An Experimental Analysis for Four Circular-Arc Cams

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Abstract

The performance of four circular-arc radial cams is investigated as an extension of previously studied two-circular arc cam profiles. The peculiarities of four circular-arc design are characterized by experimental tests by using a suitable low-cost easy-operation test-bed that has been developed at LARM in Cassino.

Introduction

A cam is a mechanical element that is used to drive another element, namely follower, through a given motion by direct contact. The cam-follower mechanism is very simple and cheap, it has few moving parts and has a compact mechanical design. Because of these characteristics, cam mechanisms are used extensively in modern machinery, [1]. Cam mechanisms together with crank mechanisms are the most common types of mechanisms for converting a rotational movement to a controlled reciprocating movement.

In design procedures for cam-follower systems a cam is often assumed to operate at a constant speed. However the motion characteristics of the follower can be very different when the cam speed varies. In some applications better dynamic characteristics are obtained by varying the cam operation speed, [2].

Cam profile can be directly designed as based on a desired transmission relationship. However, from general point of view, in industrial practice, a cam profile is usually designed in a non-dimensional form. A cam profile determines the transmission relationship between cam and follower motions. Since the property of the cam profile directly affects the performance of a cam mechanism, how to design the cam profile with more advantageous efficiency with respect to a design requirement is still a challenging task for mechanical engineers, [3].

Cam profiles can be designed and machined with shapes that can be very complex. There are two types of cam profiles: general cam profiles that are obtained by an envelope of straight-lines or circles, [1, 4]; cam profiles that are obtained as a collection of straight-lines and circular arcs, [5]. Cam profiles, which are designed as collection of circular arcs and straight-lines, are called as circular-arc cams, [6]. They can be easily machined but they can be properly used in low-speed applications only. Polycentric cams are also used for very interesting and useful biomechanical applications such as knee and femoral prosthesis [7]. A limited number of circular arcs is usually advisable so that the design, construction and operation of these cam transmissions can be not very complicate and a circular-arc cam can become a compromise for simplicity and economic characteristics that are the basic advantages of circular-arc cams, [6].

At LARM in Cassino a research line is devoted to study circular-arc cams with the aim of both investigating on many circular arcs in cam profiles and how to approximate any cam profile with a suitable collection of circular-arcs in the profile. The extension of using many circular arcs can be also understood as an attempt of minimizing time and cost of industrial manufacturing, mainly for a production with low-cost machinery. Therefore, in this paper we have presented an analysis of a cam design with four circular-arc profile as a first attempt of extending previous results on two and three circular-arc cam profiles to more general cam profiles.

In this paper, the problem of a characterization of cam profiles with four circular arcs is addressed by using a suitable test-bed, that has been designed and built at LARM. The proposed analysis has been carried out with the aim to identify main characteristics of four circular-arc cams in order to determine the maximum operation speed for an optimal cam use, but also to discuss critical behaviour for practical efficient applications.

Experimental tests have been carried out by running a cam prototype at different angular velocities. Accelerations and actuation forces have been measured and compared for different operation conditions.

Circular-arc cam profiles

A circular-arc cam profile is designed as a collection of straight-lines and/or circular arcs, [6]. They can be used in low speed applications only, since the sudden change of the curvature radius at the points joining circular arcs gives negative effects as vibratory noise. Additional disadvantage is related to a limitation in the choise of an arbitrary follower displacement.

Referring to Fig. 1 the following characteristic loci of a four circular-arc cam profile can be considered: the base circle G_0 of the cam profile, which is centred in point O, with radius ρ_0=40.00 mm; the first circle G_1, with radius ρ_1=16.22 mm, second circle G_2, with radius ρ_2=22.00 mm, circle G_3, with radius ρ_3=324.12 mm, and circle G_4, with radius ρ_4=17.00 mm; and the circle G_5, with radius (ρ_0+h)=52.00 mm, which is centred on the cam rotation axis O. Lift parameter h=12.00 mm is the maximum height that is reached by the follower. By assuming a fixed frame OXY as in Fig. 1, characteristic points of cam profile can be identified as point A $(x_A; y_A)$, which is the point joining G_0 with G_1; B $(x_B; y_B)$, which is the point joining G_1 with G_2; C $(x_C; y_C)$, which is the point joining G_2 with G_3; D $(x_D; y_D)$, which is the point joining G_3 with G_4; E $(x_E; y_E)$, which is the point joining G_4 with G_5. As pointed out in the sketch of Fig. 1, the circular arc can be oriented in any direction, but the fundamental design condition is the common tangent at the joining points.

