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ENHANCED SHAPE MEMORY ALLOY ACTUATORS

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Abstract Shape memory alloys (SMA) provide an opportunity to develop ultra-light mechanical actuators with far superior economic and environmental performance to traditional actuators. Despite their many favorable attributes, SMA actuators are subject to a series of inherent limitations, in particular, a relatively slow expansion rate. The authors have proposed a novel method that enables a significant enhancement of the heat transfer rate in a cost effective and robust manner. An advanced predictive model has been developed to enable the optimisation of a virtual prototype before engaging in experimental validation and commercialisation of this novel technology.

1. Introduction

Shape memory alloys (SMA) provide an opportunity to achieve significant environmental benefit over traditional actuators. SMA actuators are subject to a series of constraints to implementation, in particular, a relatively slow expansion rate, which typically occurs by free convective heat transfer to the ambient environment (Van Humbeeck 1999; Huang 2002). Alternate cooling methods have been proposed, including forced convection with a highly conductive media (Rediniotis and Lagoudas, 2002). This method allows very high actuation frequencies, however the requisite hardware introduces a significant cost and weight penalty.

The authors have proposed a novel method that enables an increased heat transfer rate in a cost effective and robust manner (Leary, Schiavone and Subic 2009). The benefits of the proposed method have been proven experimentally by the authors for a particular specimen configuration. In preparation for commercialisation of this technology, an advanced predictive model is required to enable the design refinement and optimisation of a virtual prototype before engaging in experimental validation.

This work reports on a Finite Difference Equation (FDE) implementation to enable greater predictive certainty in the specification of lagging parameters. An assessment of FDE attributes according to the design requirements identified the preferred FDE implementation. The adopted implementation was developed to enable rapid simulation of SMA parameters prior to physical testing. These out-
comes provide a template for the implementation of SMA actuators that will enable significant mass reduction and increased design flexibility in electromechanical automotive systems.

2. The design problem

Shape memory alloys undergo a crystallographic transformation in the solid state. The transformation effect results in a significant volumetric change which can be utilised in the design of ultra-light mechanical actuators.

Typically, response time is a critical constraint to the implementation of SMA actuators in automotive systems. SMA actuation is achieved by resistive heating which is acceptably fast. However, SMA cooling is achieved by heat transfer mechanisms that are inherently slower than resistive heating (Van Humbeeck 1999), and response time is dominated by the associated heat transfer rate (Leary and Schiavone 2008).

A novel method has been developed by the authors to enable an increased rate of convective heat transfer by the addition of a lagging material, enabling optimisation of the heat transfer rate in a cost effective and robust manner (Leary, Schiavone and Subic 2009). The method utilizes cylindrical heat transfer media, i.e. lagging, to manipulate the heat transfer rate (Figure 1).

![Fig. 1](image)

Increasing lagging thickness results in an increased resistance to conductive heat transfer concurrently with a reduced resistance to convective heat transfer. The total resistance to heat transfer displays a local minima, known as the critical radius, $r_{cr}$ (Holman 1990). Cylindrical lagging allows heat transfer resistance to be either increased or decreased depending on whether the lagging is greater-than or less-than the associated critical radius. Selection of the lagging media and dimensions allows control of the critical radius to optimise the cooling rate within the design constraints.
3. Finite Difference Equations

The Second Law of Thermodynamics identifies that a temperature gradient will result in a transfer of heat. The associated local temperature is predicted by the one-dimensional heat diffusion equation (Equation 1).

$$\frac{\partial T(x,t)}{\partial t} = \alpha \frac{d^2 T(x,t)}{dx^2}$$  \hspace{1cm} (1)

A Finite Difference Equation (FDE) provides an approximate solution to differential equations such as the one-dimensional heat diffusion equation, and was applied in this work to enable robust and rapid estimation of the influence of lagging parameters on SMA response. Numerous FDE embodiments are available, each with associated truncation error and stability.

3.1 Truncation error

The intent of the FDE approximation is to replicate the associated differential equation. However, the discretization of the problem results in a difference between these solutions, known as the truncation error. Truncation error is dependant on the associated FDE method, and can be reduced by increasing mesh size at the expense of computational efficiency.

3.2 Stability

The FDE method originates from a Taylor series expansion, and consequently there is a possibility for instability in results. Stability is a function of the FDE embodiment and can be evaluated by completing a Von Neumann Stability Analysis (Richtmyer and Morton 1957).

Of the proposed FDE methods the following have been found to be particularly effective in solving the heat transfer problem:

1. Forward difference equation (Explicit)
2. Backward difference equation (Implicit)
3. Central difference equation (Crank and Nicholson)
3.3 Forward difference equation (Explicit)

The forward difference equation uses known parameters at an initial time step to calculate values at the next time step. For example, the explicit method considers the temperature of three connected nodes, $T_{m-1}$, $T_m$, $T_{m+1}$, at time $p$, and uses their known values to calculate the temperature of the central node, $T_m$, at time $p+1$ (Equation 2). This method is computationally straightforward as each equation has only one unknown, and it can be solved without simultaneous methods. However, the forward difference equation is unstable if the associated Fourier number ($Fo = \alpha \Delta t / \Delta x^2$) is not maintained between 0 and ½. The associated truncation error is $O[\Delta t, \Delta x^2]$.

