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A Shape Memory Alloy-Based Morphing Axial Fan Blade—Part I: Blade Structure Design and Functional Characterization

Annalisa Fortini[1]
Metallurgy Research Group,
Engineering Department in Ferrara (ENDIF),
Ferrara ■, Italy

Alessio Suman
Fluid Machinery Research Group,
Engineering Department in Ferrara (ENDIF),
Ferrara ■, Italy

Nicola Aldi
Fluid Machinery Research Group,
Engineering Department in Ferrara (ENDIF),
Ferrara, Italy

Mattia Merlin
Metallurgy Research Group,
Engineering Department in Ferrara (ENDIF),
Ferrara, Italy

Michele Pinelli
Fluid Machinery Research Group,
Engineering Department in Ferrara (ENDIF),
Ferrara ■, Italy

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The possibility to realize adaptive structures is of great interest in turbomachinery design, owing to the benefits related to enhanced performance and efficiency. To accomplish this, a challenging approach is the employment of shape memory alloys (SMAs), which can recover seemingly permanent strains by solid phase transformations whereby the so-called shape memory effect (SME) takes place. This paper presents the development of a heavy-duty automotive cooling axial fan with morphing blades activated by SMA strips that works as actuator elements in the polymeric blade structure. Concerning the fan performance, this new concept differs from a conventional viscous fan clutch solution especially during the nonstationary operating condition. The blade design was performed in order to achieve the thermal activation of the strips by means of air stream flow. Two polymeric matrices were chosen to be tested in conjunction with a commercially available NiTi binary alloy, whose phase transformation temperatures (TTRs) were experimentally evaluated by imposing the actual operating thermal gradient. The SMA strips were then thermomechanically treated to memorize a bent shape and embedded in the polymeric blade. In a specifically designed wind tunnel, the different polymeric matrices equipped with the SMA strips were tested to assess the fluid temperature and surface pattern behavior of the blade. Upon heating, they tend to recover the memorized shape and the blade is forced to bend, leading to a camber variation and a trailing edge displacement. The recovery behavior of each composite structure (polymeric matrix with the SMA strips) was evaluated through digital image analysis techniques. The differences between the blade shape at the initial condition and at the maximum bending deformation were considered. According to these results, the best coupling of SMA strips and polymeric structure is assessed and its timewise behavior is compared to the traditional timewise behavior of a viscous fan clutch. [DOI: 10.1115/1.4031272]

Introduction

Actuators are devices which perform a task, such as moving an object, either on demand or in response to certain changes in their environment (temperature, pressure, etc.). In a modern car, more than one hundred actuators are used to control engine, transmission and suspension performance, to improve safety and reliability and enhance driver comfort [1]. Most of these actuators today are electric motors and solenoids. For this reason, the control systems account for the majority of the weight and volume of vehicle components and in some cases, they are too bulky, expensive, and not sufficiently robust for the intended application.

Renewed interest in automotive control systems is especially due in order to limit fuel consumption and exhaust emissions. More than half of the energy in vehicles is lost as heat to the different cooling systems (engine, driver, and passenger compartment space and auxiliary devices) and exhaust gas. Reducing the amount of energy lost in vehicle cooling systems will enhance the efficiency of the vehicles [2].

Technological progress has ensured the obtainment of high efficiency levels as a result of the real-time performance evaluation. The entire control system is therefore optimized, even in nonstationary operating conditions. The integration of smart materials in actuation systems represents an excellent technological opportunity for the development of simple, very compact, and reliable actuator devices. These structures are thus transformed from static to dynamic or, in some cases, adaptive as they can react directly to environmental stimuli. Smart materials can simplify products, add new functions, upgrade performance, improve reliability, and reduce component cost, mechanical complexity, and size.

The present paper focuses on an innovative passive control system for the performance optimization of heavy-duty automotive cooling axial fan. This challenging approach enables an optimal response to possible changes in turbomachinery operating conditions, avoiding any external actions on the shaft rotational velocity. The system is regulated by a sensorless control taking advantage of SMAs elements, whose phase transformation enables the production of favorable aerodynamic blade shape changes, according to the air flow temperature. Unlike conventional actuation and control systems employed in cooling fans (i.e., on/off clutch and air sensing modulated viscous clutches), the SMA actuation allows to control and adjust the fan performance to the engine thermal requests. This fan's setup can allow an almost continuous operation of the turbomachinery in the maximum efficiency point and not only for a discrete number of operating points. Given that the thermally activated phase transformation does not occur instantly, the SMA enables the development of heavy-duty machines which continuously modulate their working point, following the requested operating change seamlessly. As a result, the passive SMA-controlled system allows to: (i) eliminate the active controls (electric motor, thermostats and valves, and temperature probe), (ii) adapt the cooling fan to the

[1]Corresponding author.

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engine thermal requests, (iii) change the performance independently from the engine rotational velocity, (iv) reduce the coolant warmup time during cold engine starts, and (v) eliminate the heat-soak issue. Nevertheless, the nonlinear and hysteretic thermomechanical responses of the SMA actuators prevent, to date, the precise positional control and hence compensation techniques involving proportional and derivative control are often employed.

This two-part work addresses the reliability of the SMA thermoresponsive actuators for a heavy-duty automotive cooling axial fan. The selection and characterization of the SMA and polymeric materials presented in this first part were aimed at developing the blade structure design. To assess the morphing capability of the composite structure, experimental tests were carried out in a purpose-built wind tunnel. This experimental characterization was intended to provide an evaluation of the reliability of an SMA-based morphing axial fan blade and a comparison with a traditional viscous fan clutch.

