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Approximate Feedback Linearization Control for Spatial 6-DOF Hydraulic Parallel Manipulator

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Abstract: Traditional feedback linearization approach (TFL) requires *a priori* knowledge of plant, which is difficult and the computational efficiency of controller is low due to the complex dynamics of spatial 6-DOF hydraulic parallel manipulator. In order to improve the tracking performance of spatial 6-DOF hydraulic parallel manipulator and to conquer the drawbacks of TFL, a novel approximate feedback linearization approach, non-model based method, is proposed in this paper. The mathematical model of spatial hydraulic parallel manipulator is established. The approximate feedback linearization control is designed for the parallel manipulator in joint space, with position and stored force in the previous time step are employed, as a learning tool to yield improved performance. Under Lyapunov theorems, the stability of the presented algorithm is confirmed in the presence of uncertainties. Simulation results show the proposed control is easy and effective to realize path tracking, and it exhibits excellent performance and high efficiency without a precision dynamics of plant. Furthermore, the presented algorithm is well suitable for most industrial applications.

Keywords: Parallel manipulator, hydraulic system, approximate feedback linearization, path tracking.

1. INTRODUCTION

Parallel manipulator has been extensively investigated due to the advantages of high force-to-weight ratio, high stiffness and accuracy, and its widespread applications in various fields such as machine tools, high fidelity simulators, and so on [1, 2]. Additionally, spatial hydraulic parallel manipulator has the characteristics of rapid responses and large output force, etc. Spatial 6-DOF hydraulic parallel manipulators have been applied as the motion system of flight simulators, vehicle simulators, ship simulators, and large spacecraft-mounted system. However, the high nonlinearity and strong coupling, resulted from the complex dynamic properties of spatial hydraulic parallel manipulator, always exists in such a system. Hence, it is very important to develop a simple and effective controller, with the merits of both classical PID control, simple and better real time that other controllers, and traditional feedback linearization approach, excellent static and dynamic control performances, for spatial 6-DOF hydraulic parallel manipulator to develop its merits.

Many approaches have been employed for parallel manipulator [3-8], the strategies may be divided into two schemes, joint-space control [9-12], and workspace control [13-15]. The current joint space controllers are developed and implemented to treat the system as independent SISO system in joint space. A classical proportional plus integral plus derivative control in joint space has been applied in industry, but it can not always guarantee high control performances for spatial parallel manipulator [3]. Su presented a robust auto-disturbance rejection controller in joint space for a 6-DOF parallel manipulator [16]. The adaptive control scheme [17, 18], artificial neural networks and fuzzy control [19, 20] are also suggested to spatial parallel manipulator. However, the characteristics of hydraulically driven system are not taken into account in the above controllers. Kim proposed a robust nonlinear control scheme in joint space for a hydraulic parallel manipulator based on Lyapunov redesign method, and the dynamics of hydraulic parallel manipulator is involved in the controller [21]. Yet, the dynamic coupling is not considered, which only be treated as disturbance. On the other words, the workspace control scheme seems to have the potential to provide a superior DOF control only after system states information is acquired via costly direct measurements or cumbersome state estimation. Davliakos presented a model-based control for a 6-DOF electro-hydraulic Stewart-Gough platform without considering uncertainties [22]. Chen studied the feedback linearization control of a two-link robot using a multi-crossover genetic algorithm [23]. Unfortunately, the method is not suitable for high real-time control system, especially for spatial 6-DOF hydraulic parallel manipulator.

In this paper, the theoretical and simulation studies are performed to develop an approximate feedback linearization control scheme for spatial 6-DOF hydraulic parallel manipulator. The parallel manipulator is described as thirteen rigid bodies, and the hydraulic system is given with hydromechanics principle. The novel contribution is that a non-model-based approximate feedback linearization control is presented in this paper. The presented controller can avoid the drawbacks of classical PID approach and traditional feedback linearization method, which is not based on a priori knowledge of dynamics but exploits a novel feedback linearization under PID control scheme. The data information of

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position and pressure in previous step of each leg is employed in the control scheme, as the feedback of spatial 6-DOF hydraulic parallel manipulator. The aim of the developed approximate feedback linearization control is to improve the control performance of path tracking of hydraulic parallel manipulator, through implementing the approximate linearization of nonlinear and strong coupling spatial hydraulic parallel manipulator, without aggravating the computational burden.

