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Full Length Article

A hybrid press system: Motion design and inverse kinematics issues

M. Erkan Kütük, L. Canan Dülger *

Mechanical Engineering Department, Faculty of Engineering, University of Gaziantep, Turkey

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ABSTRACT

A hybrid machine (HM) is a system integrating two types of motor; servo and constant velocity with a mechanism. The purpose is to make use of the energy in the system efficiently with a flexible system having more than one degree of freedom (DOF). A review is included on hybrid press systems. This study is included as a part of an industrial project used for metal forming. The system given here includes a 7 link mechanism, one of link is driven by a constant velocity motor (CV) and the other is driven by a servo motor (SM). Kinematics analysis of the hybrid driven mechanism is presented here as inverse kinematics analysis. Motion design is very crucial step when using a hybrid machine. So motion design procedure is given with motion curve examples needed. Curve Fitting Toolbox (CFT) in Matlab® is offered as an auxiliary method which can be successfully applied. Motion characteristics are chosen by looking at requirements taken from metal forming industry. Results are then presented herein.

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1. Introduction

Variable motion outputs can be obtained by two different ways in industrial applications. The first one is traditional machines and the other one is programmable machines. Hybrid machine idea is proposed to combine two techniques and to utilize from their good specifications and to remove their disadvantages. The basic principle of hybrid systems is to bring together the motion of a large CV motor with a small SM via a mechanical linkage mechanism. In these systems the constant velocity motor provides the main torque and motion requirements while the servo motor assists the modulations on the present motion. The CV motor undertakes a big amount of workload and the SM is like a real time regulator to change the task.

The first study is performed by Dülger (initially Tokuz) and Jones in hybrid configuration [1]. A constant velocity motor and a servo motor were integrated by a differential gearbox which further drives a slider crank mechanism [1]. Kireçci and Dülger have designed a hybrid manipulator with 3 DOF system; DC motor, gear unit, 2 DC SM, servo amplifier, motion control card, a slider crank mechanism and a screw mechanism [2]. Kireçci and Dülger have then offered a configuration of a planar two degree of freedom, seven link mechanisms by showing the reduction peak power requirement of servomotor was 3.5 times less than the peak power of CV motor [3]. Seth has performed a review work about programmable hybrid mechanisms [4]. Ouyang et al. have proposed a five bar linkage consists of a five bar linkage, an AC CV motor and a frequency controller, an AC brushless servo motor and a servo amplifier with a gear transmission, a shift encoder, a flywheel and a belt [5]. Yuan et al. have investigated two hybrid machines with a seven link, two DOF linkage mechanisms [6]. Zhang has proposed a hybrid five bar mechanism [7]. Connor et al. have presented a study on the synthesis of hybrid five bar path generating mechanisms using genetic algorithms [8]. Dulger et al. have presented a study on modeling and kinematic analysis of a hybrid actuator; a seven link mechanism with an adjustable crank [9]. Yu has offered a study with HM system using five bar mechanism [10]. Li et al. have studied on a hybrid driven mechanical press for precision drawing using a nine-bar linkage [11]. Li and Zhang have applied a seven bar linkage configuration with kinematics analysis and optimum design of hybrid system [12]. Du and Guo have studied on a metal forming press. Traditional configurations are studied, and a new hybrid configuration is proposed [13]. Meng et al. have then offered a new press mechanism. Link dimension optimization was performed. A significant reduction is obtained in the peak velocity and acceleration of the servo motor [14]. Li and Tso have presented a seven bar mechanism [15]. Tso and Li have later used a seven bar mechanism to investigate the stamping capacity and energy distribution between the servomotor and the flywheel with different motion inputs [16]. He et al. have studied on trajectory planning and optimization of a 25 tons industrial prototype with 2 DOF systems [17]. Tso has again used a seven bar mechanism. A control system with iterative learning control and feedback control techniques was developed [18]. Li et al. have proposed a novel hybrid driven mechanical press for deep drawing process [19]. Kütük has then studied on a hybrid driven two DOF systems with its inverse kinematics and motion design.

* Corresponding author. Tel.: +90 342 317 25 11; Fax: +90 342 360 11 04.
E-mail address: dulger@gantep.edu.tr (L.C. Dülger).
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Table 1
Classification of the studies.

Name [reference]	DOF	Actuators	Application	Mechanism
Tokuz [1]	2	DC Motor & DC Servo	Press	Slider Crank
Dulger & Kireçci [2]	3	DC Motor & 2 DC Servo	Motion Modulation	Slider Crank & Screw
Kireçci & Dulger [3]	2	DC Motor & DC Servo	Motion Modulation	Seven Bar
Ouyang et al. [5]	2	AC Motor & AC Servo	Press	Five Bar
Yuan et al. [6]	2	DC Motor & DC Servo	Press	Seven Bar
Zhang [7]	2	DC Motor & DC Servo	Point to point positioning	Five Bar & Screw
Dulger et al. [9]	2	DC Motor & DC Servo	Modulation for textile industry	Seven Bar
Li et al. [11]	2	DC Motor & DC Servo	Precision Drawing	Nine Bar
Li & Zhang [12]	2	DC Motor & DC Servo	Deep Drawing	Seven Bar
Du & Guo [13]	2	DC Motor & DC Servo	Metal forming (Dwell)	Seven Bar
Meng et al. [14]	2	DC Motor & DC Servo	Press	Seven Bar
Li & Tso [15]	2	AC Motor & AC Servo	Press	Seven Bar
Tso &Li [16]	2	AC Motor & AC Servo	Press	Seven Bar
He et al. [17]	2	DC Motor & DC Servo	Forging	Seven Bar
Li et al. [19]	2	DC Motor & DC Servo	Deep Drawing	Seven Bar

Kütük has also considered all types of mechanisms especially used in press application. Motion requirements are given by press manufacturer here. A mathematical model concerning its power and energy use is not included in this study [20].

