MATHEMATICAL MODELLING AND SIMULATION OF THE HUMAN ARM FOR CONTROL PURPOSE

(PEMODELAN MATEMATIK DAN SIMULASI LENGAN MANUSIA UNTUK TUJUAN KAWALAN)

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2009

DEDICATIONS

To all *Intelligent Active Force Control Research Group* (IAFCRG) members – a **big thank you** for all your contributions and participation……

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ABSTRACT

The project focuses on the modelling and control of a two-link planar mechanical manipulator that emulates a human arm. The arm is subjected to a vibratory excitation at a specific location on the arm while performing a trajectory tracking tasks in two dimensional space, taking into account the presence of ‘muscle’ elements that are mathematically modelled. A closed-loop control system is applied using an active force control (AFC) strategy to accommodate the disturbances based on a predefined set of loading and operating conditions to observe the system responses. Results of the study imply the effectiveness of the proposed method in compensating the vibration effect to produce robust and accurate tracking performance of the system. The results may serve as a useful tool in aiding the design and development of a tooling device for use in a mechatronic robot arm or even human arm (smart glove) where precise and/or robust performance is a critical factor and of considerable importance. The project is in fact complementing the on-going research in the Faculty of Mechanical Engineering (FME), UTM that is geared towards developing a robust force control system. In addition to that, the research shall also serve as a basis for potential investigation into the field of biomedical related to the application of a *robust* control technique to effectively control human arm movement particularly when it is subjected to undesirable forcing. The fact that a human arm (to a certain extent) resembles a two-link mechanical linkage serves to provide an analogy leading to the following main and important hypothesis: the control of the human arm’s movement can be effectively carried out using a number of control methods that make use of sensory information just like the mechanical arm counterpart. The results of the study clearly indicate that the modelled arm with ‘muscle’ elements can be simulated to demonstrate the effectiveness and robustness of the control techniques to suppress or reject various disturbances including vibration applied to the system taking into account a number of predefined input trajectories.

ABSTRAK

Projek tertumpu kepada pemodelan dan kawalan suatu lengan mekanikal dua-penghubung yang menyerupai lengan manusia. Lengan tersebut ditindak oleh suatu ujaan getaran pada satu lokasi di lengan ketika ia melakukan tugas penjejakan trajektori dalam dua dimensi dengan mengambil kira kehadiran unsur 'otot' yang telah dimodel menggunakan kaedah matematik. Suatu sistem kawalan gelung tertutup menggunakan strategi daya kawalan aktif (AFC) dipakai untuk memampas gangguan berdasarkan keadaan operasi dan bebanan yang telah ditentukan bagi meneliti sambutan sistem. Hasil keputusan kajian menunjukkan keberkesanan kaedah yang dicadangkan dalam memampas kesan getaran sekaligus menghasilkan prestasi penjejakan sistem yang lasak dan jitu. Keputusan juga boleh digunakan ke arah mereka bentuk serta membangunkan suatu perkakas atau alat bantu untuk lengan robot mekatronik ataupun lengan manusia sendiri (sarung tangan pintar) yang memerlukan prestasi jitu dan/atau lasak sebagai faktor kritikal dan terpenting. Projek yang dijalankan sebenarnya boleh dihubungkaitkan dengan satu projek yang sedang berjalan di Fakulti Kejuruteraan Mekanikal (FME), UTM melibatkan pembangunan satu sistem kawalan daya lasak. Selain dari itu, penyelidikan ini juga boleh dijadikan suatu asas untuk menjalankan kerja penyelidikan dalam bidang bio-perubatan yang melibatkan aplikasi teknik kawalan lasak untuk mengawal lengan manusia dengan berkesan terutama sekali apabila ia di bawah tindakan daya yang tidak diingini. Memandangkan lengan manusia (melihatkan strukturnya) adalah seperti lengan mekanikal dua-penghubung; ia boleh membawa kepada suatu hipotesis penting, iaitu kawalan gerakan lengan manusia boleh dilakukan melalui beberapa kaedah kawalan yang menggunakan maklumat deria seperti juga dengan lengan mekanikal. Hasil kajian juga dengan dengan jelas memaparkan lengan yang telah dimodel dengan memasukkan unsur 'otot' boleh disimulasikan untuk mempamerkan keberkesanan teknik kawalan lasak yang dicadangkan bagi tujuan pemampasan pelbagai jenis daya ganggunan termasuk getaran yang bertindak terhadap sistem dengan mengambil kira pelbagai trajektori masukan yang telah ditentukan.

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ABSTRACT

MATHEMATICAL MODELLING AND SIMULATION OF THE HUMAN ARM FOR CONTROL PURPOSE

(Keywords: Human arm, mechanical manipulator, vibration, active force control)

The project focuses on the modelling and control of a two-link planar mechanical manipulator that emulates a human arm. The simplicity of the control algorithm and its ease of computation are particularly highlighted in the study. The arm is subjected to a vibratory excitation at a specific location on the arm while performing a trajectory tracking tasks in two dimensional space, taking into account the presence of ‘muscle’ elements that are mathematically modelled. A closed-loop control system is applied using an active force control (AFC) strategy to accommodate the disturbances based on a predefined set of loading and operating conditions to observe the system responses. Results of the study imply the effectiveness of the proposed method in compensating the vibration effect to produce robust and accurate tracking performance of the system. The results may serve as a useful tool in aiding the design and development of a tooling device for use in a mechatronic robot armor even human arm (smart glove) where precise and/or robust performance is a critical factor and of considerable importance.