$$T_{n+1}^{p+1} = FoT_{n-1}^p + (1 - 2Fo)T_n^p + FoT_{n+1}^p$$  \hspace{1cm} (2)

3.4 Backward difference equation (Implicit)

The implicit method of the finite difference equation requires that the initial state of the system is fully understood. From this data an expression for the temperature of nodes in the following time step is created (Equation 3). The expression must be solved simultaneously by the inversion matrix method and requires significantly higher computational resources than the explicit method. However, the associated truncation error is reduced and is independent of mesh selection: $O[\Delta t, \Delta x^2]$.

$$-FoT_{n-1}^{p+1} + (1 + 2Fo)T_n^{p+1} - FoT_{n+1}^{p+1} = T_n^p$$  \hspace{1cm} (3)

3.5 Central difference equation (Crank-Nicholson)

The Crank-Nicolson equation combines the explicit and implicit methods, resulting in an average of the two, yielding a smaller truncation error due to a decreased sensitivity to changes within $x$. The Crank-Nicolson method is an implicit scheme in which a series of simultaneous equations are solved for each time step (Equation 4). The Crank-Nicolson method considers six nodes whereas only four nodes were considered in the simple explicit and implicit methods. The Crank-Nicolson method provides high accuracy results and is unconditionally stable, allowing for maximum flexibility in the choice of discretization. (Crank and Nicol- son 1947). The truncation error is second order accurate with both space and time, $O[\Delta t^2, \Delta x^2]$, illustrating the minimal effect the discretization of the equation has on the FDE solution.
\[-F_{oT_{n-1}^{p+1}} + (2 + 2F_{o})T_{n}^{p+1} - F_{o}T_{n+1}^{p+1} = F_{o}T_{n-1}^{p} + (2 - 2F_{o})T_{n}^{p} + F_{o}T_{n+1}^{p}\] (4)

4. Simulation

The Crank-Nicholson method was applied to solve the one-dimensional heat equation for a simple polar geometry consisting of a 0.254mm diameter SMA wire surrounded by an annulus of lagging material (Table 1). To simulate a typical actuation scenario, two-stages of boundary conditions were applied to simulate wire contraction (heating) and expansion (cooling) respectively.

**Table 1** Material properties applied (Leary *et al.* 2009).

<table>
<thead>
<tr>
<th>Material</th>
<th>$T_i$ [°C]</th>
<th>$\rho$ [g/cm$^3$]</th>
<th>$k$ [W/mK]</th>
<th>$h$ [W/m$^2$]</th>
<th>$D_{\text{min}}$ (mm)</th>
<th>$D_{\text{max}}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMA</td>
<td>100</td>
<td>6.45</td>
<td>21.9</td>
<td>–</td>
<td>0.254</td>
<td>0.254</td>
</tr>
<tr>
<td>Lagging</td>
<td>21</td>
<td>2.1</td>
<td>0.59</td>
<td>–</td>
<td>0.254</td>
<td>50</td>
</tr>
<tr>
<td>Shell</td>
<td>21</td>
<td>0.910</td>
<td>0.12</td>
<td>–</td>
<td>0.254</td>
<td>50</td>
</tr>
<tr>
<td>Air</td>
<td>21</td>
<td>–</td>
<td>–</td>
<td>6</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

SMA actuation was simulated by applying an initial temperature boundary condition, $T_i$, associated with the SMA actuation temperature and convection to the environment to a system that was initially at ambient temperature (Table 1). The SMA was assumed to reach its actuation temperature instantaneously. The lagging material temperature increases monotonically, until the heat flow rate stabilises and the system reaches steady-state (Figure 2). Once steady-state conditions were achieved, the SMA wire temperature boundary condition was removed to simulate deactivation. In this stage the SMA wire temperature is determined by cooling to the ambient environment (Figure 3). The exothermic heat transfer of phase change was ignored (Van Humbeeck 1999).
Fig. 2  Representative contraction (heating) phase FDE solution.

Fig. 3  Representative expansion (cooling) phase FDE solution.
5. Outcomes

The proposed FDE analysis enables rapid simulation of the performance of a range of SMA lagging parameters, providing an opportunity to predict the performance of feasible design parameters before building physical prototypes.

The proposed FDE analysis enables the evaluation of a specific configuration. To assess a larger design space requires an automated Design of Experiments (DoE) approach. Taguchi methods may be applied to generate a partial factorial DoE approach to enable automated analysis of a large number of feasible design configurations. To ensure robust outcomes of the automated analysis it is necessary to ensure that the steady-state condition is reached during the heating phase. This can be achieved by ensuring that the root-mean-square (RMS) temperature difference between last two iterations of the FDE is sufficiently small. The system performance is then characterised by the total time required for the SMA to reach the deactivation temperature (Table 1).

The contraction and expansion phases of the SMA simulation were linked for a range of feasible lagging parameters and the deactivation time recorded. Initial outcomes indicate that:

1. Deactivation time is minimized if paste and shield conductivity are maximized. The design constraints restrict the material selections available for the shell, and the associated conductivity is likely to be significantly lower than the paste (Table 1). This restriction may be mitigated by minimizing shell thickness.

2. The predicted cooling time is compatible with experimental observations and critical radius theory and indicates a reduction of cooling time with increasing...
radius until a local minima is reached; additional increase in radius results in an increasing cooling time.

References