Literature Survey

Research on possible ways to control the automotive cooling fan has been proposed since the 1970s [3]. Cooling fans can be actuated and controlled by (i) a friction-type fan clutch (commonly named on/off clutch) and (ii) an air sensing modulated viscous clutch.

The on/off clutches were most widespread in the past especially in North America for heavy-duty vehicles. On/off clutches operate by design with the fan either at an idle rotational velocity (typically ±200 rpm) or at a fully engaged rotational velocity (±2000 rpm). These types of clutches penalized the power efficiency in providing engine cooling [4].

The modulated viscous clutches have a continuous velocity control that provides the proper cooling air flow rate proportional to engine cooling load by means of a bimetal element [5]. The bimetal element senses the air temperature approaching the drive from the radiator opening and closing a valve spring to either store the fluid (low fan velocity) or allow full flow to the working area, providing maximum fan velocity. The bimetal element expands and contracts in proportion to the variation in temperature. The two basic benefits derived from the utilization of fan clutches are reduced horsepower drainage to the fan and a reduction in the average noise output of the fan.

As reported in Ref. [4], the average power consumption of an on/off friction clutch is higher than that of a modulating fan clutch providing the same average cooling rate. A modulating fan clutch theoretically consumes only 22% of the power of an on/off clutch, providing equivalent average cooling during a duty cycle, which requires on/off fan engagement 20% of the time.

Even if the modulated viscous clutches allow the control of the fan velocities, the proper management of the engine cooling rate and, in particular, of the engine temperature must be realized by linking the coolant engine temperature with the cooling capacity of the fan. The clutches join the engine shaft with the cooling fan which does not follow the engine thermal requests strictly since it is closely connected with the engine rotational velocity, without being affected by the airflow temperature. Also, engine encapsulation increases the retarders that lead to unacceptable time response lag from indirect sensing in new generation vehicles [4].

In fact, in some cases the electric driven fans have replaced the clutch-driven fan and the rotational fan velocity is controlled by some sensors positioned in the cooling circuit [6]. This approach improves the engine thermal management but, on the other hand, by using many sensors and devices makes the control system more complicated.

Driven by the need to maximize overall system performance, engineers and designers have sought to increase the multifunctionality of several design components. As a result, the so-called stimulus-responsive materials have increasingly captured worldwide interest. Among these, the SMAs represent a challenging solution for a wide range of engineering applications [7]. The SMAs are a class of metallic materials with the ability to recover seemingly permanent strains, as a result of a temperature and/or stress induced solid phase transformation. The reversible crystallographic phase transformation of the SMAs has been widely used in solving engineering problems where the actuation purposes have been fulfilled by the SME. When a constraint condition is applied to an SMA material, the phase transformations are associated with a significant reversible deformation capability, which leads to the generation of considerable stresses.

As a result, SMA elements are attractive especially for the development of aerodynamic applications where this actuation solution prevents the introduction of flow-disturbing control elements [8]. The thermal and mechanical properties of SMA allow new design solutions for actuators, structural connectors, vibration dampers, sealers, release or deployment mechanisms, inflatable structures and manipulators [8,9]. In these devices, SMAs in the form of wires or strips are usually embedded in thermoplastic and thermosetting polymer matrices to work as active elements. SMA-based actuators provide high force to weight ratio, long fatigue life, and high corrosion resistance; hence, these materials have been employed in many applications such as active helicopter rotor blades, adaptive airfoils, and deployment of control surfaces and flaps [10–12]. Several studies [13–16] deal with the use of SMAs as linear actuators, to realize reconfigurable airfoils which enable an increase in the efficiency of the wing in flight at several different flow regimes. Recently, Sofla et al. [17] have proposed the design of a shape morphing wing for small aircraft which takes advantage of an antagonistic SMA-actuated flexural structural form that enables the changing of the wing profile by bending and twisting, thus improving the aerodynamic performance. More recently, the Boeing Company has developed an active aerodynamic device, known as variable geometry chevron, able to reduce noise during takeoff and able to increase cruise efficiency [18]. The SMA morphing capability in conjunction with the simplicity and compactness of active deformable structures provide substantial performance benefits. Compared to other types of standard actuation, an SMA control system allows the design of devices with reduced complexity, higher overall reliability, easier serviceability, cheaper implementation, and more compact arrangement in conjunction with improved lightness [7].

The notion of smart advanced blades, which can control themselves and reduce (or eliminate) the need for an active control system, is a highly attractive solution in blade technology. Current systems based on morphing or adaptive blades, beyond aerospace applications, are used in wind turbine applications, where fast actuation without complicated mechanical systems and large energy-to-weight ratios are required. In such cases, it is important to save in weight and complexity in the rotor design and its auxiliary mechanisms while also reducing the costs of energy generation [19,20].

Unfortunately, specific studies on fan performance modification using the SMA devices are scarce or even not available in literature. In addition, the variation of the blade shape based on the strain provided by the SMAs is not widely investigated. The objective of this study is to assess the capabilities of the SMA-based morphing blade, which is inherently deformable and adaptable, to change its shape and consequently the local flow field to enhance overall fan performance. The SMA phase transformation leads to camber variation and trailing edge displacement, which allows the modulation of the blade shape.

This work focuses on the development of an SMA activated blade used in a heavy-duty automotive cooling axial fan. The thermal activation of SMA elements could be used to control the cooling fan performance in order to adapt the coolant fluxes with engine thermal requests. Actual thermal requests and fan performance represent the starting point of the blade design.