The project is in fact complementing the on-going research in the Faculty of Mechanical Engineering (FME), UTM that is geared towards developing a robust force control system. In addition to that, the research shall also serve as a basis for potential investigation into the field of biomedical related to the application of a *robust* control technique to effectively control human arm movement particularly when it is subjected to undesirable forcing. The fact that a human arm (to a certain extent) resembles a two-link mechanical linkage serves to provide an analogy leading to the following main and important hypothesis: the control of the human arm’s movement can be effectively carried out using a number of control methods that make use of sensory information just like the mechanical arm counterpart.

The results of the study clearly indicate that the modelled arm with ‘muscle’ elements can be simulated to demonstrate the effectiveness and robustness of the control techniques to suppress or reject various disturbances including vibration applied to the system taking into account a number of predefined input trajectories.

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

Vibration control of manipulators has received considerable attention in the literature. The control techniques developed in the literature can be grouped into two main categories, namely, the passive and active control techniques. Generally, passive control techniques have limited effectiveness for this particular problem and they tend to be bulky. On the other hand, an active controller senses the response, generates and imposes the required corrective forces using actuator that injects the necessary energy into the system. Performance of most of the active vibration control techniques for robots with flexible members, rely on a proper dynamic model. This need may cause difficulties since there are unavoidable simplifications in models. In addition, dynamics of a robot could change significantly by an operation such as picking up a payload or changing relative orientation of linkages. Therefore, it is very important to use a vibration control technique whose performance is relatively independent from the system parameters. Thus, modelling and measurement inaccuracies may lead to unstable control resulting in exaggeration rather than attenuation of the oscillation amplitudes. Another advantage of active controllers are that they are significantly more versatile and compact than the passive counterparts. Active vibration control of robotic structures has been an active research area over the past 10 years or so. The proposed study aims to investigate the effect of modelled muscle flexibility with vibratory excitation on a two-link human-like arm incorporating a robust control technique designed to perform a trajectory tracking task. The result obtain shall be compared to a resolved motion acceleration control (RAC) with proportional-derivative (PD) controller taking into account exactly the same loading and operating conditions.

1.2 Objective and Scope of Research

The specific objectives of research are:

- To model the dynamics of the human arm and compare it with the mechanical counterpart.
- To investigate the performance of the arm by means of incorporating a number of feedback control strategies through a simulation study.

The scope of the study is as follows:

- Consider a two-link planar arm as the mechanical equivalence to human arm
- Modelling of the arm and muscle elements
- Consider PID and AFC control methods
- Consider various disturbance models including vibration excitation and input trajectories
- Simulation using MATLAB, Simulink and Control System Toolbox.

CHAPTER 2

MODELLING AND CONTROL OF A HUMAN-LIKE ARM INCORPORATING MUSCLE MODELS

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Proc. IMechE Part C: Journal of Mechanical Engineering Science, Vol. 223, pp. 1569-1577

Modelling and control of a human-like arm incorporating muscle models

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The manuscript was received on 24 July 2008 and was accepted after revision for publication on 5 January 2009.

DOI: 10.1243/09544062JMES1289

Abstract: This article focuses on the modelling and control of a two-link planar mechanical manipulator that emulates a human arm. The simplicity of the control algorithm and its ease of computation are particularly highlighted in this study. The arm is subjected to a vibratory excitation at a specific location on the arm while performing trajectory tracking tasks in two-dimensional space, taking into account the presence of 'muscle' elements that are mathematically modelled. A closed-loop control system is applied using an active force control strategy to accommodate the disturbances based on a predefined set of loading and operating conditions to observe the system responses. Results of the study imply the effectiveness of the proposed method in compensating the vibration effect to produce robust and accurate tracking performance of the system. The results may serve as a useful tool in aiding the design and development of a tooling device for use in a mechatronic robot arm or even human arm (smart glove) where precise and/or robust performance is a critical factor and of considerable importance.

Keywords: active force control, muscle model, two-link arm, robust, vibration control

1 INTRODUCTION

Vibration control of manipulators has received considerable attention in the literature. The control techniques developed in the literature can be grouped into two main categories, namely, the passive and active control techniques [**1**]. Generally, passive control techniques have limited effectiveness for this particular problem and they tend to be bulky. The passive control method is typically an open-loop scheme that relies on fixed valued parameters of some of the related physical quantities in the system without having the extra energy introduced into the system during its operation. On the other hand, an active controller senses the response, then generates and imposes the required corrective forces using an actuator that injects the necessary energy into the system. Performance of most of the active vibration control techniques for robots with flexible members relies on a proper dynamic model. This need may cause difficulties since there are unavoidable simplifications in models. In addition, the dynamics of a robot could change significantly by an operation such as picking up a payload or changing relative orientation of linkages. Therefore, it is very important to use a vibration control technique whose performance is relatively independent of the system parameters. Thus, modelling and measurement inaccuracies may lead to unstable control resulting in exaggeration rather than attenuation of the oscillation amplitudes. Another advantage of active controllers is that they are significantly more versatile and compact than the passive counterparts. Active vibration control of robotic structures has been an active research area over the past 10 years or so. The proposed research deals with the modelling and control of a two-link planar robotic arm or manipulator. Engineering principles are applied to this biomechanical system to better understand the dynamics of the human arm. It is evident that a human arm can routinely attain a complex motions by coordinating many degrees-of-freedom skilfully and effortlessly [**2**]. Computational studies have made progress to tackle the problem, particularly in arm motion control. A mathematical model

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is necessary to facilitate the understanding of the dynamics characteristics of the coupled links. A robust and stable performance of a robot arm is essential as it deals with the capability of the arm to compensate for the disturbance effects, uncertainties, and parametric and non-parametric changes, which are prevalent in the system, particularly when the arm is executing tasks involving the interaction of the robot's end effector with the environment.