2. SYSTEM MODEL

The spatial 6-DOF hydraulic parallel manipulator are configured with a moving platform and a fixed base connected by six identical hydraulic legs in parallel, illustrated in Fig. (**1**).

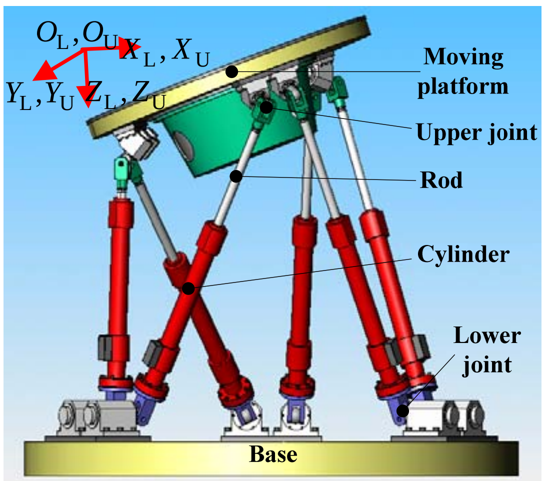


Fig. (1). Spatial 6-DOF parallel manipulator.

The O_U-$X_UY_UZ_U$ is body coordinate system fixed to the moving platform, and the origin O_U is the center of mass of the moving platform with payload. The O_L-$X_LY_LZ_L$ is the inertial coordinate system. O_L and O_U are the same point in the initial pose of the spatial hydraulic parallel manipulator.

Only one leg of the spatial 6-DOF parallel manipulator should be taken into account for deriving the dynamic equations, since all the legs of parallel manipulator are identical. The inertial forces of leg resulted from linear motions are described as,

$$J_{ai,\bar{q}}^T\left(J_{aci,ai}^T m_a \dot{v}_{aci} + J_{bci,ai}^T m_b \dot{v}_{bci}\right) = F_{lvi} \tag{1}$$

where m_a, m_b are the mass of rod and cylinder, respectively. v_{aci}, v_{bci} are 3x1 velocity vector of mass center of rod and cylinder, $J_{ai,\bar{q}} \in \Re^{3x6}$, $J_{aci,ai}, J_{bci,ai} \in \Re^{3x3}$ are Jacobian matrices.

$$v_{aci} = J_{aci,ai} J_{ai,\bar{q}} \dot{\bar{q}}\,,\ v_{bci} = J_{bci,ai} J_{ai,\bar{q}} \dot{\bar{q}} \tag{2}$$

In the inertial coordinate system, the inertial force of leg stemmed from rotation is formulated as,

$$J_{ai,\bar{q}}^T J_{wi,ai}^T\left((I_{ai} + I_{bi})\dot{\omega}_{li} + \omega_{li} \times (I_{ai} + I_{bi})\omega_{li}\right) = F_{lai} \tag{3}$$

where $J_{wi,ai} \in \Re^{3x3}$ is a Jacobian matrix, $\omega_{li} \in \Re^3$ is angu-lar velocity vector of leg in inertial frame, I_{ai}, I_{bi} are the inertia matrices of rod and cylinder in inertial frame.

$$I_{ai} = R_l I_a^a R_l^T = I_{ax}^a l_{ni} l_{ni}^T + I_{ay}^a (I - l_{ni} l_{ni}^T) \tag{4}$$

$$I_{bi} = R_l I_b^b R_l^T = I_{bx}^b l_{ni} l_{ni}^T + I_{by}^b (I - l_{ni} l_{ni}^T) \tag{5}$$

$$\omega_{li} = J_{wi,ai} v_{ai} = J_{wi,ai} J_{ai,\bar{q}} \dot{\bar{q}} \tag{6}$$

where $I_a^a, I_b^b \in \Re^{3x3}$ are the center inertia matrices of rod and cylinder of leg, $l_{ni} \in \Re^3$ is unit leg vector, computed by,

$$l_{ni} = (Ra_i + c - b_i)/\| Ra_i + c - b_i \| \tag{7}$$

where a_i, b_i are the upper joint and lower joint coordinate, respectively, c is the position vector of mass center of the moving platform in inertial frame, R is a 3x3 rotation matrix, referred in [2].

