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Synthesis of Planar Mechanisms, Part II: Specified Stroke, Time Ratio and Transmission Angle

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Abstract:

Analytical synthesis of mechanisms is a useful tool towards machinery design and production. The analytical approach is useful for computer-aided design applications. Stroke , time ratio and transmission angle are important parameters in mechanism synthesis. Usually, those parameters are related nonlinearly to the planar mechanism dimensions. The paper presents an approach for the synthesis of three types of planar mechanisms fulfilling the requirements for stroke, time ratio and transmission angle. A case study is presented on each mechanism type. The synthesis is performed by deriving a set of nonlinear equations for the desired kinematical parameters of the mechanism. The MATLAB command 'fsolve' is used to solve the set of nonlinear equations and provide the optimal dimensions of the planar mechanism.

Keywords: - Planar mechanisms; kinematic synthesis; specific stroke, time ratio and transmission angle; MATLAB application.

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I. INTRODUCTION

Mechanisms represent the skeleton of machinery. Successful synthesis of mechanisms leads to a successful machine design. On the other hand classical mechanism synthesis techniques lead to mechanisms satisfying some kinematic requirements such as stroke, time ratio, specific link positions, specific function generation etc.

Mechanism synthesis techniques ranges from simple graphical techniques going through analytical approaches with many assumptions and trials to sophisticated techniques using optimization application.

some publications are reviewed over the last decade to highlight some of the efforts focused on mechanism synthesis. Simionescu and Beale (2002) studied the optimal synthesis of 5-bar suspension system used in automotives [1]. Figliolini and Angeles (2002) proposed an algorithm for the synthesis of conjugate Geneva mechanism with curved slots [2]. Lebedov (2003) developed a vector method for the analysis of guidance and transmission mechanisms applied to 4-bar mechanisms [3]. Balli and Chand (2003) studied the synthesis of a planar 7-bar mechanism with variable topology using complex number dyadic approach for motion, path and function generation [4].

Laribi and others (2004) used a combined genetic algorithm-fuzzy logic method to solve the path generation problem [5]. Sen and others (2004) presented a methodology for the synthesis of link geometry for interference free planar all revolute joints mechanisms [6]. Russel and Sodhi (2005) presented a method for the designing of slider-crank mechanisms to achieve multi-phase motion generation applications by adjustable planar 4-bar motion generators [7]. Bustos and others (2005) proposed the use of genetic algorithms with a finite-element-based error function for the synthesis of 1DOF mechanisms [8]. Wu and Chen (2005) used an adjustable link to synthesize exactly any input-output relationship using a planar 4-bar mechanism [9].

Kyung and Sacks (2006) presented a parameter synthesis algorithm for planar higher pair mechanical systems [10]. Sunkari and Schmidt (2006) used a synthesis algorithm for a planar mechanism based on McKay-type algorithm [11]. Varbanov and others (2006) studied the application of an expert system in the design of planar mechanisms [12]. Hongying and others (2007) presented a computerized method using coupler-angle function curve to approximately synthesize a 4-bar path mechanism [13]. Ding and Huang (2007) proposed 2 basic loop operations for the topological structure analysis of kinematic chains with some applications [14]. Gregorio (2007) studied the singularity analysis of 1DOF planar mechanisms by giving geometric conditions for any type of singularity [15].

Hwang and Fan (2008) used polynomial equations for the acceleration pole in the synthesis of slider-crank mechanisms [16]. Chen and Angeles (2008) introduced a family of linkages for motion generation and presented a synthesis method to one linkage visiting up to 11 poses exactly [17]. Shen and others (2008) investigated the synthesis of a 4-bar mechanism with rolling contacts for motion and function generation [18]. Litvin and others (2009) proposed a new approach for the generation of functions based on the application of multi-gear drive [19]. Pennock and Israr (2009) investigated the kinematics of an adjustable 6-bar linkage using a novel technique [20]. Du and others (2009) developed methods for robust assessment and robust mechanism synthesis when random and internal variables are involved [21].

Wei and Dai (2010) investigated the geometric and kinematic analysis of a 7-bar mechanism [22]. Parlaktas and others (2010) presented a novel method for the analysis and design of a certain type of geared 4-bar mechanism with collinear input and output shafts [23]. Huang and Zhang (2010) presented a method for robust tolerance design of function generation mechanisms with joint clearance [24]. Nie and others (2011) proposed a method to the kinematic configuration analysis of kinematic chains with R-pairs [25]. Soong and Chang (2011) proposed a technique for the exact function generation problems of 4-bar linkages using variable length driving links [26]. Tanik (2011) studied the transmission angle of compliant slider-crank mechanisms via two theorems [27].