In applications in which the flexibility of the robot becomes a problem, research shows that movements of the manipulator can create and dampen unwanted vibration in the flexible structure. This result leads to two major areas of study; first, how to command the robot to perform a task without exciting vibrations in the flexible members and, second, how to dampen the unwanted vibrations that exist in the system [**3**]. One area of research involves determining trajectories that eliminate or minimize induced vibration. Such schemes are not useful for controlling the vibration once it occurs. An inertial damping scheme using a manipulator to dampen vibration is an attractive compromise between controlling system complexity and system performance [**4**]. The poor end effector positional accuracy of flexible robotic manipulators has limited their applications to tasks that are error tolerant. The positional inaccuracies stem from both tracking errors and structural deflections of the robot. Therefore, the controller main objective is to produce good tracking characteristics of the robot while actively damping out the unwanted vibrations of the links. To achieve this goal, many researchers have developed control schemes that have led to a significant reduction in the vibrations of the arm by finding a compromise between the positional accuracy of the end effector and the high-speed operation of the robot [**5**].

Many other robot control methods have been proposed, such as proportional-integral-derivative (PID) control [**6**], resolved acceleration control (RAC) [**7**], adaptive control [**8, 9**], hybrid force–position control [**10**, **11**], computed-torque control [**12**], intelligent control [**13, 14**], and active force control (AFC) [**15–20**]. It is a well-known fact that the conventional PID control is the most widely and practically used scheme in industrial robots due to its good stability, characteristics, simple controller structure, and reliability [**6**]. It provides a medium-to-high performance when it comes to robot's operation at relatively low speed with little or no disturbance effects. However, the performance suffers severe setbacks at the onset of adverse operating conditions. A number of research works have been conducted to seriously address the issue and determine ways to counter the weaknesses [**21, 22**], but more often than not the control algorithms involved are highly mathematical and complex – thereby limiting their use to mostly numerical application.

The proposed study aims to investigate the effect of modelled muscle flexibility with vibratory excitation on a two-link human-like arm incorporating a robust control technique designed to perform a trajectory tracking task. It is, in effect, an extension to the works done in reference [**17**]. The result obtained shall be compared to a resolved motion acceleration control with proportional-derivative (PD) controller taking into account exactly the same loading and operating conditions.

This article is structured as follows: section 2 describes the dynamics of the two-link arm based on Lagrangian formulation. This is followed by a description of the proposed control methods employed in the study, i.e. RAC (section 3) and AFC (section 4). The modelling of the muscles and vibratory disturbance is subsequently explained in section 5 and the complete integration of all the models is presented through the simulation study described in section 6. A number of operating and other loading conditions are explicitly highlighted in this section. Results of the study are discussed in section 7 and, finally, the conclusion and directions for future works are summarized in section 8.

2 DYNAMICS OF THE MECHANICAL ARM

The dynamics of the manipulator is not completely consistent with that of a human arm as depicted in Fig. 1(a). By modelling the coupled links as a conservative system, friction is neglected, which is inherent in realistic applications. In addition, the computational model is unable to impose the geometric constraints characteristic of the human joints. The applicability of Lagrange's equation of motion in

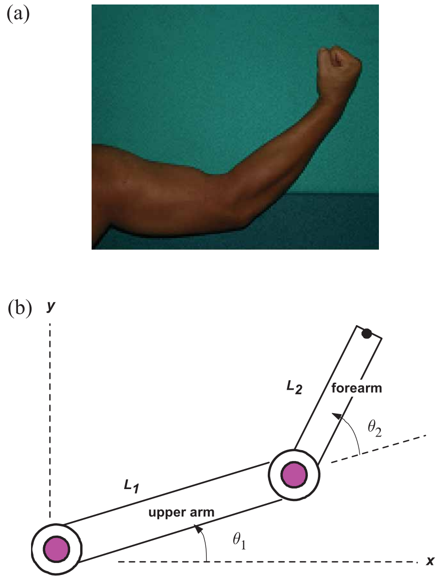

Fig. 1 (a) A typical human arm and (b) a mechanical two-link arm

robotics is demonstrated by modelling the two-link planar robotic arm as shown in Fig. 1(b). Note that the mechanical arm in this context is conveniently modelled as the main rigid structure (bone) of the human arm as similarly suggested by Yamaguchi [**23**].

In Fig. 1(b), subscripts 1 and 2 refer to the parameters of the first link (upper arm) and second link (forearm), respectively, L is the length of the arm, and θ is the angular (joint) position of the arm. Lagrange's formulation is used to derive the equation of motion for the non-linear dynamic system. The general dynamic equation for a series rotating manipulator can be described as follows [**24**]

$$\boldsymbol{\tau} = \mathbf{H}(\theta)\ddot{\theta} + \boldsymbol{h}(\theta, \dot{\theta}) + \boldsymbol{G}(\theta) + \boldsymbol{\tau}_{\mathrm{d}} \tag{1}$$

where $\boldsymbol{\tau}$ is the actuated torque vector, $\mathbf{H}$ is the $N \times N$ inertia matrix of the actuator (plus drive) and the manipulator, $\boldsymbol{h}$ is the Coriolis and centripetal torque vector, $\boldsymbol{G}$ is the gravitational torque vector, and $\boldsymbol{\tau}_{\mathrm{d}}$ is the external disturbance torque vector.