The inertial forces and moments of the moving platform can be given as,

$$m_p \ddot{c} = F_p \tag{8}$$

$$I_p \dot{\omega} + \omega \times I_p \omega = M_p \tag{9}$$

where m_p is the mass of the moving platform, ω is a 3x1 angular velocity vector of the moving platform in inertial frame, $I_p \in \Re^{3x3}$ is inertia matrix of the moving platform, $I_p = R I_p^p R^T$.

The generalized active force of the spatial 6-DOF parallel manipulator can be expressed as,

$$F_{active} = J_{l,\bar{q}}^T F_a + G \tag{10}$$

where $F_a \in \Re^6$ is the leg output force, G is gravity term, given by,

$$G = \begin{bmatrix} m_p g^T & 0_{1x3} \end{bmatrix}^T + J_{ai,\bar{q}}^T (J_{aci,ai}^T m_a + J_{bci,ai}^T m_b) g \tag{11}$$

Combining (1)-(11), the complete dynamic equations for spatial 6-DOF parallel manipulator may be derived by Kane method.

$$M(q)\ddot{\bar{q}} + C(q, \dot{\bar{q}})\dot{\bar{q}} - G(q) = J_{l,\bar{q}}^T F_a \tag{12}$$

where M is a 6x6 mass matrix, C is a 6x6 centrifugal terms, q is generalized pose of the moving platform, $\dot{\bar{q}}$ is generalized velocity of the moving platform, $\dot{\bar{q}} = \begin{bmatrix} \dot{c}^T & \omega^T \end{bmatrix}^T$.

$$M(q) = \begin{bmatrix} m_p I_{3x3} & 0 \\ 0 & I_p \end{bmatrix} + \sum_{i=1}^{6} \left\{ J_{ai,\bar{q}}^T \begin{bmatrix} J_{aci,ai}^T m_a J_{aci,ai} + \\ J_{bci,ai}^T m_b J_{bci,ai} + \\ J_{wi,ai}^T (I_a + I_b) J_{wi,ai} \end{bmatrix} J_{ai,\bar{q}} \right\} \tag{13}$$

$$C(q,\bar{q})=\begin{bmatrix} 0_{3x3} & 0 \\ 0 & \tilde{\omega} I_p \end{bmatrix} + \sum_{i=1}^{6}\left\{ \begin{matrix} J_{ai,\bar{q}}^T \begin{bmatrix} J_{aci,ai}^T m_a\, d(J_{aci,ai} J_{ai,\bar{q}})/dt + \\ J_{bci,ai}^T m_b\, d(J_{bci,ai} J_{ai,\bar{q}})/dt \end{bmatrix} + \\ J_{ai,\bar{q}}^T J_{wi,ai}^T \begin{bmatrix} (I_{ai}+I_{bi}) d(J_{wi,ai} J_{ai,\bar{q}})/dt + \\ J_{wi,ai} J_{ai,\bar{q}} \dot{\bar{q}} \times (I_{ai}+I_{bi}) J_{wi,ai} J_{ai,\bar{q}} \end{bmatrix} \end{matrix} \right\} \quad (14)$$

The hydraulic system which is composed of servovalve and unsymmetrical cylinder is the driving source of the spatial hydraulic parallel manipulator. The load flow q_{Li} supplied by valve is a function of spool valve displacement x_{vi}, which is proportional to its command voltage signal V_i and load pressure p_{Li} [24].