This first part focuses on the blade development and discusses the capability of the SMA elements to modify the blade shape. This paper develops according to the following points: (i) definition of the thermal requirement in heavy-duty applications, (ii) selection and characterization of the SMA elements, (iii) selection of the polymeric structure, (iv) characterization of the blade structure (polymeric matrix with the SMA strips) through experimental tests developed in a wind tunnel with an evaluation of the reliability of the SMA blade, and (v) comparison between the SMA activation and the viscous clutches in terms of reaction time and time-lag with respect to thermal input.

Working Conditions

The primary focus of this work is to provide the control of a heavy-duty automotive cooling axial fan. In this application, the rotational velocity of the fan is almost constant, but the engine load changes according to the working condition of the operating machine. For these reasons, the thermal energy that must be removed from the engine changes during operation and the cooling fan must be designed in order to remove the thermal energy at the engine load peak [21]. A typical temperature variation for a heavy-duty engine is reported in Fig. 1 that is related to the temperature measurements reported in Ref. [22] for a heavy-duty diesel engine TDC 6V2015 (6 cylinder, engine displacement of 12 l) during warmup.

The temperature trend reported in Fig. 1 refers to the cooling water temperature and represents only the typical temperature variation that occurs in a typical cooling circuit. It can be noticed that the maximum temperature does not exceed 95 °C and the cooling water reaches a stable temperature at about 420 s from the engine start. The steep ramp and the following sinusoidal temperature variation are due to the action of the thermostat valve that controls the water flow rate through the cooling circuit. For the aim of this study, the temperature gradient that characterizes the engine warmup is related only to the temperature difference between the start and end warmup temperature compared to the warmup time. From the temperature and time data reported in Fig. 1, it can be seen that the temperature gradient, obtained as the angular coefficient of a liner interpolation between the first point and the final point of the engine warmup, is equal to about 9 °C/min.

Blade Structure Design

The morphing blade design was performed with the aim of realizing a functional composite structure which allows the control the working condition parameters of the axial fan, taking advantage of the SME. To accomplish this, the SMA strips were used as actuator elements, embedded in the polymeric blade structure. The intent to use the embedded SMA elements refers to realize a fan in which the blade shape changes continuously as a function of an external stimulus such as the airflow temperature. In order to study the capability of the morphing blade to adapt its shape according to the fan's operation temperature, the SMA thermal activation was achieved by a hot/cold air stream flow. The embedded strips were put in contact with the fluid flow by means of several slots.

SMA Strip Selection. The choice of the SMA compound is one of the most important steps in the fan's design. The best SMA compound must have the closest TTR to those encountered by the fan during the operation. For this reason, the commercially available NiTi SMA (Memry Metalle Company) of nominal composition $Ni_{50.2}Ti_{49.8}$, as a 1.5-mm thick plate was chosen. Starting from the supplied foil, the strips were cut by means of electro-erosion machining in order to minimize microstructural alterations resulting from thermomechanical stresses induced by cutting processes.

As mentioned above, the SMA materials offer advantages in terms of high reversible strains, high damping capacity, wide reversible changes of mechanical and physical properties, and the ability to generate extremely high recovery stresses (upto 800 MPa). Among the different SMA compositions, the near equiatomic NiTi alloys are by far the most widely used shape memory materials for engineering applications. The SME is the property of the material to recover mechanically induced strains (upto 10%) when it is deformed in the low temperature phase (martensite) and subsequently heated to the high temperature phase (austenite). This thermal change forces the return to the austenite and brings the SMA to its original macroscopic shape. In the martensitic phase, SMA can be easily deformed according to the lattice arrangement. In the stress-free condition, the transformation from austenite to martensite occurs during cooling: it begins at the martensitic start temperature M_s and ends at the martensitic finish temperature M_f. Conversely, the reverse transformation, from martensite to austenite, occurs upon heating: this begins at the austenitic start temperature A_s and ends at the austenitic finish temperature A_f. These four temperatures are known as TTRs.

According to the ASTM F2004 standard, differential scanning calorimetry (DSC) tests, by means of a TA Instruments DSC Q2000, were carried out on a small fraction of the strips. A portion of the untreated material was chosen to be characterized in order to obtain useful quantitative information for the shape memory treatments described below. For the DSC measurements, a constant heating/cooling rate of 10 °C/min was set. This thermal gradient is comparable with the actual thermal gradient in the automotive cooling circuits (see Fig. 1) and allows the material characterization in the actual operating condition. A complete thermal cycle (heating/cooling) of the obtained phase transformation is given in Fig. 2. The characteristic TTRs were extrapolated from the DSC plot through the tangential line method (intersections of a baseline and the tangents to each peak) [23]. The experimental values are summarized in Table 1. As mentioned, TTRs are fundamental for the development of the thermomechanical treatment used to memorize the shape, described as follows.

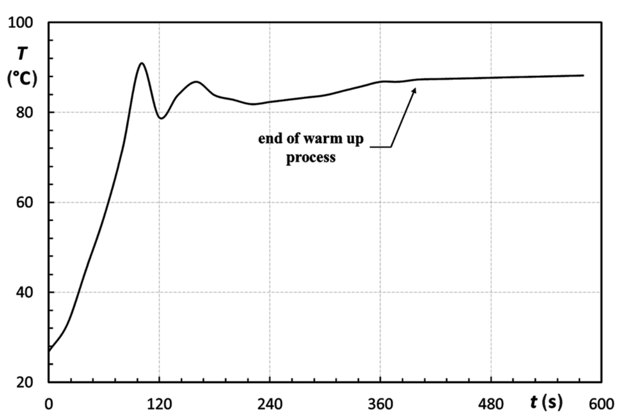

Fig. 1 Temperature trend during the engine warmup [22]

