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Numerical and experimental analysis of non-circular gears and cam-follower systems as function generators

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Abstract

The paper shows an analysis of two mechanisms that are typically used as function generators. The former consists of a pair of non-circular gears, which drives a slider-crank mechanism, the latter is a cam-follower system. Both mechanisms are designed to obtain a specific motion law. In this paper the proposed application is to generate a pulsating blood flow during cardiopulmonary by-pass for cardiac surgery. The prescribed motion law can be obtained by a volumetric pump, which can be used to modulate the blood flow in external circulation machines. The reciprocating motion consists of a quick forward stroke, corresponding to the Systolic phase, and a slow return stroke, corresponding to the Diastolic phase. The study has been focused on specific transmission characteristics that are related to a mechanical blood pumping design. In particular, experimental tests have been analyzed to understand benefits and drawbacks for using non-circular gears and polynomial cams in pure mechanical transmissions with limited motion regulation but with specific prescribed motion law. The contribution of the paper can be recognized in comparing numerically and experimentally a traditional cam transmission with a non-circular gear solution to show proper operation feasibility for both solutions without using complex control equipment, even for a robust/reliable demanding application like a blood pumping system.
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1. Introduction

A function generator is a mechanism synthesized to satisfy the optimal Input/Output relationship for a specified application. In many industrial applications a purely mechanical device is often desirable to obtain the required motion with robust operation, like for example for automatic equipment in printing presses, textile industry, packaging machines, quick-return mechanisms [1–3]. The generation of a specific motion law is

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essential also in recreational equipments and rehabilitation devices, in which the maximization of human output is fundamental.

Several mechanical devices can be designed to obtain a prescribed motion law of the output element. Among them, cam-follower mechanisms are widely used in modern machinery. These devices can reproduce almost any characteristics of the follower's motion and they are not particularly difficult to design and build. Their manufacturing costs are rather limited, as well as the number and dimensions of moving parts [4,5]. When a mechanical system is used to obtain a required motion of the output link, non-circular gears are another possible choice. The application of non-circular gears in function generating mechanisms has been proposed and discussed in [6,7]. By designing a pair of non-circular gears, which are able to perform a proper gear ratio function, the output member of a mechanism can be effectively forced to move according to a prescribed law of motion, when operated at a constant input velocity [8,9]. In typical arrangements, a pair of variable radius pitch curves is synthesized to drive a slider-crank mechanism according to a prescribed motion law. For many applications non-circular gears provide some benefits over cams, although they are more difficult to design and expensive to manufacture. The main advantages are the lower weight-to-strength ratios and absence of gross separation or decoupling of moving parts [10].

In this paper, two function generators are designed to drive a flow modulator for external blood circulation, during cardiopulmonary by-pass for cardiac surgery.

In the first mechanism, the output motion is obtained by using a pair of non-circular gears. The pitch curves synthesis is formulated by means of the inverse kinematic analysis of the system. Then, the teeth profiles are generated by assuming the pressure angle to be constant along each tooth, but variable from tooth to tooth.

The second mechanism consists of a cam-follower system, which is commonly used to achieve complex and very variable transmission laws between input rotative shafts and output linear or rotative motion of the follower. The cam has been designed according to the prescribed motion law and with suitable values for the base and follower radii. Both mechanisms have been prototyped by means of a CNC milling machine. Suitable testbeds have been designed at Department of Mechanical Engineering, University of Calabria in Arcavacata di Rende and LARM: Laboratory of Robotics and Mechatronics in Cassino in order to carry out experimental validation. An analysis and comparison for both mechanical devices have been carried out at University of Cassino in order to validate the used design methods and to compare main characteristics of the two mechanical systems, according to the specific proposed application. Preliminary result of the proposed application has been presented in [11].

2. Description of the requested motion law

The application task is to generate a pulsating blood flow during cardiopulmonary by-pass for cardiac surgery. In human body, the blood flow follows a pulsating law consisting of two phases known as the Systole and the Diastole [12]. During the systolic phase, the cardiac muscle contracts in order to pump blood into the cardiovascular circuit, and during the diastolic phase the heart's relaxation occurs. In physiological conditions, the contraction phase is quicker than the relaxation one, being the duration ratio about 1:2.

Starting point of the design process is the definition of the Input/Output relationship, i.e. the motion that the function generator must satisfy. Therefore, the aim is to design a mechanical device, which can be able to drive the piston of a pump that is used to modulate the blood flow during the external circulation [13].

Several mechanisms have been proposed to reproduce these characteristics in the external blood circulation, as reported in [14]. A roller pump can be used in order to generate a constant flow, and then to modulate it by means of a volumetric pump. The periodic motion law for the modulator's piston can be determined on the basis of emo-dynamic considerations, [15]. The required law of motion consists of two phases, corresponding to the forward and return stroke of the piston. The two phases are defined separately by two polynomial functions. Four boundary conditions, listed in Table 1, have been properly established at each extreme of the two regions to guarantee continuity between the two curves up to the first derivative of the acceleration, so that a regular dynamic behavior of the proposed mechanisms could be expected. In order to fulfill the boundary

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