$$q_{Li} = C_d \cdot w \cdot x_{vi} \sqrt{\frac{1}{\rho}(p_s - \mathrm{sign}(x_{vi}) p_{Li})} \quad (15)$$

$$x_{vi} = k_0 V_i \quad (16)$$

where k_0 is the proportional ratio between spool valve position and its command voltage, C_d is flow coefficient, The load flow for each cylinder is given as,

$$q_{Li} = A_1 \cdot \dot{l}_i + c_{tc} \cdot p_{Li} + c_{tic} \cdot p_s + \frac{(1+n^4)\cdot A_1 \cdot L}{2(1+n^2)(1+n^3)E} \dot{p}_{Li} \quad (17)$$

where q_{Li} is load flow of the ith hydraulic actuator, w is area grads, ρ is fluid density, p_s is supply pressure of servosystem, A_1 is the effective acting area of piston, c_{tc} is the leakage coefficient, E is bulk modulus of fluid, l_i is the length of the ith actuator, n is the ratio of area, $n = A_2/A_1$. The force equilibrium equation of each actuator is given by,

$$A_1 \cdot p_{Li} = f_{ai} + f_{fi} \quad (18)$$

where f_{fi} is joint space friction force in the ith actuator, see reference [2].

3. CONTROL DESIGN

Under the assumption that the parallel manipulator is known, the friction, system geometric and inertia parameters can be exactly obtained. Spatial 6-DOF parallel manipulator can be linearized by traditional feedback linearization method only for the system without driven system or the desired force can be perfectly repeated. Traditional feedback linearization approach, computed torque control, is given as,

$$F_{Ld} = J_{l,\bar{q}}^{-T} \begin{bmatrix} M(q)(\ddot{\bar{q}}_d + K_d \dot{e} + K_p e) + \\ C(q,\dot{\bar{q}})\dot{\bar{q}} - G(q) \end{bmatrix} + F_f \quad (19)$$

Appling the control scheme (19) to spatial 6-DOF parallel manipulator (12), the linearized and decoupled error equation is shown as,

$$\ddot{e} + K_d \dot{e} + K_p e = 0 \quad (20)$$

where K_p and K_d are positive definite diagonal matrices, e is the tracking error vector. Unfortunately, the assumptions, the parallel manipulator is known, is violated for real system due to the complexities of spatial 6-DOF parallel manipulator, especially for hydraulic parallel manipulator. Moreover, the repeating of load force is very difficult to realize for hydraulic system resulting from the precision of pressure sensors of cylinder and friction. Hence, the method can not be suitable for real spatial 6-DOF hydraulic parallel manipulator. The approximate feedback linearization is used to solve the problem without a prior knowledge of the parallel manipulator.

Mostly, the nature frequency of servovalve selected to be much higher than the power mechanism of hydraulic system, (15) can be linearized using Taylor formulation, rewritten by,

$$q_{Li} = k_{qi} \cdot V_i - k_{ci} p_{Li} \quad (21)$$

Combing (15)-(17) with (21), the command of voltage for the servovalve of the hydraulic system is derived as,

$$V_i = \frac{1}{k_{qi}}[A_1 \cdot \dot{l}_i + c_{tic} P_{si} + (k_c + c_{tc}) p_{Li} + \frac{(1+n^4)\cdot A_1 \cdot L}{2(1+n^2)(1+n^3)E} \cdot \dot{p}_{Li}] \quad (22)$$

where k_{qi} is a gain for the ith servo-valve, k_{ci} is a flow pressure coefficient of the ith servovalve. c_{tic}, c_{tc} are constant coefficients related to leakage. Taking into account the system dynamics of the spatial hydraulic parallel manipulator, including mechanical system and hydraulic system, the approximate feedback linearization control law is developed as

$$u_{x_v} = A_1/k_q \left[\dot{l}_d + K_{p1} e + h(t)\right] \quad (23)$$

where K_{p1} is a positive definite gain matrix, e is the leg error vector, $e = l_d - l$, $h(t)$ is determined for approximate feedback linearization. Substituting (23) to the spatial hydraulic parallel manipulator in presence of various disturbances, yields

$$\dot{e} + K_{p1} e = \mathrm{H} - h(t) \quad (24)$$

$$\mathrm{H} = (c_{tc} + k_c)\cdot F_{Li}/A_1 + c_{tic} p_s / A_1 + (1+n^4) A_1 \cdot L \cdot \dot{F}_{Li} / [2(1+n^2)(1+n^3)E] \quad (25)$$

$$F_L = J_{l,\bar{q}}^{-T}\left[M(q)\ddot{\bar{q}}_d + C(q,\dot{\bar{q}})\dot{\bar{q}} + G(q)\right] + F_f \quad (26)$$

