ISSN 1392 - 1207. MECHANIKA. 2007. Nr.6(68)

Transient characterisation and analysis of shape memory alloy wire bundles for the actuation of finger joints in prosthesis design

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1. Introduction

Shape Memory Alloys (SMA's) are part of a new generation of lightweight, strong and relatively cheap actuators which have the potential to revolutionize the field of biomedical engineering. At present, DC motors are the most widely applied actuators employed in the design of prosthetic devices. These mechanical systems place restrictions on the number of degrees of freedom possible.

SMA wires have the property of shortening (by up to 5%) [1] when heated and thus have the ability to apply forces. This is known as the Shape Memory Effect (SME) [2]. This phenomenon occurs when the wire is heated above a certain temperature, where its crystalline structure changes from a relatively soft martensitic state to a relatively hard austenitic state [3]. Heating can be achieved by applying a voltage drop across the wire and thus causing a current to flow, resulting in a resistive heating effect known as joule heating. One of the major issues with SMA behaviour is the substantial hysteresis which occurs during any cyclic heating/cooling stage. Work has been undertaken, with some success, by various groups [4, 5] attempting to compensate for the deviations caused by the slower cooling stage when used as dynamic actuators.

Recently SMA's have been applied in robotics actuation as they exhibit muscle-like properties [6-9]. SMA's, owing to their small size and excellent force to weight ratios, provide an opportunity to facilitate additional degrees of freedom to prosthetic designs. This work focuses on characterizing SMA's for use as actuators of individual phalanges in hand prosthesis. Characterisation of the human hand was carried out initially in order to establish the functionality requirements for comparative purposes. Knowledge of the range of motions of the fingers, as well as the forces required for everyday tasks, is viewed as critical if a prosthetic hand, whose performance matches as closely as is possible to that of a working limb, is to be developed.

A typical 150 μm diameter SMA wire, while having a high force to weight ratio, still only produces a maximum force of 3.24 N [1]. Research indicated that forces substantially higher than this would be required for actuation of the fingers. As a result of this, bundling of the wires was investigated. This relatively new technique has been previously investigated by various groups. Moseley et al [10] demonstrated that large forces can be achieved without sacrificing actuator bandwidth. DeLaurentis et al [11] experimented with wire bundles of varying diameter with a view to establishing the optimal arrangement for attaining maximum forces. Characterisation of the transient and steady-state contraction and relaxation of Nitinol wires has been carried out by others [12]. Our work compares the transient and steady-state characteristics of SMA wire bundles with the force and displacement characteristics of the human hand. This comparison will provide the foundation for the development of a prosthetic hand with the required capabilities.

2. SMA behaviour

SMA's consist of a group of metallic materials that demonstrate the ability to return to some previously defined shape or size when subjected to an appropriate thermal procedure [10]. At room temperature, the material is in a martensitic state and is easily deformed. Upon heating, the crystal structure changes to a more compact Body Centre Cubic (BCC) form as the phase changes from martensite to austenite [6]. The wire must be exposed to a 'relaxation' force if the contraction/extension cycle is to occur.

Most SMA's have a hysteresis loop width of 27.8°C to 67.8°C. At low temperatures, the SMA is 100% martensite. As the temperature is increased, A_1, the Austenite start temperature is reached (Fig. 1). This behaviour is known as thermoelastic martensite transformation [6]. As the temperature rises, the percentage of Austenite in the SMA increases until the austenite finish temperature, A_2, is reached. As the temperature rises, the percentage of Austenite in the SMA increases until the austenite finish temperature, A_2, is reached. At this point the SMA is 100% austenite. During cooling, the material begins to revert to the martensite start temperature, M_1, and continues to do so until the material is 100% martensite at M_2. As a result of the substantial hysteresis (due to energy dissipation) that occurs on heating/cooling, accurate control of SMA's can be difficult.

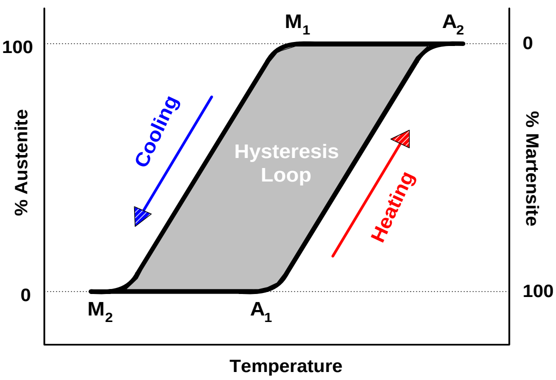

Fig. 1 Hysteresis loops in SMA's

3. Hand characterisation

This stage of the work involved obtaining information on the dynamic performance of the human hand. This sets suitable target forces and angular displacements/velocities for an artificial limb design. The forces required for typical gripping actions were obtained from a number of sources. A broad range of data in this area was available [13-16]. This information is summarised in Table. These forces (max. at distal phalanx) were developed by gripping a cylindrical bar of 31.7 mm diameter, which was previously determined to be the optimum diameter that allows an average test subject to produce their maximum force [13]. The max and min forces values as well as the percentage contribution of each phalanx are shown in Table.

