Modification of the Amount of Heat Transfer by Shape Morphing of Annular Fins

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Abstract

A reliable and practical way to increase the amount of heat transfer is using fins to extend the heat transfer surface. Geometry and total area of fins are the main parameters which determine the efficiency of fins. Therefore, morphing of fins could be used as a tool to change the amount of heat transfer and functionality of fins at will. A powerful and feasible way to provide the force needed to deform the fins, is using strain-recovering metallic alloys. In this paper, a model of a tube with three attached annular fins, is created and numerical analysis is performed on this model in order to assess the functionality of fins. The numerical simulation includes structural analysis, thermal analysis and modal analysis. By structural analysis, it is confirmed that morphing of fins (which is provided by a certain amount of force) will not result in failure. In order to investigate thermal functionality of fins, thermal analysis is performed on both deformed and non-deformed states of the structure. Also, modal analysis is used to determine the natural frequencies and mode shapes of the structure and their variations relevant to deformation. The results of this paper indicate that the method presented in this paper is fully capable of modifying the amount of heat transfer if necessary.

Keywords: Annular fins, Shape morphing, Heat transfer.

Introduction

In many engineering applications, improvement in heat transfer performance is essential. In general, there are two different approaches in order to enhance the heat transfer coefficient, *passive* and *active*. Passive techniques do not require direct application of external power, whereas, active techniques do (Bergles, 2002). One significant passive method to improve heat transfer performance is surface extension, which could be achieved by using fins. Fins can be of a variety of geometries and can be attached to the inside, outside or both sides of ducts or circular tubes, where the heat transfer coefficient on that fluid side is low. Fins can also be joined to the high heat transfer coefficient fluid side to increase structural strength or to provide mixing of highly-viscous liquids (Shah and Sekulic, 2003).

It may be necessary to vary the magnitude of exchanged heat relevant to changes in operation conditions such as ambient temperature. Shape morphing of fins could result in dramatic changes on the amount of heat transfer, which is possible by utilizing Shape Memory Alloys (SMAs).
SMAs are a group of alloys that undergo temperature-induced phase transformations and can retrieve their former shape (Tadaki et al, 1988). Shape morphing by SMAs has had a broad range of applications since past few decades. For instance, application of SMAs has been a great success in various fields of Minimally Invasive Surgery (MIS), such as endoscopic surgeries where flexible endoscope is used to diagnose and treat diseases (Song, 2010). SMAs have also widely been used in the field of robotic applications. For example, Loh et al. (2006) introduced a new design for a prosthetic hand using SMAs. Tao et al. (2006) designed a robotic fish with a caudal peduncle actuator mechanism that can provide fast response and a strong thrust. Vast majority of applications of shape morphing by SMAs lie in the field of aviation or aerospace engineering. For instance, Kancharala (2008) contributed to finite element based simulation and sensitivity analysis of morphing airfoil with integrated shape memory alloy. Also Prahlad and Chopra (2001) worked on design of a variable twist tiltrotor blades using shape memory alloy actuators.
Regarding to aforementioned contributions to shape morphing by SMAs, it seems that SMAs are fully able to deform fins in order to change the amount of heat transfer. In this paper, applicability of SMAs to deform annular fins around a thin-walled circular tube is investigated. It is assumed that hot water flows inside the tube and air flows from outside to cool the tube. Steady-state thermal analysis is performed on the tube in two different conditions; when SMA wires are not operating and the fins are at their normal shape and when the SMA wires are operating and the fins are deformed.

Modeling and Simulation

The tube and the fins around it, are modeled as it is shown in Figure 1. The inner radius of the tube is 29 mm, wall thickness is 3 mm and the outer radius of the fins are 52 mm. Also, it is considered that the tube and the fins are made of Aluminum 7178-T6. Table 1 presents some characteristics of Aluminum 7178-T6 which are used for simulation (Kaufman, 1999).