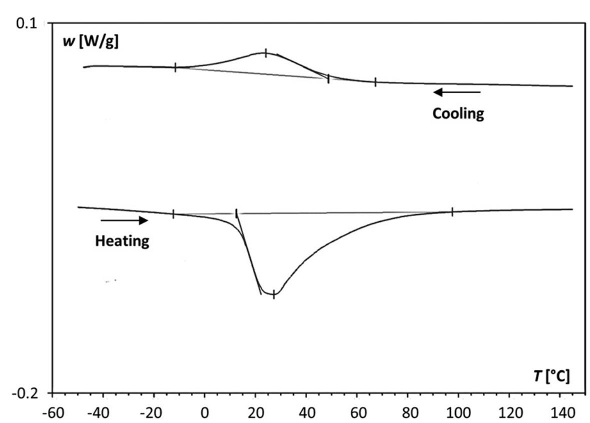

Fig. 2 DSC curves of the untreated NiTi material

Table 1 TTRs of SMA material in the untreated condition

Austenite start temperature (A_s)	10 °C
Austenite finish temperature (A_f)	57 °C
Martensite start temperature (M_s)	48 °C
Martensite finish temperature (M_f)	−4 °C

In Fig. 3, a representative scheme of the treatment is depicted. In order to delete any residual stress of previous deformation history, the samples were first placed in a tube furnace and annealed at 700 °C for 20 min followed by controlled cooling to room temperature. The development of the best thermomechanical treatment for memorizing the defined bent shape, which allows the bending of the blade, was experimentally carried out. Temperature and time parameters were chosen according to the results of a previous study, where it was experimentally found that heating the material at 450 °C for 25 min represents the best shape memory setting, allowing 92% of shape recovery [24]. To memorize the bent shape, the strips were subjected to a double thermomechanical treatment. After the annealing, they were first strained in the martensitic state by immersion in a propylene glycol bath cooled to −15 °C. The strips were strained and wound on a cylindrical jig to reach a circular shape. This setup was then placed into a tube furnace in constrained conditions, in order to avoid the shape recovery on heating. To memorize this first shape, the material was heated at 450 °C for 25 min and subsequently quenched in the propylene glycol bath cooled to −15 °C. After this treatment, the strips were again strained in the martensitic state (performed during the immersion in the propylene glycol bath cooled to −15 °C) applying opposite bending couples acting at the ends, and locked into a specifically designed arc clamp. To memorize this bent shape, they were again thermally treated, at the aforementioned temperature and time conditions. Finally, the heat-treated NiTi strips were strained to a flat shape, applying a uniform bending load, to be embedded in the blade structure.

Polymeric Structure Selection. The blade shape is a typical forward-swept blade used in partially shrouded cooling fans for automotive applications. The sketches of the fan setup and the blade shape are reported in Fig. 4. The polymeric blade design was performed with the aim of being produced by means of injection molding. Since SMA strips induce the necessary bending force on the polymeric blade structure when thermally activated by air stream flow, they were located into purpose-built slots in direct contact with the stream flow. The two slots gather from the blade polymeric structure does not modify the blade surface and does not influence the aerodynamic performance of the airfoils. According to the most widely used polymeric matrices in blade fan production, two polymeric mixtures of Nylon PA 6.6, glass fibers and elastomer, were chosen to be tested: Compound A had a lower amount of glass fiber reinforcement compared to Compound B.

The key issue was to realize a blade capable of withstanding the prescribed loads and also able to change its shape. The structure was designed in order to be sufficiently compliant and flexible to support the large deflections induced by the strips and to allow the shape recovery, but also stiff enough to withstand the aerodynamic loads.

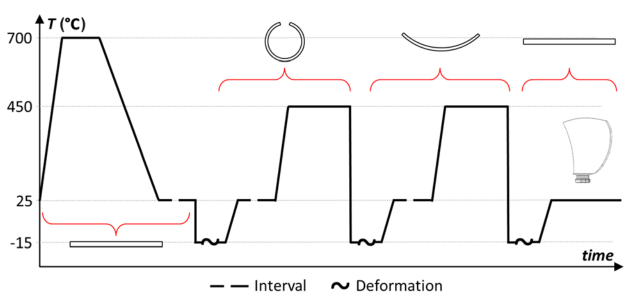

Fig. 3 Representative scheme of the SMA thermomechanical treatment

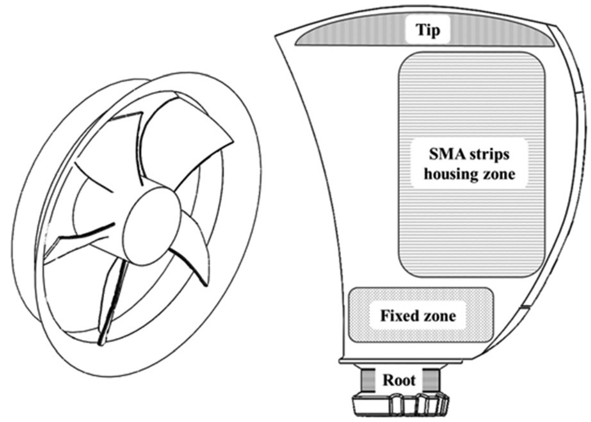

Fig. 4 Fan setup and blade shape sketches

In Fig. 4, the blade sketch, with the essential region, is reported. As can be seen, the embedded SMA strips were located in the range of about 50–85% of the blade span and next to the trailing edge, in order to achieve the desired deflection upon activation. Conversely, the region near the root is depicted as fixed since no actuation elements were placed. The position of the SMA strips realizes a camber curvature variation of the airfoil: blade shape modification allows the variation of the fan performance analyzed by computational fluid dynamics (CFD) numerical simulation, proposed in the second part of this work [25]. AQ4

Experimental Apparatus

In order to test the two selected polymeric blade structures under the SMA loading, specific experimental tests were conducted in a purpose-built wind tunnel, named single blade test facility (SBTF), where it was possible to measure the air temperature and velocity, the surface blade temperature and to detect the blade shape changes. The blade was positioned according to the flow direction that represents the relative flow velocity in the real operating conditions.