The error converges to zero and the high nonlinear and strong coupling parallel system is linarized and decoupled, if the right-hand side of (24) becomes equal to zero, which made the algorithm works like computed torque controller, even with a simpler control scheme without computation of dynamics. To make the right hand side of (24) be close to zero, a good approximation may be derived by taking $h(t)$ equal to H at a previous small time step, $\mathrm{H}|_{t-\Delta t}$. However, the existing of $h(t)$ in (24) may result in large valve position in the case e is relatively high due to uncertainties. With a view of avoiding the problem, the standard PD controller can be applied momentarily. Hence, a factor matrix can be utilized as,

$$h(t) = k\,\mathrm{H}\big|_{t-\Delta t} = diag\{k_1 \cdots k_6\}\,\mathrm{H}\big|_{t-\Delta t} \tag{27}$$

$$k_i = \begin{cases} 0 & |e_i| \geq \varepsilon \quad or \quad |\dot{e}_i| \geq \dot{\varepsilon} \\ 1 & |e_i| < \varepsilon \quad or \quad |\dot{e}_i| < \dot{\varepsilon} \end{cases} \tag{28}$$

where ε and $\dot{\varepsilon}$ are positive real values corresponding to sensitivity thresholds. To smooth the switch of k, the switch is modified to be continuous [3], expressed as,

$$k_i = \exp\left(-(\frac{|e_i|}{e_{i\max}} + \frac{|\dot{e}_i|}{\dot{e}_{i\max}}) \right) \tag{29}$$

where $e_{\max}, \dot{e}_{\max}$ represent another sensitivity thresholds. With proper selection of the thresholds, the following error equation can be derived by using (27).

$$\dot{e} + K_{p1}e \approx 0 \tag{30}$$

To make the control system stability, the gain K_{p1} can be chosen to be positive diagonal matrix. The spatial 6-DOF hydraulic parallel manipulator with nonlinearity and coupling is approximately decoupled and linearized with the proposed control scheme.

4. RESULTS AND DISCUSSION

The control performance of the approximate feedback linearization control scheme (AFLC) is evaluated on a relatively large spatial 6-DOF hydraulic parallel manipulator, the parameters of the spatial hydraulic parallel manipulator are summarized in Table **1**, and the sample time is set to 1ms. The spatial parallel manipulator is established using Simulink, shown in Fig. (**2**).

Table 1. Parameters of Spatial 6-DOF Hydraulic Parallel Manipulator

Parameters	Value	Unit
Max./Min. stroke of cylinder, $l_{\max}/l_{\min}$	-0.37/0.37	m
Initial length of cylinder, l_0	1.830	m
Upper joint radius, R_u	0.560	m
Lower joint radius, R_d	1.200	m
Mass of the moving platform	137	Kg
Inertia of the moving platform	12, 12, 21	Kg•m^2
Active area of piston, A_1, A_2	0.0031/ 0.0015	m2
Supply pressure, p_s	7.3×10^6	Pa
Effective bulk modulus, E	7.0×10^8	Pa

To ensure that the simulation analysis of the proposed AFLC control in spatial hydraulic parallel manipulator is effective and valuable, the dynamic model should be validated by different modeling method or experiment. To confirm the obtained dynamic model, a completely dynamic model is built through SimMechanics, one of physical modeling approaches, like ADAMS, in accordance with the physical relationship of parallel manipulator. Under the same driven forces, the responses to the two dynamic models are shown in Fig. (**3**). The detail validation of the derived dynamic model can refer the reference [25].