For the two-link arm considered in the study, the relevant equations can be derived as follows

$$\tau_1 = H_{11}\ddot{\theta}_1 + H_{12}\ddot{\theta}_2 - h\dot{\theta}_2^2 - 2h\dot{\theta}_1\dot{\theta}_2 + \tau_{\mathrm{d}1} \tag{2}$$

$$\tau_2 = H_{22}\ddot{\theta}_2 + H_{21}\ddot{\theta}_1 + h\dot{\theta}_1^2 + \tau_{\mathrm{d}2} \tag{3}$$

where

$$H_{11} = m_2 L_{\mathrm{c}1}^2 + J_1 + m_2(L_{\mathrm{c}1}^2 + L_{\mathrm{c}2}^2 + 2L_1 L_{\mathrm{c}2}\cos\theta_2) + J_2 \tag{4}$$

$$H_{12} = H_{21} = m_2 L_1 L_{\mathrm{c}2}\cos\theta_2 + m_2 L_{\mathrm{c}2}^2 + J_2 \tag{5}$$

$$H_{22} = m_2 L_{\mathrm{c}2}^2 + J_2 \tag{6}$$

$$h = m_2 L_1 L_{\mathrm{c}2}\sin\theta_2 \tag{7}$$

$$L_{\mathrm{c}1} = L_1/2 \tag{8}$$

$$L_{\mathrm{c}2} = L_2/2 \tag{9}$$

where m is the mass of the link and J is the mass moment of inertia of the link.

Note that the external disturbance torque vector $\boldsymbol{\tau}_{\mathrm{d}}$ in the study can be referred to the muscle models with vibratory excitation (tremor) assumed to act at the end of the forearm or wrist. Also, the gravitational terms (vector $\boldsymbol{G}$) were ignored because the arm is assumed to move horizontally.

3 RESOLVED ACCELERATION CONTROL

RAC was first proposed by Luh *et al.* [**7**]. As an acceleration control method, RAC takes into account the kinematics of the robot for the generation of the actuating commands. The acceleration, velocity, and position errors are required by the RAC scheme for the generation of the control signals as shown in Fig. 2. The equation for the computation of the acceleration command $\ddot{q}_{\mathrm{c}}$ incorporating a PD element that is based on generalized coordinate q is as follows

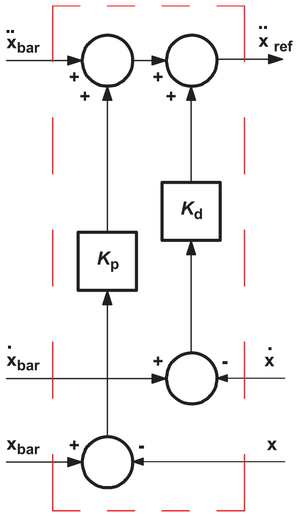

Fig. 2 Typical RAC configuration

$$\ddot{q}_{\mathrm{c}} = \ddot{q}_{\mathrm{r}} + K_{\mathrm{d}}(\dot{q}_{\mathrm{r}} - \dot{q}) + K_{\mathrm{p}}(q_{\mathrm{r}} - q) \tag{10}$$

where $\ddot{q}_{\mathrm{r}}$ is the reference acceleration, $\dot{q}_{\mathrm{r}}$ and $\dot{q}$ are the reference and current velocities, respectively, q_{r} and q are the reference and current positions, respectively, and K_{d} and K_{p} are the derivative and proportional constants, respectively.

Considering the Cartesian coordinates, the above RAC expression can be formulated as follows

$$\ddot{\boldsymbol{x}}_{\mathrm{ref}} = \ddot{\boldsymbol{x}}_{\mathrm{bar}} + K_{\mathrm{p}}(\boldsymbol{x}_{\mathrm{bar}} - \boldsymbol{x}) + K_{\mathrm{d}}(\dot{\boldsymbol{x}}_{\mathrm{bar}} - \dot{\boldsymbol{x}}) \tag{11}$$

where $\ddot{\boldsymbol{x}}_{\mathrm{ref}}$ is the reference acceleration in Cartesian space, $\ddot{\boldsymbol{x}}_{\mathrm{bar}}$ is the input command acceleration vector in Cartesian space, $\dot{\boldsymbol{x}}_{\mathrm{bar}}$ is the input command velocity vector in Cartesian space, $\boldsymbol{x}_{\mathrm{bar}}$ is the input command position vector in Cartesian space, and $\boldsymbol{x}$ is the actual position vector in Cartesian space.

Note that, for convenience, the expression in equation (11) is referred to as a RAC–PD control scheme or simply a PD control scheme.

The Cartesian inputs were later transformed into the joint coordinates by means of suitable kinematic transformations. Thus, the reference acceleration in Cartesian space $\ddot{\boldsymbol{x}}_{\mathrm{ref}}$ should be converted to the joint space equivalent $\ddot{\theta}_{\mathrm{ref}}$ for the appropriate control command signal to the actuator via a suitable transfer function as highlighted in the following section.

4 ACTIVE FORCE CONTROL

AFC is a force control strategy originated by Hewit and Burdess towards the early 1980s [**16**]. The effectiveness of the extended AFC scheme has been demonstrated in works by Mailah and fellow researchers [**16–20**, **25**].