SBTF Description. As depicted in Fig. 5, the SBTF was composed of (i) a convergent device, (ii) a polyvinyl chloride pipe with a diameter of 250 mm and length of 3000 mm, (iii) a flow straightener, (iv) a polymethyl methacrylate transparent measurements section with a square section of 250 mm × 250 mm and 1000 mm in length, and (v) exhaust pipe with a diameter of

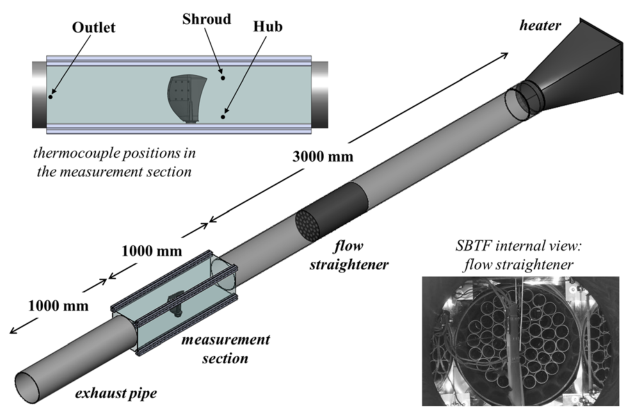

Fig. 5 SBTF functional scheme

250 mm and 1000 mm in length. The wind tunnel was driven by an axial fan with a nominal 1500 m^3/h flow rate.

A 22 kW-electric heater allowed the obtainment of an air flow stream characterized by a highly reproducible timewise thermal gradient, which can reach values of up to about 12 °C/min in heating mode and up to about 6 °C/min in cooling mode. These temperature gradients are consistent with (i) the operating conditions of the fan when used in its normal duty (see Fig. 1) and (ii) the constant heating/cooling rate used for the SMA material characterization (see previous paragraph).

In order to evaluate the thermofluid dynamic conditions, a hot wire anemometer (for cold conditions), a pitot static tube (for hot conditions), and several calibrated thermocouples were installed in the SBTF. A pitot static tube (Velocical Plus, TSI) and hot wire anemometer (Velocical Plus, 964 TSI) were placed at the inlet of the transparent measurements section. The accuracy of the velocity measurements is equal to 3% of the reading. The velocity field along the blade span was continuously measured to verify the uniformity of the air velocity during the test provided by the flow straightener position in the second half section between the heater and the measurement section.

Mineral insulated thermocouples type K were placed in correspondence to the heater, in the neighborhood of the blade (at the shroud and hub positions) and at the outlet section as can be seen in Fig. 5. Several welded tip thermocouples type K were also placed on the blade surface and on the SMA strips to acquire the temperature variation. The control was performed by a National Instrument NI 9213 thermocouple measurement device and a LABVIEW software acquisition. The thermocouples are individually calibrated in a thermostatic bath against a reference temperature sensor and a first-order linear calibration curve is obtained in the range of 288–480 K. The accuracy of these sensors is estimated as equal to ±0.5 K.

Thanks to the transparency of the measurements section, the modification of the blade shape was continuously evaluated by means of digital image analysis techniques. Three digital cameras were aligned in correspondence to the blade tip, suction side, and pressure side, respectively. The temperature trends were synchronized with the video acquisition (1024 × 768) pixels in order to control the overall shape evolution related to the temperature trend. The resolution of the video acquisition allows a spatial resolution up to 0.16 mm that is considered suitable for evaluating the blade shape modification during the activation tests.

Thermal Cycle. The SMA thermal activation and the resulting blade deflection were achieved by (i) a heating ramp and (ii) a cooling ramp, described as follows. Starting from the room temperature, the blade was first heated by a hot air stream flow which caused the activation of the SMA strips and the blade deflection. The blade reached the maximum deflection as the fluid flow reached the maximum temperature. Subsequently, the blade was cooled down to room temperature in order to achieve the martensitic phase transformation.

Figure 6 shows the experimental temperature trends as a function of the time in correspondence to the sections illustrated in the sketch of Fig. 5. As can be seen, it was possible to achieve uniform thermal conditions of the air flow stream on the blade during the execution time, both in the heating ramp (maximum hub-to-shroud temperature difference of about 1.5 °C) and in cooling ramp (maximum hub-to-shroud temperature difference of about 0.4 °C).

