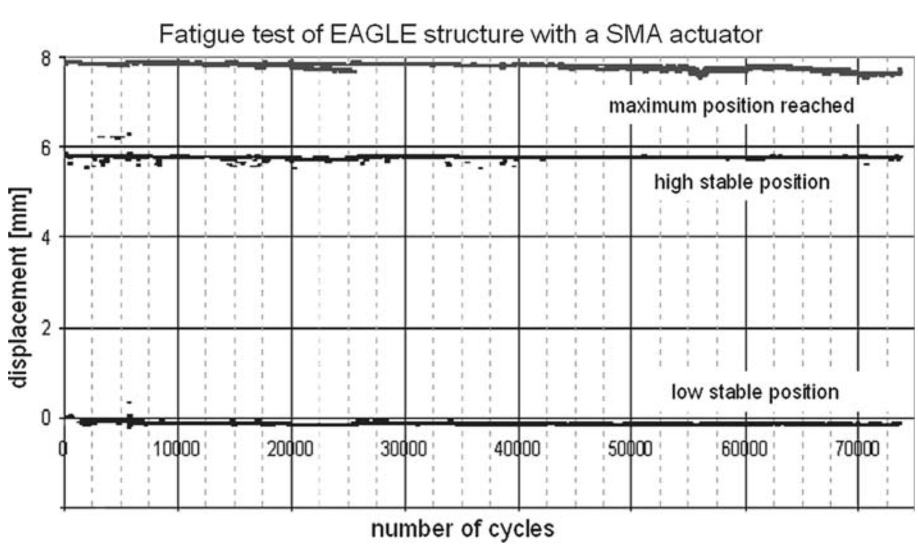

Fig. 11 Complete device fatigue test results with SAES GETTERS "SmartFlex" wire; during the test it has been measured the piston displacement and it has been registered its position in real time

The mechanism was designed with a bi-stable kinematics in order to protect the wire from thermal and mechanical overstress. The mechanism model was simulated with CAD tools in order to verify the kinematics. This activity was conducted directly with the supplier and produced a series of working prototypes ready to be tested on vehicles.

The testing activity, conducted to evaluate the prototype system, demonstrated that the mechanism is ready to respect automotive requirements.

This work also underlines some of the stringent design criteria that engineers should face when designing an innovative automotive device using shape memory materials. Such considerations will also help suppliers in understanding the specific issues and the complexity of the shape memory material engineering process.

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