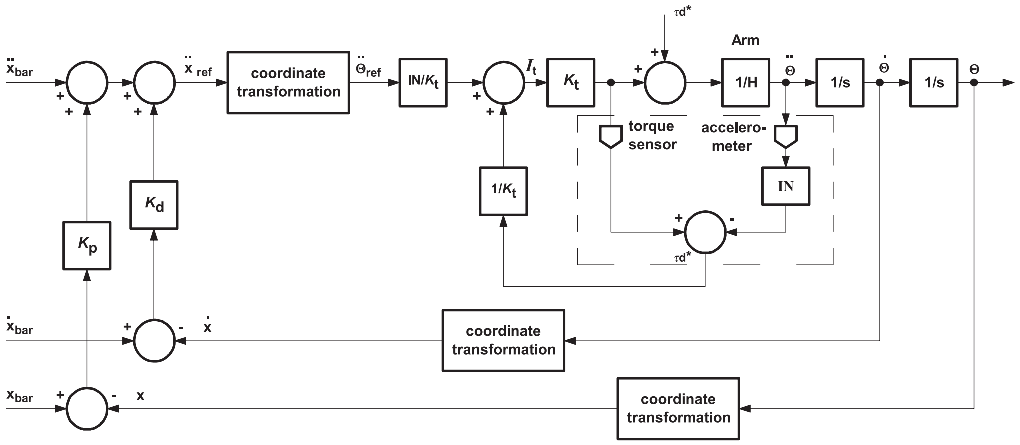

Fig. 3 RAC–PD with AFC scheme for the control of a robot arm

It has been proven that the AFC scheme is very robust in compensating the disturbances introduced into systems compared with other control strategies, provided a suitable estimated inertia matrix is available. In addition to that, the AFC-based algorithms are found to be relatively simple, computationally less intensive, and readily implemented in real-time applications [**16**, **17**]. A schematic of the AFC scheme with RAC–PD element applied to a robot arm is shown in Fig. 3.

The control torque generated by the actuator is typically given as [**16**]

$$\tau = K_t I_t \tag{12}$$

where K_t is the actuator constant and I_t is the motor current. In order to cancel out the actual disturbances τ_d, the estimated disturbance torque τ_d^* has to be computed and is given as follows

$$\tau_d^* = \tau - \mathbf{IN}\ddot{\theta} \tag{13}$$

where **IN** is the estimated inertia matrix, τ_d^* is the estimated disturbance torque, $\ddot{\theta}$ is the measured acceleration signal, and τ is the measured applied control torque.

From equation (13), it should be highlighted that if both the acceleration signal and applied control torque were accurately measured and that the estimated inertia matrix appropriately acquired, it will result in the triggering of the disturbance compensation action in the AFC loop. In other words, the actual disturbance torque is considered totally rejected by the system without having any prior knowledge on the actual disturbance itself. As shown in Fig. 3, the estimated parameter τ_d^* is fed back into the AFC loop to cancel out τ_d. The estimated inertia matrix used in the study was obtained through a crude approximation method as described in reference [**16**]. The actuated torque and acceleration of the arm were assumed to be perfectly modelled. In the actual physical system, a torque sensor installed at the actuator (motor) shaft maybe directly used to measure the actuated torque of the motor. Alternatively, a current sensor can be used instead to obtain the current reading I_t and then simply multiply it with the motor torque constant K_t to obtain the actuated torque τ indirectly as described by equation (12). The latter configuration is significantly advantageous compared to the former due to the fact that it is much more economical and simple to implement [**16–18**]. The acceleration signal can be easily acquired by means of an accelerometer attached at strategic location on the rotating body mass. Due care must be observed to ensure that the sensors are accurately calibrated prior to the system operation so that correct readings are obtained as these shall be used in the execution of the main AFC algorithm. The use of data acquisition system is essential in carrying out the real-time measurement and control process, typically via a computer program.

5 MODELLING OF MUSCLE WITH VIBRATORY EXCITATION

The strategy for building a muscle model is to first introduce the basic mechanical elements of a spring and damper, and explain how series and parallel arrangements can be made to accurately model the viscoelastic behaviour of soft tissues. The Maxwell and Kelvin models are good for soft tissues under both compressive and tensile loads [**23**].

The Maxwell model can be represented by a purely viscous damper (with a damping constant c) and a purely elastic spring (with a spring stiffness k) connected in series, as shown in Fig. 4 [**23**]. The governing dynamic equations for a Maxwell muscle model based on Fig. 4 are given as follows

$$m\ddot{x} + k(x - x_1) = f_0 \sin(\omega t) \tag{14}$$

$$c\dot{x}_1 - k(x - x_1) = 0 \tag{15}$$

$$F_t(t) = c\dot{x}_1 \tag{16}$$

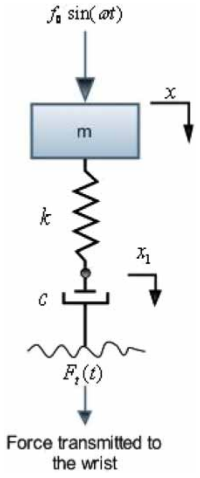

Fig. 4 Maxwell muscle model

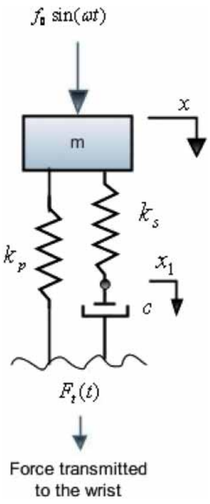

Fig. 5 Kelvin muscle model

where m is the mass of muscle, k is the stiffness coefficient of the muscle, c is the damper coefficient, $f_o \sin(\omega t)$ is the harmonic force with f_o amplitude and ω forcing frequency, $F_t(t)$ is the force transmitted to the wrist, x displacement of the mass, and x_1 is the displacement of the damper.

For the Kelvin model as shown in Fig. 5, a spring with stiffness k_p is added to the Maxwell model in parallel with the spring–damper (connected in series) system. The spring that is attached in series with the damper is necessary to allow an instantaneous deformation, because the damper prevents anything in parallel with it from changing length instantaneously [**23**]. With proper specifications of the parallel spring with constant k_p, series spring with constant k_s, and damping coefficient c, the Kelvin model can be made to effectively match the behaviour under both short-term and long-term conditions.