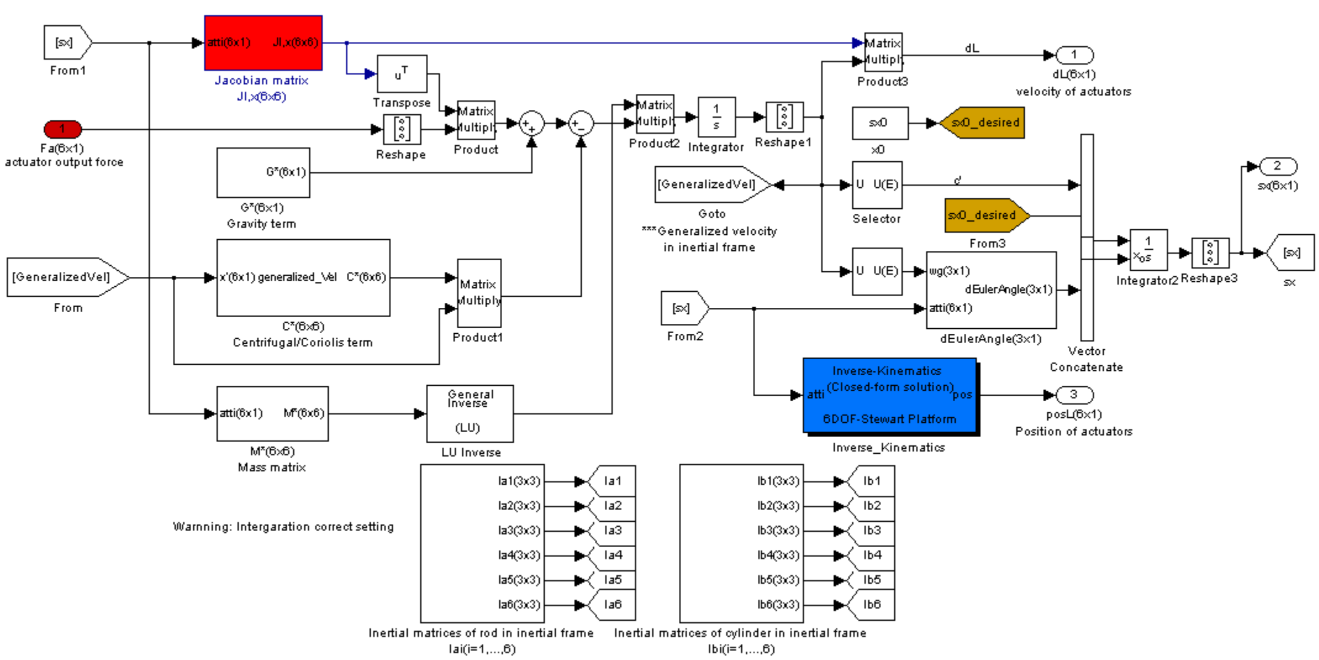


Fig. (2). Dynamic model of spatial 6-DOF parallel manipulator in Simulink.