Blade Activation

As mentioned above, to achieve the phase transformation from martensite to austenite, the heating ramp has to follow a prescribed temperature gradient and has to reach the designed temperature peak. In Fig. 7, the temperature trends, for the polymeric structure and SMA strips, measured by using the welded tip thermocouples are reported. Given that uniform thermal conditions of

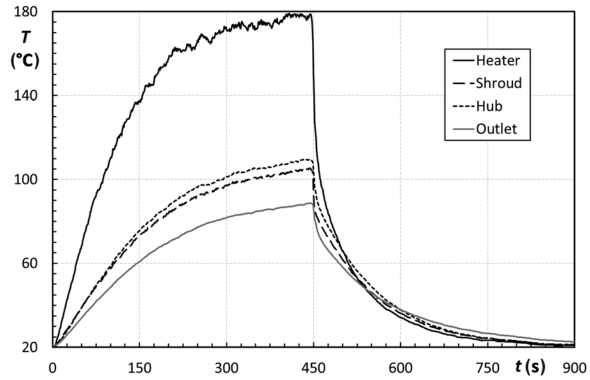

Fig. 6 SBTF thermal performance

the air flow stream and the high-reproducibility of the temperature trend on the blade were achieved by the realized SBTF, the depicted trends are representative for the two considered polymeric matrices. Temperature trends reported in Fig. 7, for polymeric structure and SMA strips, were obtained with Compound A. As can be seen from Fig. 7, the temperature gradient in both the polymeric matrix structure and the SMA strips are quite similar and the blade shows an almost uniform surface temperature pattern. The temperature–time trends measured on the blade surface are comparable with those measured in the SBTF (see Fig. 6) revealing that the temperature gradient realized by the SBTF is suitable for the aim of the present study. The average value of the air flow temperature measured in the hub and shroud position (see Fig. 5) is reported in Fig. 7 by using grey diamonds. During the heating ramp, when the temperature of all the SMA strips reached 80 °C they tended to recover the memorized bent shape and the blade structure was forced to bend. At the peak temperature, the SMA strips induced the maximum blade deflection. To quantitatively evaluate the blade deformation on thermal activation, digital image analyses were performed. The final deformed shape of the blade is the results of the combination of the load provided by the SMA strips and the stiffness (or strength) provided by the polymeric matrix. The blade shape change in terms of mean line deflection, develop on each blade-to-blade plane as a function of the blade span location. As a result, the centrifugal force that works in the actual blade's operation does not influence the blade shape modification. The SMA strips determine the airfoil deflection along the chordwise direction without being affected by the centrifugal force that works along the blade height. An aerodynamic evaluation of the blade deformation is reported in the second part of this work [25]. The preliminary design of this composite structure takes into consideration the activation

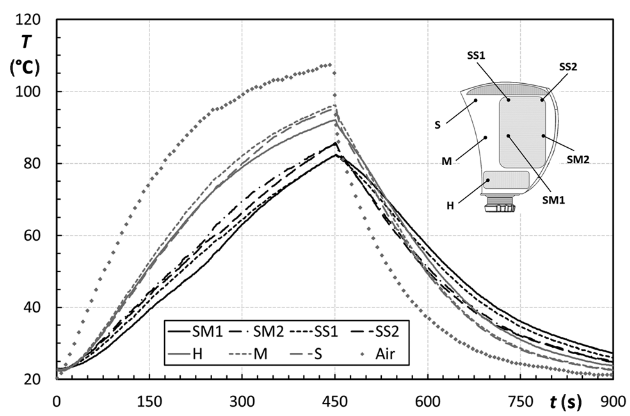

Fig. 7 Temperature trends for Compound A: polymeric structure (H, M, and S) and SMA strips (SM and SS)

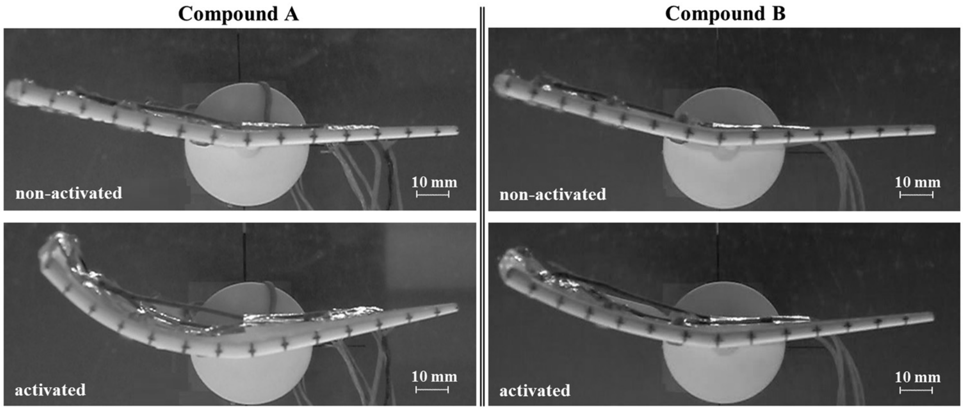

Fig. 8 Digital captures from recorded video at blade tip view

temperature in the stress-free condition (as mentioned in previous paragraph) and only by the wind-tunnel test it is possible to evaluate a posteriori the aerodynamical changes in the blade shape. In Fig. 8, the comparison between the two blade shapes, both for Compound A and Compound B, is reported: (i) initial (nonactivated) condition and (ii) maximum deflection (activated) captured from the blade tip view. From the comparison of the two activated blades, it is evident that Compound A reaches the highest strain, according to its composition. Conversely, the greater amount of glass fiber in Compound B provides more stiffness which cause a smaller deformation compared to Compound A. The deformation in both cases is localized in the trailing edge zone.

Taking into account the behavior of Compound A, when the temperature reaches its peak (activated condition), it can be seen that the greatest deformation is localized at the trailing edge where the deflection of the SMA strips imposes the maximum strain on the polymeric structure. Also, on the first part of the blade chord, the blade shape changes according to the memorized bent shape. This modification determines a variation of incidence angle during the operation, and consequently, a variation of the fan performance.