The dynamic equations for the Kelvin model based on Fig. 5 are given as follows

$$m\ddot{x} + k_p x + k_s(x - x_1) = f_o \sin(\omega t) \tag{17}$$

$$c\dot{x}_1 - k_s(x - x_1) = 0 \tag{18}$$

$$F_t(t) = k_p x + c\dot{x}_1 \tag{19}$$

In addition, the studies showed that vibration at frequencies under 40 Hz could be effectively transmitted to the arms, shoulders, and head; vibration at frequencies greater than 100 Hz was mainly constrained to the hand; and less than 10 per cent of vibration at frequencies greater than 250 Hz was transmitted to the wrist and beyond. Vibration energy can only be absorbed in the tissues to which vibration has been transmitted. Thus, in theory, the vibration energy absorption (VEA) measured at low frequencies should be distributed throughout the entire finger–hand–arm system; the VEA distribution along the finger–hand–arms–shoulder–head vibration transmission chain would decrease with an increase in vibration frequency; and the VEA at high frequencies should be limited to the local tissues close to the vibration source [**26**]. Therefore, in this study harmonic force (vibratory excitation) as an external force on the palm is investigated and is assumed to be transmitted to the wrist. Note that in the study, the vibratory excitation is assumed to occur at 3.2 and 31.8 Hz as illustrations to show the effectiveness of the proposed control scheme to reject the disturbance and minimize the vibration energy from being transmitted to the internal structure of the human-like arm.

6 SIMULATION

Simulation work is performed using the MATLAB and Simulink software packages. The Simulink block diagram for the proposed scheme is shown in Fig. 6. It comprises a number of components and subsystems:

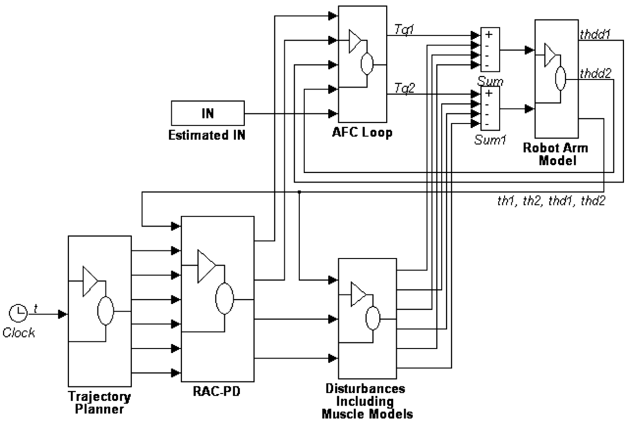

Fig. 6 A Simulink block diagram of the system

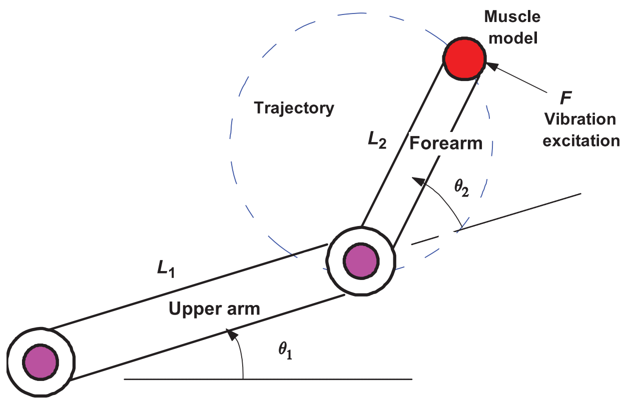

Fig. 7 Application of disturbance at the wrist

the trajectory planner, the RAC–PD section, main AFC loop, robot arm dynamics, and the disturbance model. These are interlinked by means of connecting lines representing the flow of signals and the relevant building blocks acquired from the Simulink library. In the simulation program, a number of disturbance torques can be described and introduced into the system; the ones considered in the study are those due to vibration of the muscle models assumed to act at the wrist as shown in Fig. 7. The simulation parameters used in the study are listed as follows.

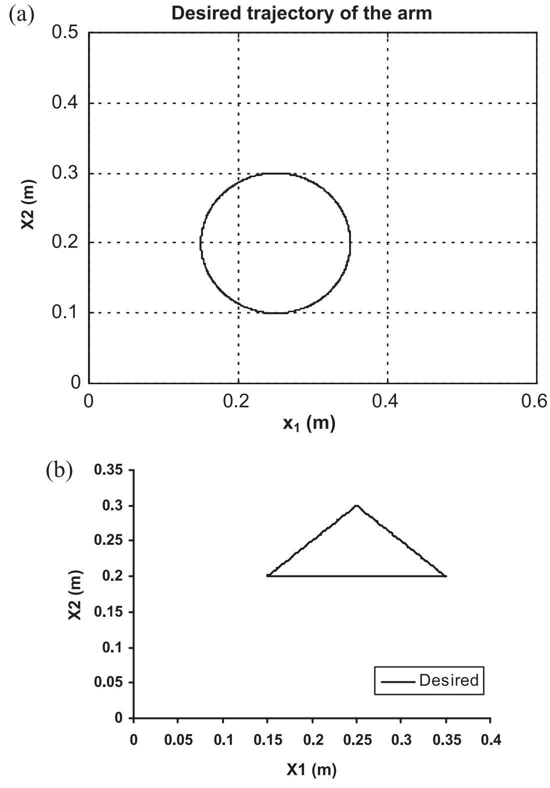

Fig. 8 Desired trajectories of the arm: (a) circular trajectory and (b) triangular trajectory

Mechanical arm parameters:

arm lengths: $L_1 = 0.25\,\text{m}$, $L_2 = 0.2236\,\text{m}$;
arm masses: $m_1 = 0.34\,\text{kg}$, $m_2 = 0.25\,\text{kg}$;
motor masses: $\text{mot}_{11} = 1.3\,\text{kg}$, $\text{mot}_{21} = 0.8\,\text{kg}$.

Controller parameters [**17**]:

controller gains: $K_\text{p} = 750$, $K_\text{d} = 500$;
motor torque constants: $K_\text{t} = 0.263\,\text{Nm/A}$;
diagonal elements of estimated inertia matrix:
$\mathbf{IN}_1 = 0.1\,\text{kgm}^2$, $\mathbf{IN}_2 = 0.01\,\text{kgm}^2$.