In this study, different ram characteristics are aimed to try and see the availability of them on a hybrid machine. The scenarios used in metal forming industry are planned to be applied. At the end of the study, the flexibility of HM is proved with quick rise, slow return and dwelling periods. Due to the fact that it is an industrial project, the properties of the motion are directly taken from the company. The first thing to do is to design the motion. Segmentation technique is used due to each point of the motion cannot be represented by only a polynomial. The fifth order polynomials are preferred to identify the motion, because six inputs can be obtained from initial and final values of position, velocity and acceleration in each segment. Some ways are questioned how it can be employed more efficiently. Curve Fitting toolbox is tried for this purpose and it is seen that CFT is very profitable in estimating and then defining the initial and final quantities of the segments. This cooperation is firstly achieved in this study and shown on a case study. Inverse kinematics analysis of a hybrid machine has already been studied, but it is desired to exhibit particularly all details of derivations. It is believed that this study will answer the questions of the researchers being interested with HM systems and offer them a procedure about all these issues.

Other studies performed in the literature are tabulated according to actuator types, applications and mechanisms chosen are given in Table 1.

A hybrid machine system is studied with inverse kinematics. A motion design procedure is performed by revising motion requirements from metal forming applications. Motion profiles are designed, and studied with required kinematics. Final decision is made by manufacturers in this field. The paper is organized as follows. Section 1 gives background on hybrid systems. Section 2 presents the motion design. Sections 3–4 show the inverse kinematics analysis for the mechanism and synthesis issues. Section 5 ends with the inverse solution curves for hybrid driven sense. Section 6 presents the main contributions of this study.

2. Motion design

The trajectories are considered with continuous position, velocity and acceleration. Initial and final conditions are given for them. Six boundary conditions are available to be used for a fifth degree polynomial [21]. The motion design is composed of obtaining the position, velocity and acceleration of the slider link. The slider displacement, velocity and acceleration are expressed in fifth order polynomials as;

$$s = ft^5 + et^4 + dt^3 + ct^2 + bt + a \tag{1}$$

$$\dot{s} = 5ft^4 + 4et^3 + 3dt^2 + 2ct + b \tag{2}$$

$$\ddot{s} = 20ft^3 + 12et^2 + 6dt + 2c \tag{3}$$

where a, b, c, d, e and f refer the coefficients of the polynomial and t denotes time.

They can be expressed in matrix form

$$\underbrace{\begin{bmatrix} 1 & t_i & t_i^2 & t_i^3 & t_i^4 & t_i^5 \\ 0 & 1 & 2t_i & 3t_i^2 & 4t_i^3 & 5t_i^4 \\ 0 & 0 & 2 & 6t_i & 12t_i^2 & 20t_i^3 \\ 1 & t_f & t_f^2 & t_f^3 & t_f^4 & t_f^5 \\ 0 & 1 & 2t_f & 3t_f^2 & 4t_f^3 & 5t_f^4 \\ 0 & 0 & 2 & 6t_f & 12t_f^2 & 20t_f^3 \end{bmatrix}}_{A} * \underbrace{\begin{bmatrix} a \\ b \\ c \\ d \\ e \\ f \end{bmatrix}}_{B} = \underbrace{\begin{bmatrix} p_i \\ v_i \\ a_i \\ p_f \\ v_f \\ a_f \end{bmatrix}}_{C} \tag{4}$$

$$A * B = C$$

where p_i, v_i and a_i are the initial displacement, velocity and acceleration, p_f, v_f and a_f are the final displacement, velocity and acceleration of the slider link, t_i and t_f are the initial and final values of the motion time, respectively. The coefficients of the fifth order polynomial are found as

$$B = A^{-1} * C \tag{5}$$

Number of segments and the points where the segments are separated from each other are directly related with the designed motion and choice of the designer [20,21].

2.1. Motion examples

Two motion curve examples are presented here to date different application characteristics. They are called as Motion 1 and Motion 2. To improve the accuracy and quality of forming products, especially in deep drawing operations, different control points are applied. This certainly reduces cracks, winks, and even if springbacks with higher productivity.

(I) Motion 1: Slider motion is a quick rise and slow return motion. Stroke of the slider is 687 mm and stroke per minute is 10. The displacement, velocity and acceleration of the slider are shown in Fig. 1. Motion 1 is comprised by five segments. The main specifications of each motion segment are given in Table 2. The segment number, time interval, initial and final

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