Table

Hand force data

	Index	Middle	Ring	Little	
	Force, N	Force, N	Force, N	Force, N	%*
Distal	56.6	61	44.3	27.5	41.6
Intermediate	32.2	34.8	25.2	15.6	32.2
Proximal	25.8	27.8	20.2	12.5	25.8
Meta	21.4	23	16.7	10.4	15.7

***** % contribution to finger forces

The maximum angular movement of each phalanx of the finger, as well as its dynamic behaviour, was investigated. Previous work has shown that the maximum angle of movement of each joint in the hand doesn't vary much from finger to finger [16]. The angular movement of the distal interphalangeal (DIP) joints stay, on average, within 0 to 80^o. The proximal interphalangeal (PIP) joints stay, on average, within 0 to 100^o and the metacarpophalangeal (MP) joints stay, on average, within -20 to 90^o. A testing apparatus was developed so that the dynamics of the angular movement of the fingers during basic gripping actions could be found.

The test rig was designed to take point displacement recordings through the use of a rotary potentiometer coupled to the individual phalanges. The potentiometer outputs are fed to NI LabView 8 software via a NI 6001 USB DAQ card. The test subjects (n =10) were required to grip a cylindrical object of 31.7 mm diameter at various rates and average trends were produced. An average time constant for this essentially first-order response was found to be approximately 0.405 s. The angular velocity of each phalanx is relatively steady at 1.37 rads/sec with the acceleration at initiation of movement of 9.08 rad/s^2. Basic experimental methods were employed to approximate the mass and volume of an average adult human hand. It was established that the adult human hand had a mass of 450-600 g and an average volume of 396 ml.

4. SMA wire bundle characterisation

A test rig was designed and built so that transient characterisation of SMA wire bundle actuators could be facilitated. The rig design is similar to that developed by previous groups [12] but the focus of this work is substantially different. The rig developed (Fig. 2) is housed in a sturdy aluminium structure to facilitate the incorporation of all instrumentation/equipment and to allow for safe movement/transportation. The unit comprises two circular Acytel discs, in which 15 × 2 mm diameter holes are drilled on a PCD of 14 mm, through which the wire bundles are secured. The wires are connected mechanically in parallel using a screw arrangement; however, they are connected electrically in series. All loading/measurement equipment is arranged concentrically in order to avoid any moments during loading. A LVDT is mounted at the top of the rig to facilitate strain measurements. The force on the wires and that generated during straining is measured using a load cell which is connected to the wires through a mechanical force transmission element.

Fig. 2 SMA characterisation test-bed

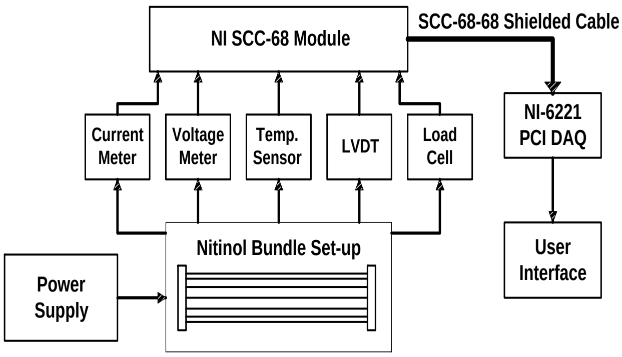

Fig. 3 System layout

The relaxation force on the wires is catered for through a combination of the weight of the circuit holder and force transmitter plus the force produced by the micrometer-controlled tension spring. A thermocouple is used during experimentation to measure the temperature in the immediate vicinity of the wires. All sensors are connected through a NI-SCC-68 module via a NI-6221 DAQ card to a Dell 1.8 GHz PC. Outputs were captured using LabView 8 and NI MAX software. The data was transported to Microsoft Excel for analysis/interpretation. Fig. 3 shows a simple layout diagram of the instrumentation arrangement.

5. Experimental testing

Bundles, consisting of fifteen, twelve, and nine 150 μm SMA wires (Wire Length 90 mm), were tested, as well as bundles made up of six and three 300 μm wires.