Table 1. Some properties of 7178-T6 Aluminum

Thermal Conductivity (W/m.K)	Tensile yield strength (MPa)	Young's modulus (GPa)	Poisson's ratio
125	538	70.7	0.33

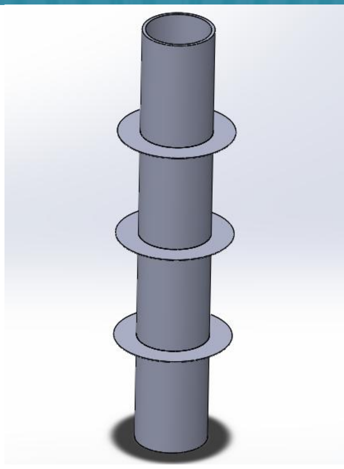

Figure 1. SolidWorks model of the tube and fins.

It is assumed that four sets of SMA wires are attached to the upper edge of the annular fins on one side and to the tube wall on the other side. Each set of SMA wires includes two SMA wires that is able to apply a maximum pulling force of 17.4N. Characteristics of the SMA wires used in this paper are listed in Table 2 [2].

Table 2. Technical characteristics of Shape Memory Alloy Actuators

Characteristic	Value	Unit
Diameter Size	0.01	*in.*
Resistance	0.47	*ohms/in*
Heating Pull Force	1.96	*pounds*
Cooling Pull Force	0.78	*pounds*
Approximate Current For 1 Second Contraction	1050	*mA*
Cooling Time LT Wire	5.4	*seconds*
Cooling Time HT Wire	0.3	*seconds*

The specifications of the software and hardware are listed in Table 3.

Table 3. Specifications of the simulation equipment

PC	Hardware	Intel ® Core ™ i7-2600, 3.4 GHz CPU, 16GB RAM
	Software	Windows 8.1 Pro 64-bit, SolidWorks 2014, ANSYS 16

Numerical Analysis

In this paper, numerical analysis consists of three steps which are described in the sections below. Meshing method in these sections is structured and also independency of number of elements is verified in each case.

Structural Analysis

Structural analysis is performed on this model in order to identify the maximum stress and maximum deformation in the structure while all sets of SMA wires are operating, which is the critical situation for the structure. As it is mentioned before, each set of SMA wires is applying a 17.4N pulling force when operating. Also, it is assumed that the tube is fixed from its top and bottom sides.

Modal Analysis

Operation of the SMA wires causes deformations in the structure, therefore possible significant variations in natural frequencies of the structure may occur. In order to investigate these changes, natural frequencies of the structure are identified by means of modal analysis while the structure is in its normal shape and compared to the natural frequencies of the structure when the SMA wires are operating. Mode shapes (of mode numbers one to six) at their respective natural frequencies are also identified.

Thermal Analysis

Thermal analysis is used to evaluate the functionality and efficiency of the fins in both deformed and non-deformed states. Heat transfer occurs by convection of air from outside of the tube, convection of hot water inside the tube and radiation. Film coefficient of convection of air is set to be 100 W/m^2.K with 23 degrees of Celsius and of water 1000 W/m^2.K with 75 degrees of Celsius. Emissivity of the tube and fins is 0.8 and ambient temperature is set on 295K.

Results and Discussion

The Structural analysis shows that the maximum stress is 354.6 MPa. The tips of the annular fins have the maximum deformation which is 2.954 mm. Figure 2 shows the deformed state of the fins caused by pulling force of SMA wires.