An experimental lay-out

New attention as been addressed to circular-arc cams by using descriptive viewpoint [8] and for design purposes, [9]. Kinematical and dynamical performances of circular-arc cams can be investigated by using test-beds like the one that has been built at LARM in Cassino. Studies on two and three circular-arc cams have been carried out at LARM, [10, 11]. These cams have been designed, built and tested using the same

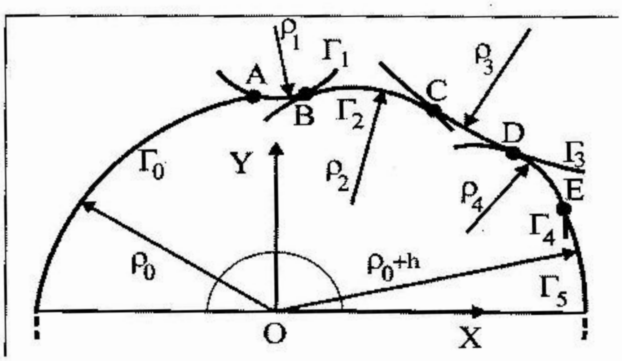


Fig. 1 A scheme of a four circular-arc cam profile characteristic loci and points.

test-bed that is shown in Fig. 2. The LARM test-bed is very cheap, its design is simple and useful for testing different kinds of cams. It is composed of commercial measuring sensors and equipment, with the aim of not to complicate the test-bed design and operation. Thus, it has been thought convenient to use LabView software [12] with NI 6024E Acquisition Card [13], to work with suitable virtual instruments which manage commercial sensors. Referring to Fig. 2a), one accelerometer S_1 [14], has been installed on the follower. In addition, dynamic properties can be experimentally evaluated by using a dynamic torsionmeter S_2 [15], which has been installed on the motor shaft. Signal conditioner and amplifiers have been used in order to provide the power supply and to reduce the noise on the output of sensors. Two different power supply sources have been used in order to provide different input voltage to sensors and motor. From a kinematic and dynamical viewpoint, the measured values can be used to characterize the cam profile through plot shape, extreme values and noise peaks, as outlined for example in [16].

Experimental analysis with laboratory tests

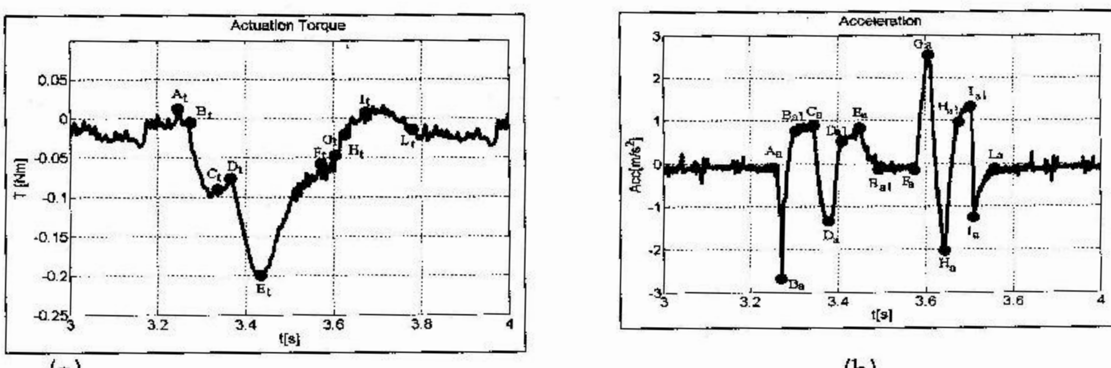
Experimental tests have been carried out on a four circular-arc cam at different cam angular velocity, which has been kept quasi-constant for each test.