Ding and others (2012) studied the analysis of planar 1DOF chains and created their atlas database [28]. Kim and Yoo (2012) applied a unified synthesis approach to planar 4-bar mechanisms for the purpose of function generation [29]. Lu and others (2012) used the contracted graph technique to derive topology graphs for type synthesis of closed mechanisms [30].

Hassaan, Al-Gamil and Lashin (2013) studied the optimal kinematic synthesis of a 4-bar planar mechanism for a specific stroke and time ratio. They used Powell's optimization technique and three functional constraints and an objective function comprising the mechanism stroke and time ratio [31]. Kiper, Bgdadioglu and Bilgincan (2014) studied the problem of function generation synthesis of a planar 5R mechanism used least squares approximation method. They expressed the input/output relationship of the mechanism as an objective function in polynomial form [32]. Larochelle (2015) presented a dimensional synthesis technique for solving the mixed exact and approximate motion synthesis problem for planar RR kinematic chain. His synthesis algorithm utilized only algebraic geometry without use of any optimization technique [33]. Hassaan (2015) studied the optimal synthesis of an offset planar crank-slider mechanism. He used Powell's optimization technique and two functional constraints for the minimum and maximum transmission angle of the mechanism [34].

II. METHODOLOGY

The proposed methodology is applied to three mechanisms: offset crank-slider, 4-bar and Al-Jazari quick return motion mechanisms. This approach is applied as follows:

- Modeling the mechanism by relating its performance functions: stroke, time ratio, minimum transmission angle and maximum transmission angle to the mechanism dimensions.

- Normalizing the model to decrease the unknown parameters by one.
- The model consists of a set of nonlinear algebraic equations in the dimensionless parameters of each mechanism.
- A number of equations are assigned equals the number of the unknown mechanism parameters.
- The desired values of the performance functions are defined and the model is reformulated incorporating those values.
- The assigned nonlinear equations are solved numerically or using MATLAB.
- The performance functions are checked.
- The approach is assessed by calculating the error between the desired and obtained performance functions.

III. OFFSET CRANK-SLIDER MECHANISM

The mechanism performance functions used in its synthesis are:

- Mechanism stroke, S.
- Mechanism time ratio, TR.
- Minimum and maximum transmission angles, μ_{min} and μ_{max}.

Fig.1 shows an offset crank-slider mechanism in its limiting positions.

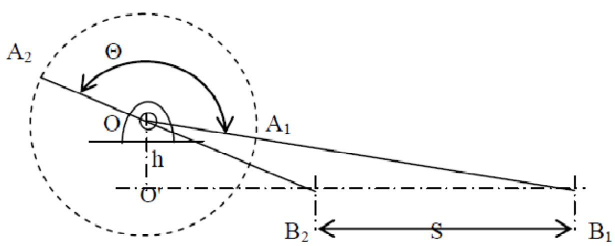

Fig.1 Offset crank-slider mechanism.

Stroke:

Let: $r_2 = OA$, $r_3 = AB$, $h = OO'$

Geometrically, the mechanism stroke, S is given by:

$$S = \sqrt{(r_3 + r_2)^2 - h^2} - \sqrt{(r_3 - r_2)^2 - h^2} \quad (1)$$

Time ratio:

Let:

ψ = angle B_1OB_2
$= \cos^{-1}\{h/(r_3+r_2)\} - \cos^{-1}\{h/(r_3-r_2)\}$

Angle, Θ: $\Theta = 180 - \psi$

Time ratio, TR:

$$TR = (360 - \Theta) / \Theta \quad (2)$$

Minimum and maximum transmission angles:

The position of the offset crank-slider mechanism in the minimum and maximum transmission angle positions is shown in Fig.2.

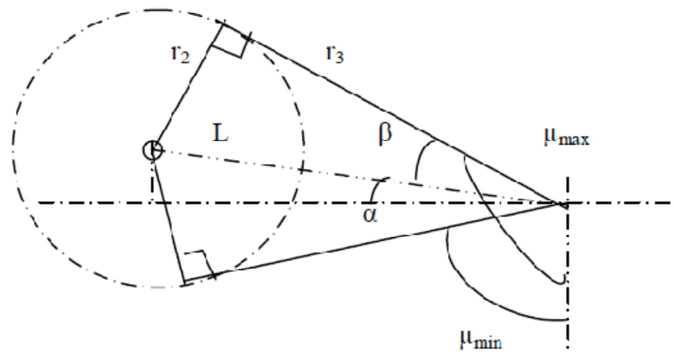

Fig.2 Minimum and maximum transmission angle of a crank-slider mechanism.