Manufacturers of Nitinol [1] specify that recommended maximum currents of 400 mA and 1750 mA should be used to actuate 150 µm wires and 300 µm respectively. Testing was carried out within a range of 220 mA to 400 mA for the 150 µm wire configurations, and within a range of 962.5 mA to 1750 mA for the 300 µm wires. Fig. 4 illustrates the correlation between current supplied and steady-state force generated for a range of 150 µm wire bundle configurations. It was observed that using currents of less than 50% of the recommended maximum led to unsuitable performance of the bundle actuator for this application.

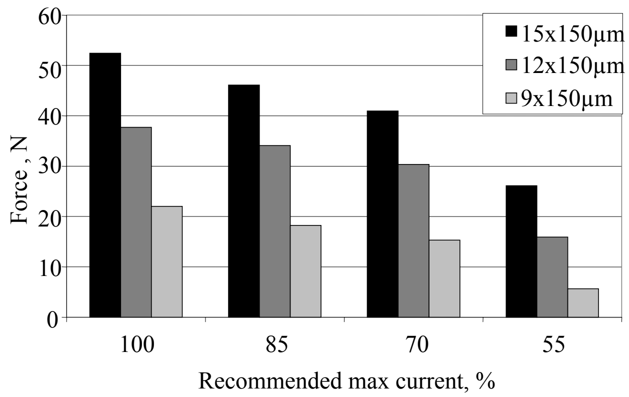

Fig. 4 Steady state force comparison

Exposing the wires to 100% of the recommended relaxation force led to optimal steady-state and dynamic performance. The variation in time constant for the dynamic response of the wire bundles over a range of energising currents is shown in Fig. 5.

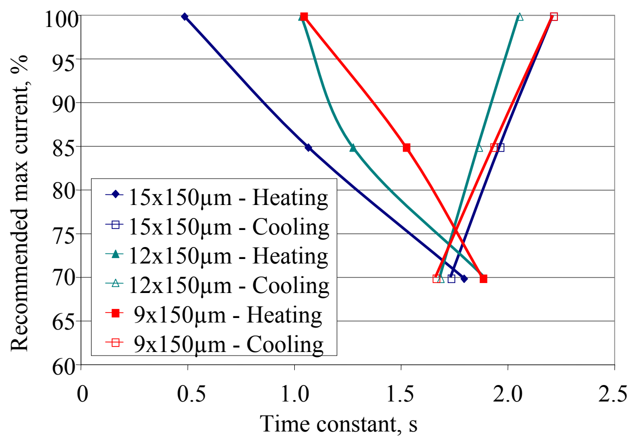

Fig. 5 Time constant variation

The extent of the hysteresis was observed to be highly dependent on the magnitude of the energising current. In general, the width of the hysteresis loop was found to decrease with decreasing current as illustrated in Fig. 6. A mathematical relationship (Eq. 1) was established between the energising current i and the extent of hysteresis H over a workable range of currents

$$H = Ai + B \tag{1}$$

where A and B are constants. This linear expression approximates the relationship between the energising current and the hysteresis for the range of energising currents considered. Analysis of this nature will be utilised in future work to establish the optimal current which results in tolerable hysteresis for this application.

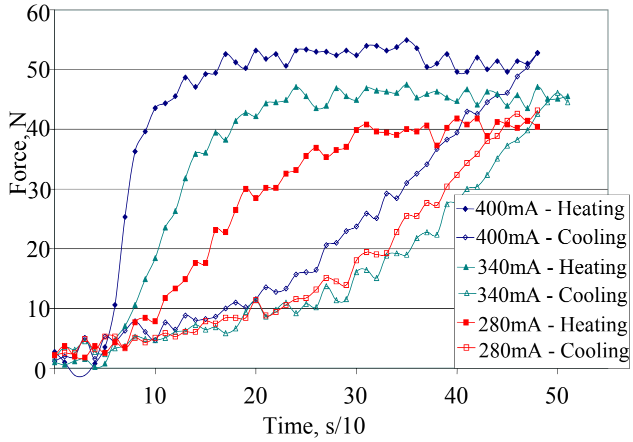

Fig. 6 Hysteresis loop variations

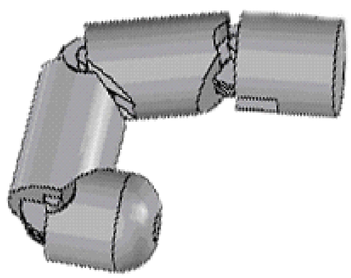

Fig. 7 Initial finger prototype design

It is anticipated that some sacrifice will have to made in regard to reaction time (transient performance) so that a controller module can be developed which can give comparable actuator performance during the cyclical heating and cooling of the wire bundle. Strain testing confirmed that the dynamic response of the contraction/extension of the wire matched the transient force behaviour for each set-up. The bundles exhibited a steady-state contraction up to 5%, or 4.5 mm, when subjected to the recommended maximum current.