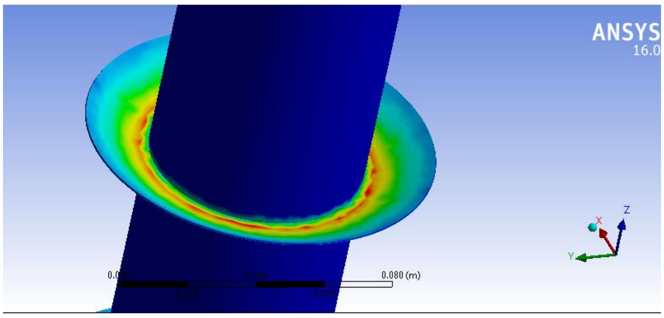

Figure 2. Deformation of fins while being pulled by SMA wires

The results from structural analysis show that the structure does not fail and the safety factor (regarding to yield strength in Table 1) is approximately 1.52.
Thermal analysis indicates that deformations of the fins result in a significant temperature change in them. When the fins are not deformed, the temperature on the fins vary from 68.91 to 35.83 degrees of Celsius. But, if the fins are deformed, temperature range on the fins is from 69.63 to 45.22 degrees of Celsius. Obviously, deformations in fins significantly increase the amount of temperature in the fins. Figure 3 shows the temperature profile on the fins in non-deformed state. Note that the temperature profile of deformed state is similar to Figure 3, but the temperature range is different.

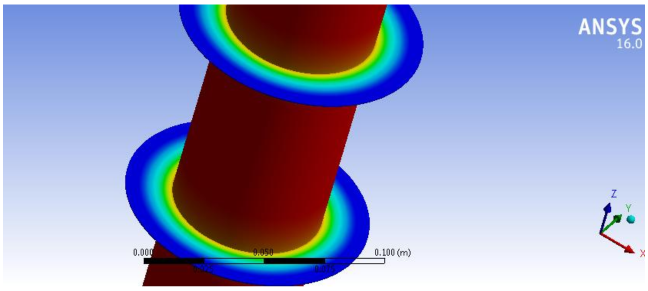

Figure 3. Temperature profile in non-deformed state (68.91 to 35.83 ^{o}C)

Table 4 presents the results of modal analysis.

Table 4. Modal analysis results

Mode No.	Natural frequencies at non-deformed state (Hz)	Natural frequencies at deformed state (Hz)
1	1779.2	1788.1
2	2142.6	2174.3
3	2588.9	2635.7
4	2735.4	2796.4
5	2870.2	2947.8
6	2918.5	3040.4

Modal analysis shows that natural frequencies of the structure increase when the fins are deformed. This could be used as a powerful means to avoid resonance. For example, consider a situation in which the wind speed on the outer surface of the tube is increased. This causes an increase in the film coefficient and therefore increases heat transfer. Also, increase in wind speed may cause the structure to resonate. In this case, if the SMA wires operate and deform the fins, natural frequencies of the structure rise and resonance would be averted, while preventing the tube from overcooling. Figure 4 presents first mode shape of the structure at deformed state. Mode shapes of both deformed and non-deformed states are alike, whereas, their respective natural frequencies are different.

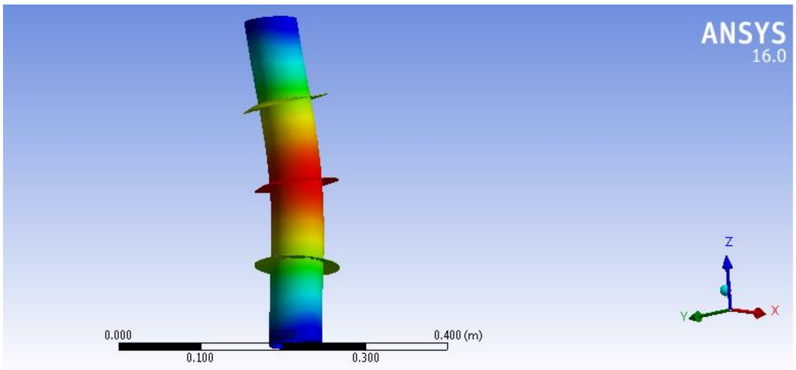

Figure 4. First mode shape of the structure in deformed state.

Conclusion

This paper investigates the applicability of shape memory alloy actuators to deform annular fins around a pipe in order to change the amount of heat transfer if necessary. A model of a pipe and three annular fins around it had been created. Numerical analysis had been performed on this model in order to identify some desired parameters such as maximum stress and deformation in the fins, temperature profile on the fins and natural frequencies of the structure in both deformed and non-deformed states. The results show that this method has the ability to increase the temperature of the fins and therefore, change the heat flux. This method could be used where it is necessary to prevent a pipe from cooling based on different conditions.

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