(a) (b)

Fig. 2 Prototypes at LARM in Cassino: a) a low-cost easy-operation test-bed for cams at LARM in Cassino; b) a built cam used in a).

The acceleration diagram can be characterized through sudden changes, as reported in Fig. 3, by referring to the corresponding points of the cam profile for the case of study of Fig. 2b). The built prototype has been designed by combining sequentially two designs of two-circular arc rise profile. The profile for experimental tests has been designed with a shape like in the sketch of Fig. 1 in order to investigate both on concave and convex circular arcs. Table 1 shows results of experimental tests. Information about acceleration has been obtained by monitoring the follower movement. Information about actuation torque has been obtained by monitoring the cam shaft. In addition, the above-mentioned experimental results can be used for identification of profile curvature of four circular-arc cams. Results of experimental tests are reported in Figs. 3 to 7 as referring to a complete revolution of cam shaft, with the aim to show the main characteristics by using also identification of the corresponding characteristic points on the kinematic design of Fig. 1.

Plots of torque evolution and acceleration response are shown as suitable results for experimental characterization of cam operation. Referring to Fig. 3a), the actuation torque value decreases from points A_t to E_t when the follower acts against the cam rotation while in the rise of the cam profile. Similarly the torque value increases from points E_t to I_t, when the follower action helps the cam rotation while in the return portion of the profile. Points A_t, A_a and so on correspond to the profile points in Fig. 2 as referring to torque and acceleration, respectively.



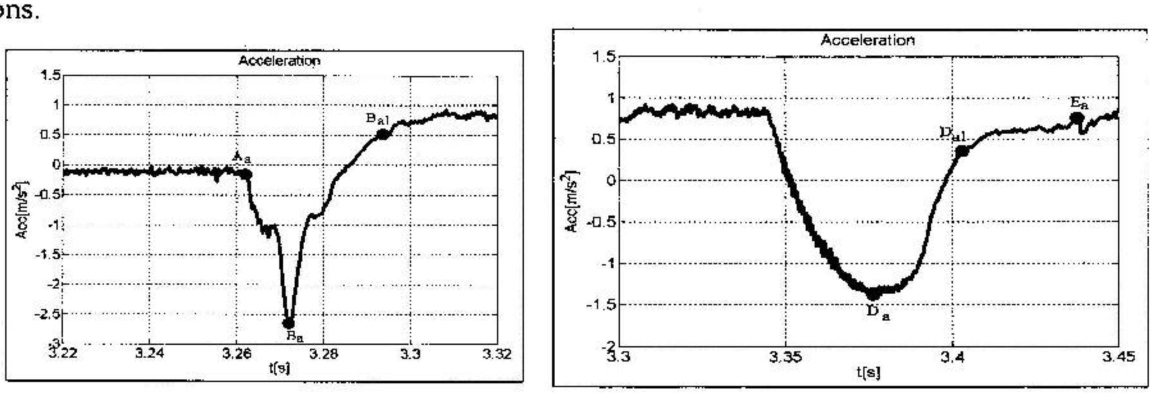
(a) (b)

Fig. 3 Experimental results for Test n° 1a in Table 1: a) actuation torque; b) follower acceleration.

Tab. 1 Operation parameters and results for laboratory tests.