To study the blade deformation achieved by the shape recovery of SMA strips, a quantitative analysis of the deformations was performed. A CAD software reconstruction of the shape at the nonactivated and activated conditions is proposed in Fig. 9. Thus, the evaluation refers to the airfoil shape at the blade tip. Note that the airfoil deformation was measured as the maximum distance (maximum camber) from the chord length (leading edge to trailing edge line). Compound A (21.4 mm) showed a higher airfoil deformation than Compound B (14.2 mm), equal to about 40%. The higher percentage of glass fiber in Compound B restricts the recovery shape capability of the SMA strips. According to the experimental results, Compound A accomplished the largest deflection induced by activation of the SMA strips and therefore this polymeric mixture was chosen for the realization of the blade structure.

Subsequent to the heating, the cooling ramp to room temperature was achieved by the supplied air provided by the fan. This allowed the transformation from austenite phase to martensite phase and the subsequent return to the initial condition

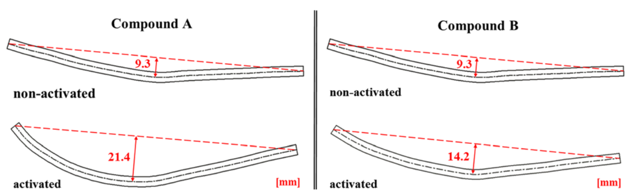

Fig. 9 Blade tip superimpositions for activated and nonactivated conditions

(nonactivated). Since the polymeric structure could be affected by a viscouselastic behavior, some sensitivity tests were conducted by the authors. Different cooling gradient temperatures were studied (up to 12 °C/min) and no viscouselastic effects were noticed in the blade structure. In the real operating conditions, the cooling ramp refers to (i) the unloading condition of the engine and (ii) the thermal gradient that still exist in the engine after its stop. The cooling ramp is usually less steep than the heating ramp and the results obtained in the cooling mode guarantee the blade structure functionality.

Time-Lag Comparison

In a traditional cooling system, the energy optimization could be achieved by controlling the engine temperature and reducing the cooling fan run time by using a fan clutch. The operation of the fan is controlled by means of some sensors placed in the cooling circuit for measuring the air temperature and thus tuning the rotational fan velocity. Nevertheless, the increasingly utilization of a great number of sensor devices and the resulting raised complexity make, in some cases, the control system too bulky, expensive and not sufficiently robust for the intended application. During the actual fan cooling operation, the air temperature changes according to the engine load and/or the effect of the ram air and, at the same time, the fan rotational velocity could be changed due to the engine operation load requirement.

Conversely, in the present study the performance modification during operation is completely obtained by the blade shape modification provided by the SMA elements without sensors and control systems.

To study the possibility of employing SMA strips as actuator elements, a comparison with common viscous clutches behavior is proposed. In Fig. 10, the timewise evolution of air temperature, airfoil camber at the blade tip, and rotational fan velocity are depicted. To highlight the differences between the two actuating solutions, the comparison between the timewise camber variation and the timewise rotational velocity variation is performed with the same timewise temperature variation. The thermal variation trend starts from 0 s and ends at 440 s, and it is inline with the heating ramp reported above (see Fig. 6) and similar to a common engine coolant temperature variation during the warmup condition.

The comparison is related to (i) the evaluation of the time lag that represents the actuator awaiting time after the thermal input (green lines in Fig. 10) and (ii) the evaluation of the time range transient actuator response (time ranges between green lines and red lines). The considered viscous clutch is an on/off viscous fan clutch but similar results can be obtained to considering a modulated viscous fan clutch. As reported by Everett [26], modulated viscous clutch allows the reduction of the power consumption but the time range transient actuators response is even so very limited AQ5

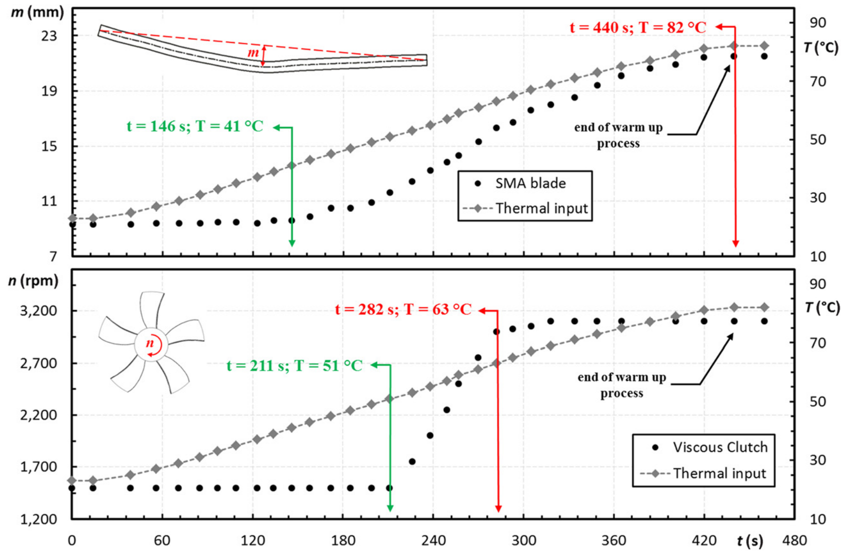

Fig. 10 Timewise evolution of air temperature, airfoil camber at the blade tip and rotational fan velocity