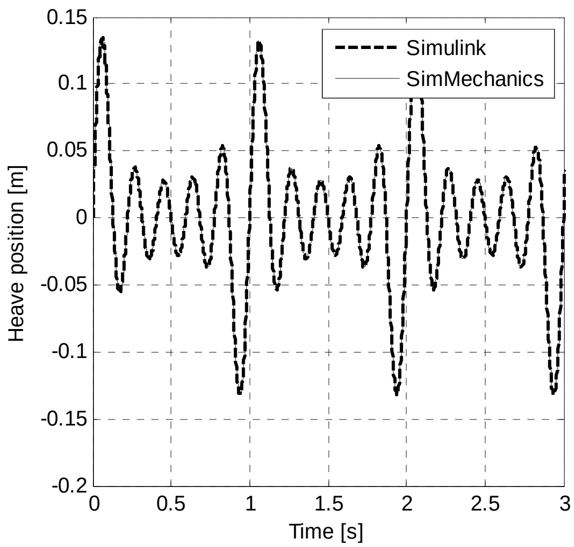
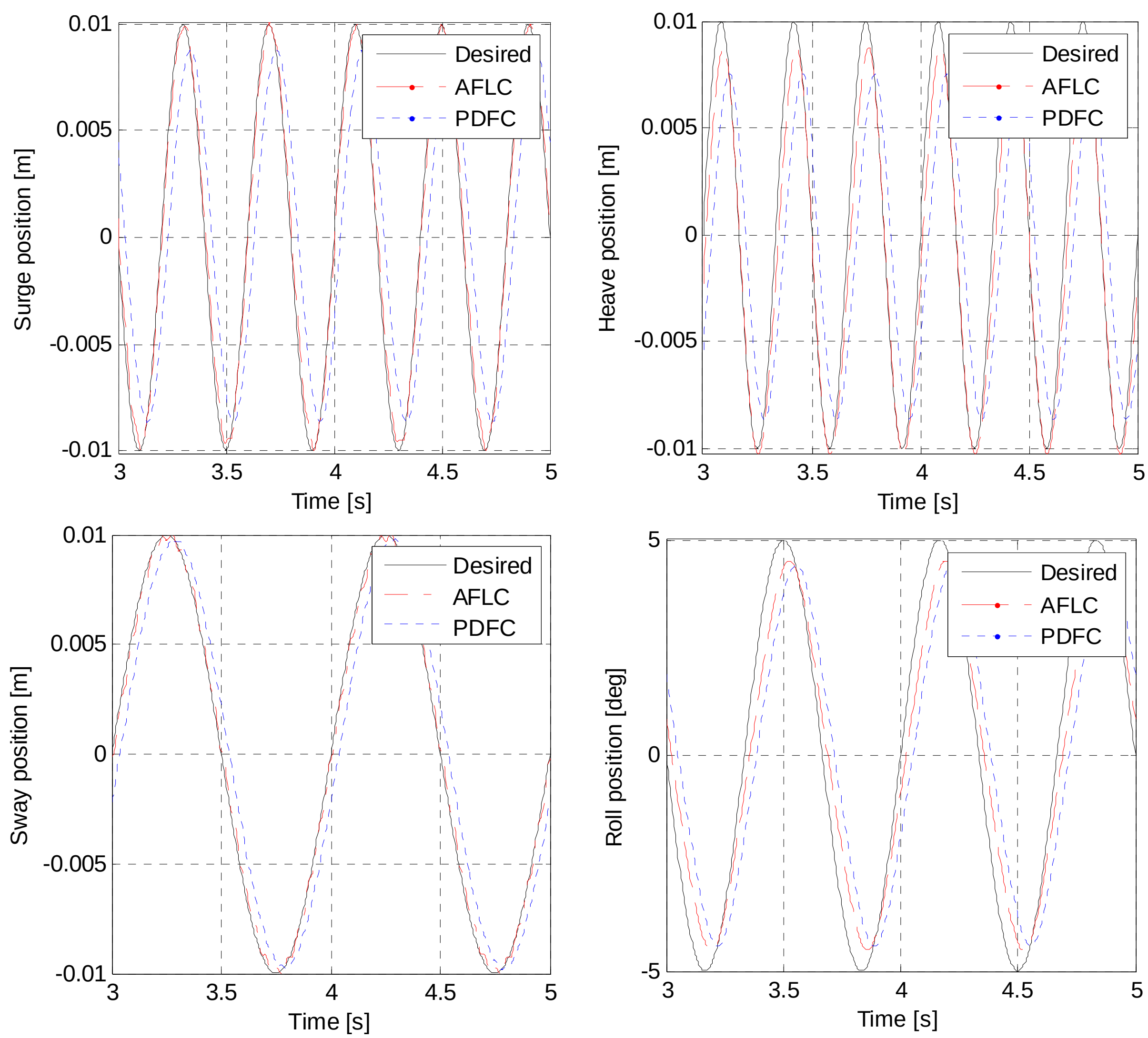


Fig. (3). Comparison of responses for the dynamic model in Simulink and SimMechanics model under the same driven forces.