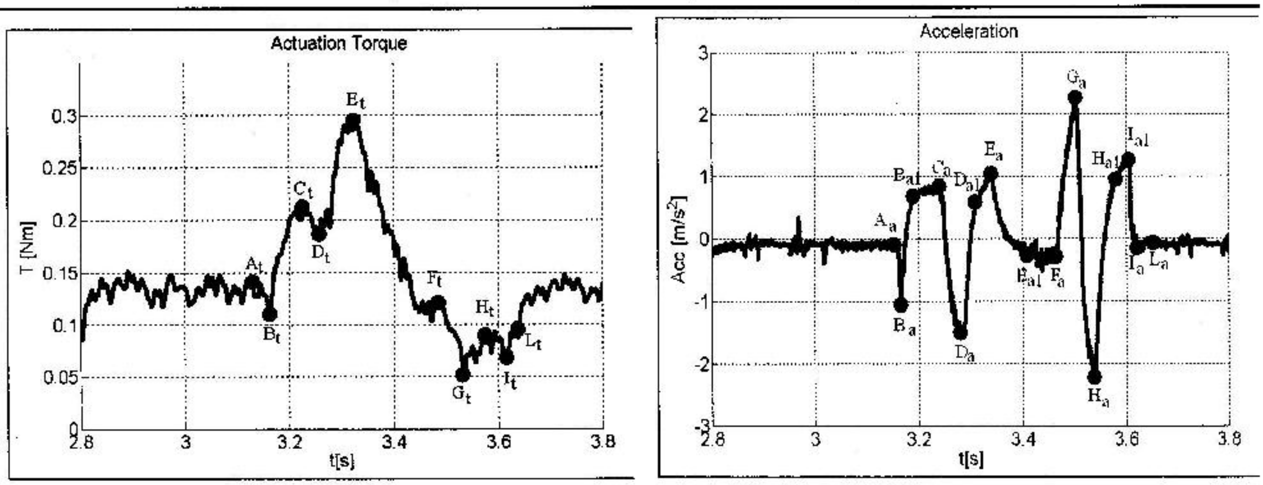
Test n°	n (rpm)	Rotation	Min a (m/s^2)	Max a (m/s^2)	Min T Nm	Max T Nm
1a	66	Counter-clockwise	-2.73	2.84	-0.21	0.03
1b	66	Clockwise	-2.11	2.37	0.01	0.30
2a	88	Counter-clockwise	-2.61	3.84	-0.18	0.02
2b	88	Clockwise	-2.98	3.63	0.03	0.29
3a	110	Counter-clockwise	-4.73	6.16	-0.17	0.01
3b	110	Clockwise	-4.12	5.94	0.08	0.27

Moreover the actuation torque values decrease when the angular velocity n increases, but the noise becomes higher because of the jumps as observable by comparing Fig. 3 with Fig. 6. Comparing Figs. 3a) and 5a) it is possible to note that the torque measured in the case of clockwise motion is less affected by vibration effects, respect to the torque measured in the case of counter-clockwise motion, since the action of inertial forces seems to have a regulariting action. From experimental viewpoint, referring to results in Figs. 3b) to 7b), it is possible to observe that at point A the acceleration has the A_a value; at profile point B the acceleration value jumps from B_a to B_{a1} because of the sudden change of the circumference radius. From point B to C the acceleration value increases again. Similarly at arc joining points C, D and E acceleration jumps are detected and the accelerations diagrams points B_{a1}, D_{a1}, E_{a1}, H_a, I_{a1} are introduced to identify the characteristic jumps. At points B, D and H the concave circumference joins with a convex circumference and the acceleration shows jumps, so that in the diagram peaks B_a-B_{a1}, D_a-D_{a1} and H_a-H_{a1} are generated whose magnitude seems to be due to the radius difference. At points E and F the circumference changes the radius value but not its convex shape and no jump is experienced or it is of minor significance. At points C, G and I the convex circumference joins a concave circumference and the jump magnitude depends on the difference of circumference radii. The value of the acceleration is quasi-constant since a dwell for the follower is obtained because of Γ_5 centred in O. From kinematic viewpoint the acceleration diagram should be symmetric with respect to the middle point between E and F. But it is not symmetric because when the follower moves along points A to E the spring pushes the follower on the cam by acting with an additional opposite force. Thus, along points F to L the absolute value of the acceleration is higher than the one in the AE arc because the spring pushes back the follower, also the diagram jumps are higher respect the jumps measured along points A to E. The acceleration jumps can be better characterized by looking the zoomed views like, for example, in Fig. 4, for the first and second jumps which show common characteristics with other jumps. From a theoretical viewpoint the jumps B_a-B_{a1} in Fig. 4a) and D_a-D_{a1} in Fig. 4b) should be immediate, but since the real behaviour of the system, mainly due to friction and inertia, they last some times. Consequently acceleration jumps propagate their affects and strongly worsen the cam behaviour, by producing large vibratory effects and limiting its possible practical smooth applications.