Muscle model parameters and disturbance for both Maxwell and Kelvin muscle models [**23**]:

$k_\text{p} = 50\,\text{N/m}$, $k_\text{s} = 50\,\text{N/m}$, $m = 1\,\text{kg}$, $c = 10\,\text{Ns/m}$;
harmonic force: $f_\text{o} = 40\,\text{N}$, $\omega = 20\,\text{rad/s}$.

The arm is assumed to execute a trajectory tracking task involving circular and triangular trajectories as shown in Fig. 8 via a trajectory planner function block

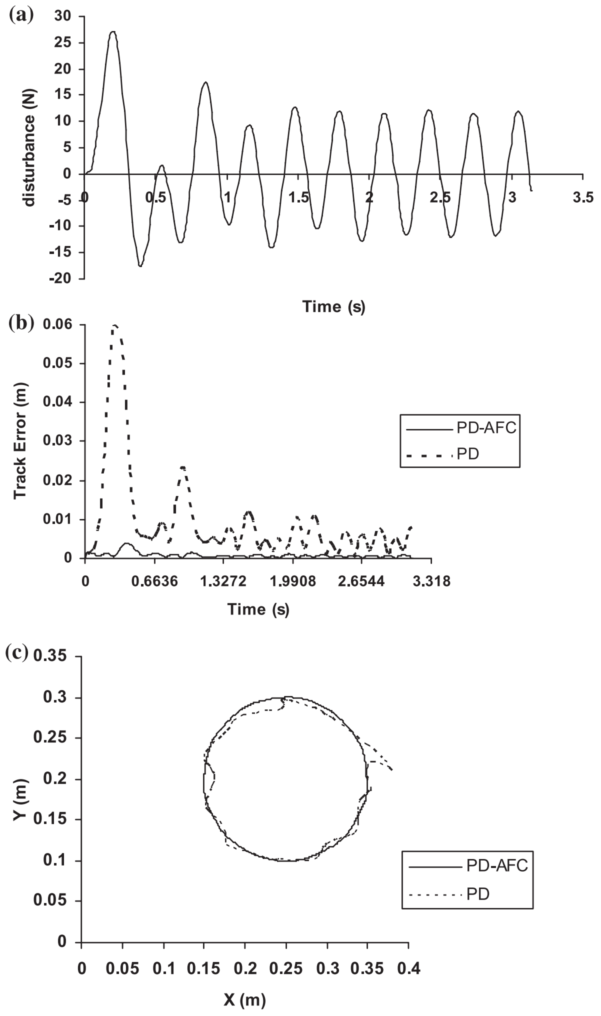

Fig. 9 Results for the Kelvin model: (a) force transmitted to the wrist; (b) track errors; and (c) actual trajectories for the two control schemes

containing the following equations

$$x_{\text{bar1}} = 0.25 + 0.1 \sin\left(\frac{V_{\text{cut}}\, t}{0.1}\right) \tag{20}$$

$$x_{\text{bar2}} = 0.1 + 0.1 \cos\left(\frac{V_{\text{cut}}\, t}{0.1}\right) \tag{21}$$

$$s = V_{\text{cut}}\, t \tag{22}$$

where $\boldsymbol{V}_{\text{cut}}$ is the tangential velocity of the arm at the wrist and is set to 0.2 m/s. x_{bar1} and x_{bar2} represent the conventional Cartesian x and y coordinates, respectively, and s is the displacement (for the triangular trajectory). Note that the simulation considers only the operation of the arm performing one complete cycle of the trajectory.

7 RESULTS AND DISCUSSION

Figures 9 to 11 show the results obtained through the simulation work. The graphical results are related to the disturbance due to harmonic force on the muscle model transmitted at the wrist of the robot arm, the track errors produced and trajectories generated by the control schemes (PD–AFC and PD only) for Kelvin and Maxwell muscle models and also the application of vibratory excitation at two different frequencies, i.e. 20 rad/s (3.2 Hz) and 200 rad/s (31.8 Hz) for circle and triangle trajectories, respectively. Indeed, the overall results are almost similar though the Maxwell model shows a slightly better performance than the Kelvin model in terms of trajectory tracking task capability. This is due to the fact that the amplitude of the disturbance for the Maxwell model is smaller, i.e. almost half of the Kelvin's counterpart as shown in Figs 9(a) and 10(a). In any case, it is obvious that the PD–AFC method is much more robust and accurate than the PD control method in compensating the disturbance