Angle β: $\beta = \tan^{-1}(r_2/r_3)$

Angle α: $\alpha = \sin^{-1}(h/L)$

where: $L = \sqrt{(r_2^2 + r_3^2)}$

Minimum transmission angle, μ_{min}:

$$\mu_{min} = 90 - (\beta - \alpha) \quad (3)$$

Maximum transmission angle, μ_{max}:

$$\mu_{max} = 90 + \beta + \alpha \quad (4)$$

The mechanism has 3 unknown dimensions: offset, h, crank length, r_2 and connecting rod length, r_3. There are 3 unknowns h, r_2 and r_3 and 4 available equations for stroke, time ratio, minimum transmission angle and maximum transmission angle. Thus, one equation has to be discarded. Here, we recommend discarding the equation of the minimum transmission angle.

Mechanism Synthesis:

- The synthesis equations are equations 1, 2, and 4.
- The equations are nonlinear in 3 unknowns: h , r_2 , r_3 .

- It is desired to design the mechanism such that the following desired values are satisfied:

Time ratio, TR: TR_d
Stroke, S: S_d
Maximum transmission angle, μ_{max}: μ_{maxd}

-The 3 equations are formulated in the form:

$$TR - TR_d = 0 \quad (5)$$
$$S - S_d = 0 \quad (6)$$
$$\mu_{max} - \mu_{maxd} = 0 \quad (7)$$

- Equations 5, 6 and 7 are solved using any nonlinear equations algorithm.
- They may be solved with MATLAB using its command '*fsolve*' [35].

Case Study 1:

It is required to synthesize an offset crank-slider mechanism in which the desired time ratio is 1.1, the stroke is 230 mm and the maximum transmission angle is 110°.

Equations 5,6 and 7 are solved using MATLAB. The results are:

$h = 104.58$, $r_2 = 111.01$
and $r_3 = 416.79$ mm

With those mechanism parameters, the mechanism performance parameters are calculated as:

- Time ratio: 1.1
- Stroke: 230 mm
- Minimum transmission angle: 101.4 degrees
- Maximum transmission angle: 110.0 degrees

IV. CRANK-ROCKER FOUR BAR MECHANISM

A crank-rocker 4-bar mechanism is shown in Fig.3 drawn in its two limiting positions.

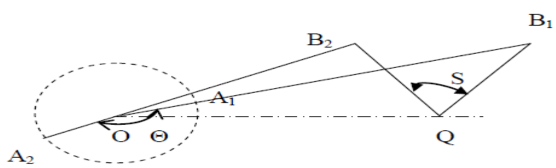

Fig.3 Crank-rocker 4-bar mechanism in its limiting positions.

Requirements: Mechanism dimensions such that the mechanism has:

- A desired stroke, S_d.
- A desired time ratio, TR_d.
- A desired maximum transmission angle, μ_{maxd}.

The mathematical models are derived in a normalized form.

Mechanism dimensions: $r_1 = OQ$, $r_2 = OA$, $r_3 = AB$, $r_4 = QB$.

Normalized parameters:

- The reference is the crank length: r_2 .
- The normalized parameters are:

$$r_{1n} = r_1/r_2 \ , \ r_{3n} = r_3/r_2 \ , \ r_{4n} = r_4/r_2.$$

In triangles: OQB_1 (first limiting position) and OQB_2 (second limiting position) [see Fig.4]:

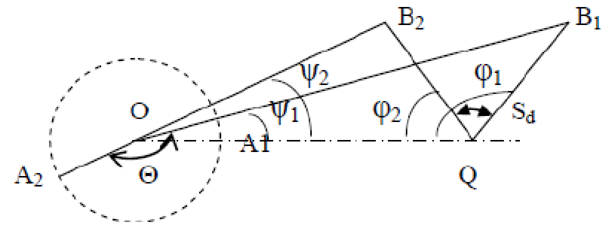

Fig.4 Stroke and time ratio of a 4-bar mechanism.