6. Discussion of results

The steady-state force produced by the 15×150 µm bundle, when supplied with maximum current, is 52 N. This value is 84% of the maximum force requirement of the distal phalanx of the middle finger. This would suggest that an actuator bundle of this sizing would be a suitable performer for the range of forces required for basic gripping actions.

The dynamic behaviour required by the fingers during a gripping action can be compared directly with the transient response characteristics of the SMA bundle actuators. This is facilitated by examination of the heating time constant τ_h, and the cooling time constant τ_c, for the bundles as indicated in Fig. 6. The τ values for each bundle are dependent on the bundle size and the magnitude of the energising current. If we are to successfully mimic human finger/hand response the time constant of the selected bundle must be similar to that of the finger. Fig. 6 shows the substantial difference between heating and cooling times for the bundles, and in particular the extent of the difference for the larger bundles. The results indicate that the performance of the 15 wire bundle is relatively comparable with the finger behaviour at high energising currents during the heating phase. However, the cooling time is substantially higher. The extent of this variation in response can be reduced through the use of an appropriate adaptive control strategy. The heating and cooling responses are very similar at the lower currents but the steady-state performance is not adequate. The extent of the variation in shape of response between heating and cooling is shown in Fig. 6 where it is observed that hysteresis becomes a major concern at higher currents (where the steady-state performance is good). It is anticipated that the most suitable prosthetic design will involve some compromise between steady-state and transient performance. Forced cooling and suitable control strategies can be used to develop the most effective prosthetic finger performance.

This work has also shown that the performance of the 150 μm wires is the most suitable for the prosthetic application. Testing with the 300 μm wires indicate sluggish response times, particularly during the cooling phase. Bundling of the wires, and the corresponding increase in surface area available for cooling, minimises the steady-state performance issues of employing smaller diameter wires. The results of the strain testing have been used to drive preliminary designs of the most suitable mechanical prosthetic finger. Having established the strain range of the actuator, in conjunction with the knowledge of the rotational angle requirements of each phalangeal joint, allows various mechanical designs to be critiqued.

7. Conclusions and further work

Work to date has indicated that SMA actuator bundles show very strong potential in achieving the dynamic and transient requirements in prosthetic fingers. Bundle sizes have been identified that can facilitate the range of tasks considered. The electrical power requirements for adequate performance, through comparison with human finger movement, have been established. A power supply will be sourced which is suitable for integration with an upper limb prosthetic device with due consideration to the size and weight restrictions imposed (comfort of the end-user paramount). Preliminary work on the effect of varying the current to the wires during actuation will prove useful when attempting to develop an effective control strategy for the actuators. Future work will involve intensive analysis of the cooling of the SMA bundles with a view to optimising the cooling response. It is anticipated that an adaptive control strategy, in conjunction with appropriate heat sinking, will be required to attempt to bring the cooling rate to an appropriate level (comparable with heating rate). Some alteration to the test rig design will be carried out to reduce friction and to increase the controllability of the actuator. Design and manufacture of a mechanical framework for the effective characterisation of these bundles, which is at the preliminary stage (Fig. 7), will be developed substantially as an immediate goal.

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K.T. O'Toole, M.M. McGrath, D.W. Hatchett

PEREINAMŲJŲ PROCESŲ IR CHARAKTERISTIKŲ TYRIMAS PROTEZŲ KONSTRUKCIJŲ, PAGAMINTŲ IŠ FORMOS ATMINTĮ TURINČIŲ LAIDŲ, SUGRIEBIMO GRANDYSE

R e z i u m ė

Šiuolaikinių rankų plaštakų protezų konstrukcijose naudojami palyginti gremėzdiški, sunkūs ir triukšmingi nuolatinės srovės varikliai. Bandoma sukurti efektyvesnius viršutinių galūnių protezus. Identifikavimą, charakteristikų nustatymą bei eksperimentinį funkcionalumo tyrimą būtina atlikti esant palankesniam jėgos ir masės santykiui. Pagrindinis darbo tikslas – atlikti išsamų lydinių su formos atmintimi (FA) panaudojimo rankų pirštų protezų pavaroms gaminti tyrimą. Atlikta išsami literatūros analizė, siekiant nustatyti maksimalias kiekvieno žmogaus rankos piršto sugriebimo jėgas esant skirtingai apkrovai. Remiantis analizės duomenimis, atlikti eksperimentai rankos reakcijos laikui sugriebimo ir paleidimo metu, nustatyti. Gauti rezultatai ir matmenys bus panaudoti galūnių protezams kurti.