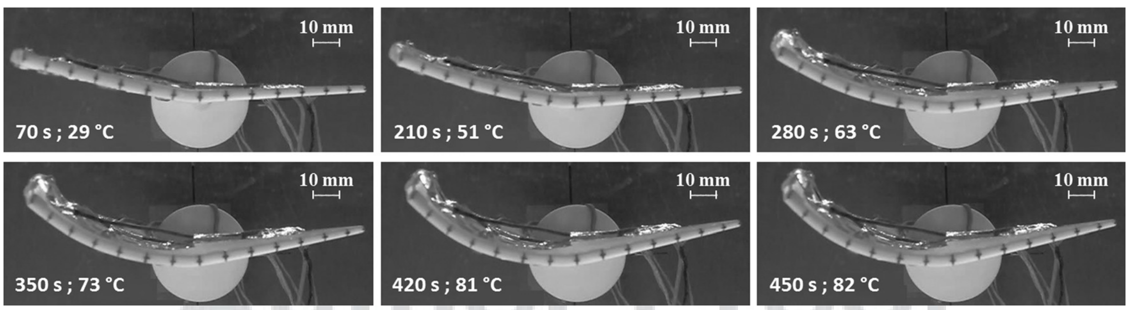

Fig. 11 Blade shape evolution during the heating ramp at the tip view

(with a thermal input range of 60 °C–71 °C (140 °F–160°F) the fan speeds moves from 1000 rpm to 2000 rpm).

As can be seen from Fig. 10, the SMA time lag is shorter than the viscous clutch, 146 s and 211 s, respectively. Then the SMA actuator requires a lower temperature to start the reaction that occurs 10 °C earlier than the viscous clutch. Regarding the time range transient actuator response, it is evident that the viscous clutch solution provided a fast change of the fan rotational velocity, as can be seen from the steep ramp in Fig. 10. This step change velocity variation does not follow the thermal input and the fan rotational velocity reaches the target velocity independently from the thermal input variation after 12 s. The fan rotational velocity reaches a value lower than the rotational velocity of the driver shaft. In this specific case, the rotational velocity of the driver shaft is equal to 3300 rpm compared to the target rotational velocity equal to 3000 rpm.

Conversely, the smooth change camber variation follows the thermal input thanks to thermal controlled SMA strips actuation. The transient SMA actuator response ends at 440 s which corresponds to the thermal input end. This experimental result confirms the capability of SMA materials to cover the lower power actuators in the automotive field. The time range actuator response indicates that the SMA strips provide a lower frequency control that fits well with engine thermal requirement. The SMA strips blade actuator could improve the match between the fan performance and engine cooling thermal request and thus enhance the engine thermal management.

In order to emphasize the progressive blade deflection provided by SMA strips activation on heating, the blade tip views are showed in Fig. 11. Each blade tip capture reports the time instant and the average value of the SMA strip surface temperature. The time steps capture highlights the smooth camber variation according to the temperature increment. Due to this progressive blade deflection, the consequent fluid dynamic phenomena evolve during the heating ramp and, for this reason, in the second part of this work [25], the authors have reported an extensive analysis of the blade shape. The engine coolant temperature control through the use of a fan with the SMA activated blades allows the adjustment as a function of the thermal request. This adjustment results from the selection of (i) the memorized shape of the SMA strips and (ii) the polymeric mixture used in the polymeric matrix.

Conclusions

In this paper, the development of a morphing axial fan blade via SMA strips activation has been proposed. Commercially available NiTi strips were characterized and two polymeric blade structures were tested.

The thermal characterization of the SMA material allows the study of the thermomechanical treatment in order to reach the suitable bent shape. The thermomechanical treatment parameters (temperature, time, and dedicated clamp) have been experimentally tuned to maximize the SME in the NiTi strips. The SMA strips were subsequently embedded in two polymeric structures with different amounts of glass fiber reinforcement to study their different bending ability.

Several experiments for each compound were performed by using a purpose-built wind tunnel and the blade modifications were grasped thanks to digital view acquisition. The blade shape change was achieved by the SMA strips embedded in the blade and thermally activated by hot air stream flow, which reproduced the actual automotive heat exchanger thermal ramps.

The comparison between the blade structures showed the influence of the glass fiber amount on the blade stiffness. The decrease in amount of glass fiber causes an increase in blade deflection during the activation. The blade deflection is localized at the trailing edge, where the SMA strips work against the polymeric compound stiffness.

As a result, the SMA strips embedded in Compound A had a greater influence on blade deflection and this blade structure (SMA strips and Compound A) was chosen to be implemented in a prototype of a heavy-duty automotive cooling axial fan.

The smooth blade shape variation imposed by the SMA strips was compared to the step fan rotational velocity variation provided by a viscous clutch. The results show that the SMA control system can follow the thermal input (and consequently the thermal request of an automotive cooling circuit) and the time-lag is less than in the case of viscous clutch. The thermal-driven SMA strips can reduce the cooling circuit thermal stress as a result of a smooth thermal-driven blade shape variation.

This preliminary analysis highlights the opportunity to generate an innovative passive control system applied to an axial fan. Future developments will concern the choice of the polymeric compound in order to provide an increased SMA strain that leads to more blade deflection.

In the second part of this work experimental tests and numerical analyses, conducted in order to link the blade shape to the fluid dynamic phenomena and the fan performance, are presented.

Acknowledgment

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The authors would like to dedicate this work in memory of Engineer Guido Rosati, whose guidance and encouragement have been of great importance to achieve the present results.

Nomenclature

A = austenite
m = camber
M = martensite
n = rotational velocity
t = time
T = temperature
w = heat flow

Subscripts and Superscripts

f = finish
s = start

Acronyms

H = hub
M = midspan
PMMA = polymethyl methacrylate
PVC = polyvinyl chloride
S = shroud
SBTF = single blade test facility
SM = strip at midspan
SMA = shape memory alloy
SME = shape memory effect
SRM = stimulus-responsive material
SS = strip at shroud
TTR = transformation temperature
VGC = variable geometry chevron

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