The well tuned PD with friction compensation controller (PDFC), common control algorithm in industry, is used to compare with the proposed approximate feedback linearization control scheme (AFLC). With the well tuned gains K_{p1}, the motions under sinusoidal inputs along all 6 DOF directions: surge (10mm/2.5Hz), sway (10mm/1Hz), heave (10mm/3Hz), roll (5deg/1.5Hz), pitch (2deg/1Hz) and yaw (5deg/2Hz) are applied to the spatial 6-DOF hydraulic parallel manipulator. The responds to these motions are illustrated in Fig. (**4**).

As shown in Fig. (**4**), the approximate feedback linearization control scheme shows excellent tracking performance superior to those of the PDFC controller along all six DOFs. Moreover, the proposed controller reduces the effects of the dynamic coupling of the spatial hydraulic parallel manipulator in all six directions and improves the control performance considerably. The maximal phase retarding is 44º in linear motions and 28.8º in angular motions under the PDFC controller, 15º in linear motions and 12º in angular motions under the AFLC controller, the maximal amplitude fading is 1.7dB in linear motions and 1.08dB in angular motions



(Fig. 4)Contd…..

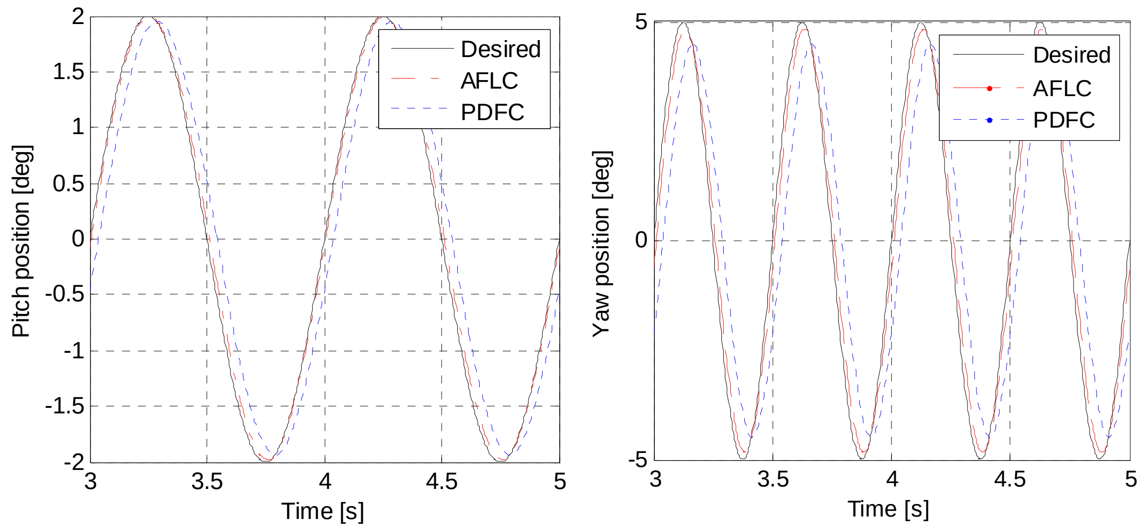


Fig. (4). Responses to the desired trajectories of spatial 6-DOF hydraulic parallel manipulator under AFLC and PDFC controllers.

under the PDFC controller, 0.88dB in linear motions and 0.80dB in angular motions under the AFLC controller. It should be noted that the effects of strong coupling of dynamics may be reduced via advanced controller, but it can not be eliminated. The proposed AFLC controller can realized the approximate linearization of the spatial 6-DOF hydraulic parallel manipulator, without computing the complex dynamics. So the execution time of the AFLC algorithms can be shorter than other algorithms.

5. CONCLUSIONS

This paper investigated a high performance control scheme for spatial multi-DOF parallel manipulator. The dynamic model of the hydraulic parallel machine tool is obtained and described. To achieve the requirement of high real time and tracking precision, a non model-based controller, approximate feedback linearization approach, is developed, which has the advantages of typical PID and traditional feedback linearization. By employing the position of actuator and force at a previous step time as feedback, the proposed approach can linearized the complex system dynamics approximately. The applied results illustrated the merits of the proposed control scheme for hydraulic parallel machine tool, and it also proved the approximate feedback linearization can be used to high precision control area of machine tool.

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