Sukurtas eksperimentinis stendas įvairių konfigūracijų konstrukcijoms iš skirtingo skersmens FA laidų pereinamojo ir stacionaraus būvio charakteristikoms tirti. Atliktas įvairių konstrukcijų skirtingų konfigūracijų iš 150 µm ir 300 µm nitinolo vielos tyrimas. Buvo naudojama sistema konstrukciją apibūdinantiems duomenims, ypatingai deformacinėms ir jėginėms įvairių konstrukcijų charakteristikoms, rinkti ir kaupti. Atliktas tiesioginis pavaros galimybių ir reikalavimų, keliamų veikiančios galūnės pagrindiniams sugriebimo veiksmams palyginimas. Šis darbas padės kurti tobulesnes protezų konstrukcijas.

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TRANSIENT CHARACTERISATION AND ANALYSIS OF SHAPE MEMORY ALLOY WIRE BUNDLES FOR THE ACTUATION OF FINGER JOINTS IN PROSTHESIS DESIGN

S u m m a r y

Most current lower arm/hand prosthesis designs incorporate relatively bulky, heavy dc motors that produce substantial noise when performing actuation which renders them uncomfortable for the end-user. The engineering challenge is to produce more effective powered upper limb prosthetic solutions. Identification, characterisation and testing of actuation methods with better force to weight ratios are essential pre-requisites for this. The main aim of this work is to carry out a comprehensive study to establish conclusively the feasibility of employing Shape Memory Alloys (SMA's) in the actuation of prosthetic finger designs. A comprehensive review of existing literature has been undertaken in order to establish the maximum grip forces at each phalanx of the human hand under different loading conditions. An experiment was developed in conjunction with this review to estimate the time response of the hand during a gripping/releasing action. These results, in combination with physical dimensions, will be used to drive the design of a prosthetic limb.

A test rig has been developed which can facilitate complete transient and steady-state characterisation of a range of SMA wire diameters and bundle configurations. A number of different configurations were tested, each configuration having a different combination of 150 µm and 300 µm diameter nitinol wires. A data acquisition system was used to capture and retain data pertaining to the full characterisation of the bundles and in particular the strain and force capabilities of the various arrangements. A direct comparison is made between the actuator capabilities and the requirements of a working limb for basic gripping actions. This work will contribute to the development of an improved powered prosthetic solution.

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ИССЛЕДОВАНИЕ ПЕРЕХОДНЫХ ПРОЦЕССОВ И ХАРАКТЕРИСТИК В ПРИВОДЕ СОЧЛЕНЕНИЯ ПРИ СХВАТЕ ДЛЯ КОНСТРУКЦИЙ ПРОТЕЗОВ ИЗ ПРОВОЛОКИ С ЗАПОМИНАНИЕМ ФОРМЫ

Р е з ю м е

В современных разработках по протезированию рук/кистей используются относительно громоздкие, тяжелые двигатели постоянного тока, которым свойственно издавать значительный шум при работе, что неудобно пользователю. Ведутся попытки разработать более эффективно действующие протезы верхних конечностей. Идентификация, характеристики и эксперименты по проверке функционирования при более удачных соотношениях силы/веса служит обязательным условием для этого. Основная цель этой работы – провести подробное исследование по использованию сплавов с эффектом запоминания формы (ЭЗФ) в разработках приводов протезов пальцев. Проведен обширный анализ публикаций, с целью получить максимальные силы схватывания в каждом пальце руки человека при разных условиях нагрузки. Учитывая этот анализ, проведен эксперимент для оценки времени срабатывания руки при схватывании/отпускании. Полученные результаты и размеры будут использованы при разработке протезов конечностей.

Разработана экспериментальная установка для получения характеристик переходного/стационарного состояний ряда конструкций из разных диаметров проволоки ЭЗФ. Проведены испытания конфигураций конструкций с разным сочетанием нитиноловой проволоки диметром 150 мкм и 300 мкм. Использована система сбора и хранения данных, характеризующих конструкции, особенно деформационные и силовые характеристики разных конструкций. Проведено сравнение возможностей привода и требований к функционирующей конечности при захвате. Представленная работа послужит для разработки протезов с более совершенным управлением.

Received September 04, 2007