$$\varphi_1 = \cos^{-1} \{[r_1^2 + r_4^2 - (r_3+r_2)^2]/(2r_1r_4)\}$$
$$\varphi_2 = \cos^{-1} \{[r_1^2 + r_4^2 - (r_3-r_2)^2]/(2r_1r_4)\}$$
$$\psi_1 = \cos^{-1} \{[r_1^2 + (r_3+r_2)^2 - r_4^2]/[2r_1(r_3+r_2)]\}$$

and

$$\psi_2 = \cos^{-1} \{[r_1^2 + (r_3-r_2)^2 - r_4^2]/[2r_1(r_3-r_2)]\}$$

Using the normalized parameters r_{1n}, r_{3n} and r_{4n} :

$$\varphi_1 = \cos^{-1} \{[r_{1n}^2 + r_{4n}^2 - (r_{3n}+1)^2]/(2r_{1n}r_{4n})\}$$
$$\varphi_2 = \cos^{-1} \{[r_{1n}^2 + r_{4n}^2 - (r_{3n}-1)^2]/(2r_{1n}r_{4n})\}$$
$$\psi_1 = \cos^{-1} \{[r_{1n}^2 + (r_{3n}+1)^2 - r_{4n}^2]/[2r_{1n}(r_{3n}+1)]\}$$

and

$$\psi_2 = \cos^{-1} \{[r_{1n}^2 + (r_{3n}-1)^2 - r_{4n}^2]/[2r_{1n}(r_{3n}-1)]\}$$

Stroke, S:

$$S = \varphi_1 - \varphi_2 \quad (8)$$

Time ratio, TR:

- Angle, ψ: $\psi = \psi_2 - \psi_1$
- Angle, Θ: $\Theta = \pi - \psi$
- Time ratio:

$$TR = (2\pi - \Theta) / \Theta \quad (9)$$

Maximum transmission angle, μ_{max}:

$$\mu_{max} = \cos^{-1}\{(r_{3n}^2 + r_{4n}^2 - (r_{1n} - 1)^2) / (2r_{3n}r_{4n})\} \quad (10)$$

Mechanism unknown dimensions:

1. Ground, r_{1n}.
2. Coupler, r_{3n}.
3. Rocker, r_{4n}.

Unknowns and available equations:

- There are 3 unknowns: r_{1n}, r_{3n}, r_{4n}.
- There 3 equations (Eqs. 8 & 9, 10).

Mechanism Design:

- The design equations are equations 8, 9 and 10.
- The equations are nonlinear in the unknown dimensions r_{1n}, r_{3n} and r_{4n}.
- It is desired to design the mechanism such that the desired values S_d, TR_d and μ_{maxd} are satisfied:
- The 3 equations 5, 6 and 7 have to be solved for r_{1n}, r_{3n} and r_{4n}.
- Eqs.5 , 6 and 7 (with Eqs.8, 9 and 10 for S, TR and μ_{max}) may be solved with MATLAB using its command "*fsolve*" [35].

Case Study 2:

It is required to design a crank-rocker 4-bar mechanism in which the desired time ratio is 1.25, the desired stroke is 40^o , the desired maximum transmission angle is 80^o and the rocker link has a 200 mm length .

Equations 5,6 and 7 are solved using MATLAB. The results are:

$r_1 = 202.896$, $r_2 = 96.678$, $r_3 = 110.580$ and $r_4 = 200$ mm

With those mechanism parameters, the mechanism performance parameters are calculated as:

- Time ratio: 1.22
- Stroke: 58 degrees
- Minimum transmission angle: 59.7 degrees
- Maximum transmission angle: 100 degrees

V. AL-JAZARI CRANK-SLIDER QUICK RETURN MOTION MECHANISM

Mechanism:

Fig.5 shows Al-Jazari crank-slider quick return motion mechanism [36].

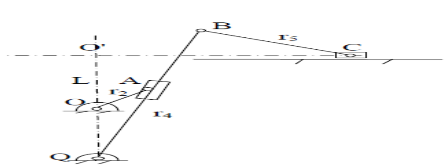

Fig.5 Al-Jazari quick return motion mechanism.

Analysis:

A dimensionless analysis is applied.

- The mechanism performance functions are: Stroke, time ratio, minimum transmission angle and maximum transmission angle.
- The limiting positions of the mechanism are shown in Fig. 6:

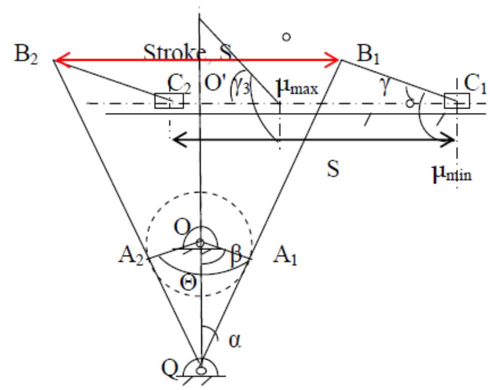

Fig.6 Kinematic parameters of the quick-return motion mechanism.