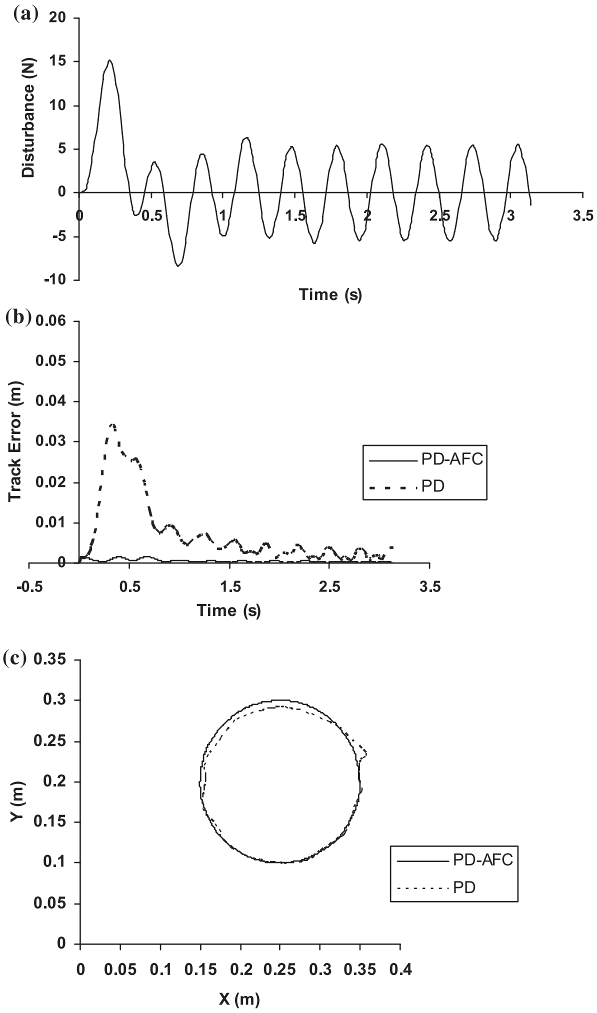

Fig. 10 Results for the Maxwell model: (a) force transmitted to wrist; (b) track errors; and (c) actual trajectories for the two control schemes

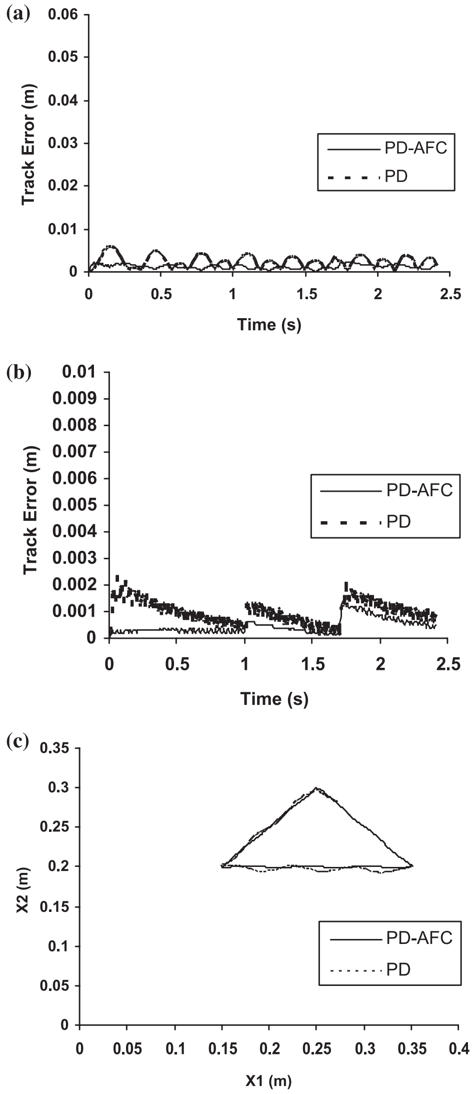

Fig. 11 Results for the triangular trajectory: (a) track errors at 3.2 Hz; (b) track errors at 31.8 Hz; and (c) actual trajectories for the two control schemes (3.2 Hz)

effects. This can be seen through the track error curves generated by the AFC-based scheme are far less than the PD control as shown in Figs 9(b), 10(b), 11(a), and 11(b).

The initial stage for the robust scheme is characterized by a relatively large error but as soon as the disturbance rejection or compensation via the AFC loop takes place, the track error is reduced to almost zero for all conditions even in the presence of the introduced disturbances. It is also clear that both the error curves exhibit consistent repetitive fluctuating patterns that conform to the vibratory nature of the applied disturbance (i.e. harmonic force on muscle model). The results can be further analysed by looking at the actual trajectories generated by both control schemes as depicted in Figs 9(c), 10(c), and 11(c). The figures show that the trajectories tracked by the PD control scheme are greatly distorted from the desired trajectory whereas for the PD–AFC scheme, they are almost indifferent. Thus, it is a very clear indication that the AFC-based scheme manages to suppress the disturbances effectively during the arm's operation.

The findings of the study may assist the researcher to design and develop a robust tool for a robot arm (or even actual human arm) particularly in the event the end effector or tooling device attached to the wrist is subjected to various forms of disturbances that include tremor (vibration) or muscle flexibility. The outcome of the study further strengthens the results obtained in previous studies [**16–20**, **25**].

8 CONCLUSIONS

An AFC-based scheme has been shown to significantly suppress the vibratory excitation on the human-like arm with muscle flexibility. Furthermore, accurate tracking performance is achieved for the given operating and loading conditions implying the potentials of the proposed method to be applied in critical application, such as in the development of special tooling devices for use in a mechatronic robot arm or even human arm (smart glove) to suppress tremors and other forms of disturbances. Further research could be carried out to complement the results obtained in the study. This may include investigation of the system subject to other operating and loading conditions, such as different types of disturbances, muscle model structures, and operating speed. The practical implementation of the proposed system is currently ongoing and preliminary results look very promising.

ACKNOWLEDGEMENTS

The authors would like to thank the Malaysian Ministry of Higher Education and Universiti Teknologi Malaysia for their continuous support in the research work. This research was fully supported by a research grant using Vote No. 78047/79112.

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CHAPTER 3

CONCLUSION

3.1 Conclusion

Specific objectives of the project have been met. An AFC-based scheme has been shown to significantly suppress the vibratory excitation on the human-like arm with muscle flexibility. Furthermore, accurate tracking performance is achieved for the given operating and loading conditions implying the potentials of the proposed method to be applied in critical application, such as in the development of special tooling devices for use in a mechatronic robot arm or even human arm (smart glove) to suppress tremors and other forms of disturbances. Further research could be carried out to complement the results obtained in the study. This may include investigation of the system subject to other operating and loading conditions, such as different types of disturbances, muscle model structures, and operating speed. The practical implementation of the proposed system is currently ongoing and preliminary results look very promising.