(a) (b)

Fig. 4 Zoomed views for acceleration jumps in Fig.3: a) from point B_a to B_{a1}; b) from point D_a to D_{a1}.



(a) (b)

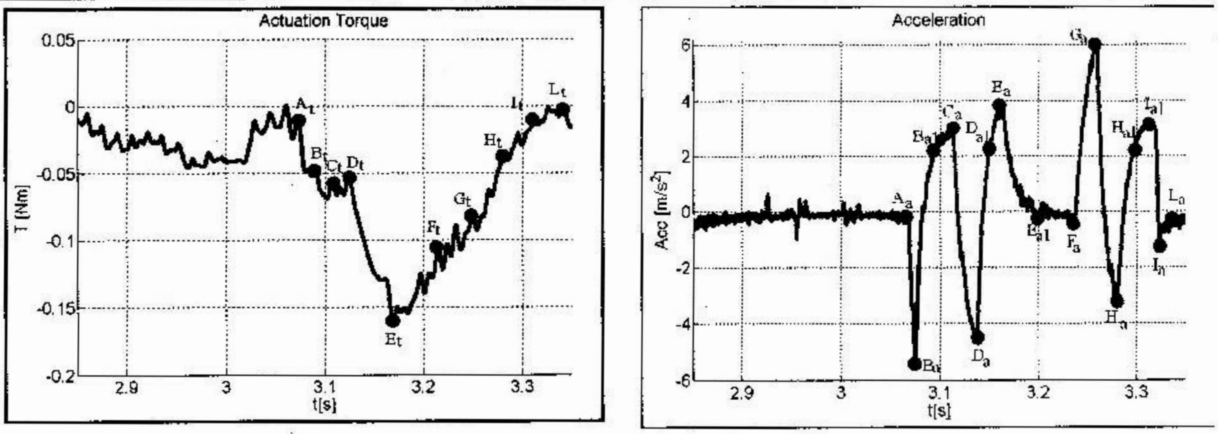
Fig. 5 Experimental results for Test n° 1b in Table 1: a) actuation torque; b) follower acceleration.

Cusps are the causes for jumps, and their shapes and size that can be affected by possible construction errors, will further increase negative effects.

Figures 6 and 7 of Tests 3a and 3b show that inertial forces and higher velocity produce larger noise and vibration. The acceleration measured during the dwell is not constant but has a linear increment from point L_a to A_a, because the input velocity is not constant during the real behaviour of the system, although flywheel has been installed.