- Time ratio, TR:

Let: $r_1 = OQ$, $r_2 = OA$, $r_4 = QB$, $r_5 = BC$, $L = OO'$

Angle β: $\beta = \cos^{-1}(r_2/r_1)$

Normalize all the dimensions by dividing by r_2.

β becomes: $\beta = \cos^{-1}(1/r_{1n})$

Crank angle, Θ: $\Theta = 2\beta$

Time ratio:

$$TR = (360 - \Theta)/\Theta \qquad (11)$$

- Stroke, S:

Angle, α: $\alpha = 90 - \beta$ degrees

Stroke, S: $S = 2r_4 \sin\alpha$

Normalized stroke, S_n:

$$S_n = S/r_2 = 2r_{4n} \sin\alpha \qquad (12)$$

- Minimum transmission anglem μ_{min}:

Occurs at the limiting positions (see figure).

μ_{min}:

$$\mu_{min} = 90 + \gamma \text{ degrees} \qquad (13)$$

Angle γ: $\gamma = \sin^{-1}\{(r_4/r_5)\cos\alpha - (L+r_1)/r_5\}$

Normalizing r_4 and r_5:

$$\gamma = \sin^{-1}\{(r_{4n}/r_{5n})\cos\alpha - (L_n+r_{1n})/r_{5n}\}$$

- Maximum transmission anglem μ_{max}:

Occurs when lever QB is in the vertical position (see figure).

μ_{max}:

$$\mu_{max} = 90 + \gamma_3 \text{ degrees} \qquad (14)$$

Angle γ_3: $\gamma_3 = \sin^{-1}\{(r_4 - r_1 - L)/r_5\}$

Normalizing r_1, r_4 , r_5 and L:

$$\gamma_3 = \sin^{-1}\{(r_{4n} - r_{1n} - L_n)/r_{5n}\}$$

Mechanism Design:

- The design equations are equations 11 - 14.
- The equations are nonlinear in 4 unknowns: r_{1n} , r_{4n} , r_{5n} and L_n.
- It is desired to design the mechanism such that the following desired values are satisfied: S_d, TR_d, μ_{min} and μ_{max}.
- The 4 equations are written in the form :

$$\mu_{min} - \mu_{mind} = 0 \qquad (15)$$

- Eqs. 5,6,7 and 15 are nonlinear and have to be solved using any nonlinear equations solution algorithm.
- They may be solved with MATLAB using its command "*fsolve*" [35].

Case Study 3:

It is required to design an Al-Jazari crank-slider quick return motion mechanism in which the time ratio is 1.5, the normalized stroke is 3, the minimum transmission angle is 80^o and the maximum transmission angle is 100^o.

Equations 5,6 , 7 and 15 are solved using MATLAB. The results are:

- Mechanism normalized dimensions:

OQ_n = 3.2361 , QB_n = 4.8541
BC_n = 0.6841 , QO'_n = 1.4992

- For a crank length of 100 mm:

OQ = 323.60 , QB = 485.41
BC = 68.41 , OO' = 149.92 mm

- Mechanism performance parameters:

Time ratio: 1.5
Normalized stroke: 3.0
Minimum transmission angle: 80.1 degrees
Maximum transmission angle: 100 degrees

VI. CONCLUSIONS

The proposed approach has given very good results for the offset crank slider and Al-Jazari quick return motion mechanisms. There was no error in the application of the proposed approach to the offset crank slider mechanism. All the desired parameters were exactly obtained. The main conclusions of the research work presented in the paper is as follows:

(1) The error in the application of the proposed approach to the 4-bar crank rocker mechanism was:
  - -2.4 % error in the time ratio.
  - 45 % error in the stroke.
  - 25 % in the maximum transmission angle.

(2) The obtained minimum transmission angles were within the recommended range of $45^o \leq \mu \leq 135^o$ [37].

(3) It was possible to reduce the error in the stroke and time ratio to zero but without any guarantee to get transmission angle within the recommended range.

(4) The author tried to shift the origin O in Fig.3 above the horizontal level OQ , but the solution algorithm returned this shift back to zero.

(5) This problem may be revealed by using adjustable link 4-bar configuration [9,38] which requires more investigation.

(6) The error in the application of the proposed approach to Al-Jazari quick return motion mechanism is:
  - zero error in the time ratio, stroke and maximum transmission angle.
  - 0.125 % error in the minimum transmission angle.

(7) The proposed approach did not depend on any optimization algorithms but simply on solving a set of nonlinear equations.

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- Author of books on Experimental Systems Control, Experimental Vibrations and Evolution of Mechanical Engineering.
- Chief Justice of IJCT.
- Reviewer of some international journals.