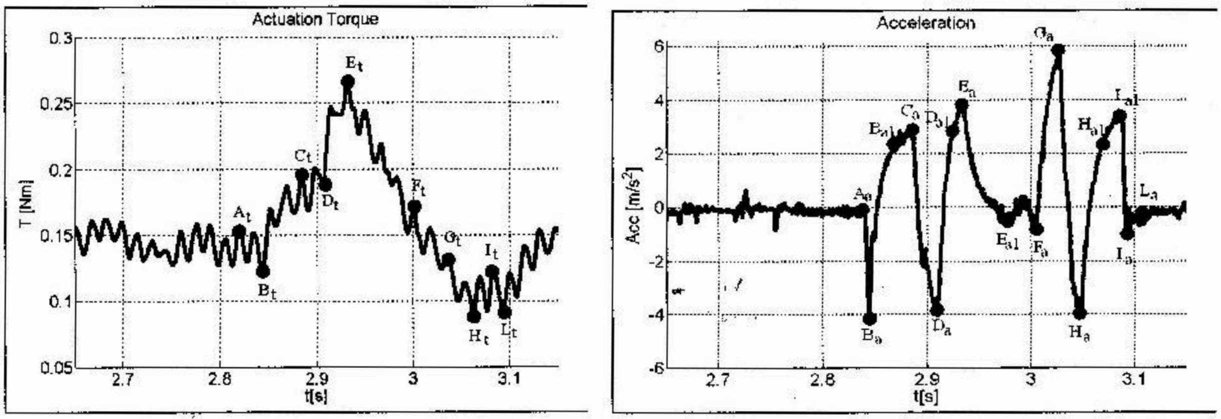
When tests are operated at 66 rpm, the acceleration diagram is quasi-constant along dwell correspond to the base circle Γ_0. For tests at 88 rpm or more, acceleration increases from L_a to A_a since the effect of non-constant input velocity seems to be more influent on real behaviour too. Then from points E_a to F_a the acceleration should be constant because of the constant radius, but the measured acceleration decreases and is affected by vibration due to previous jumps. Even if experimental measurements are carried out by using a suitable flywheel, the actuation torque is non-constant and acceleration plot shows irregularities even during the dwell arc. This is due to jumps occurring at arc joining points, but noise and alteration in acceleration and torque is also due to variations of cam profile surface as roughness, small hole defects, friction, and tolerances of the mechanical system.

From the analysis, if the jumps would be instantaneous the diagram could be approximate to a continuous one as shown in Fig. 8, by ignoring those instantaneous jumps as being controllable errors. In fact from points A_a to F_a the approximation is advisable as possible; but from points F_a to L_a the jumps affect the acceleration more strongly. When the angular velocity increases the inertial forces worsen the acceleration behaviour especially during the arc from points F to L. Therefore, the performances of the four circular-arc cams can be improved by using suitable angular velocities and small masses in order to obtain an acceleration diagram rather near to a continuous one as sketched in Fig. 8. Consequently the circular-arc cams can be used to design approximate polynomial cams, when a suitable large number of circular arcs are designed in the cam profile. In this case the cam behaviour becomes more continuous and performances could improve as suitable for practical smooth applications.



(a) (b)

Fig. 6 Experimental results for Test n° 3a in Table 1: a) actuation torque; b) follower acceleration.



(a) (b)

Fig. 7 Experimental results for Test n° 3b in Table 1: a) actuation torque; b) follower acceleration.

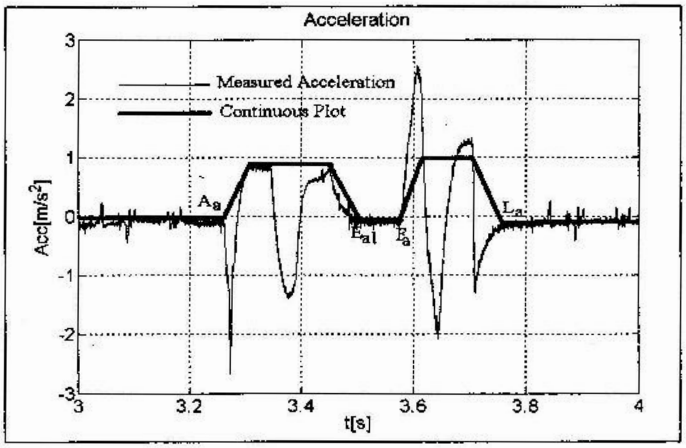


Fig. 8 A comparison between a measured acceleration and a possible continuous approximation.

Conclusions

In this paper we have attempted an experimental characterization of cam profiles with a specific reference to low-cost four circular-arc profiles. A characterization of profile performance is proposed by looking at the acceleration response of a follower, having linear-motion, when a quasi-constant velocity is imposed to the driving cam shaft. Several experimental tests are reported and discussed in order to explain the practical feasibility of the proposed experimental characterization to validate the four circular-arc design for practical applications and even to outline suitable tests for general cams. The experimental results show that the sudden change of curvature radius directly affects the acceleration response. The system behaviour shows a worsening when velocity increases and therefore cam profiles with circular arcs are proved to be of practical interests for certain ranges of speed operation only.

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