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Research Article

Complete Shaking force and Shaking moment Balancing of 3 Types of Four-bar Linkages

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Abstract

This paper presents a method for complete shaking force and shaking moment balancing of 3 types of four-bar linkages only with revolute pairs due to rotary inertia but without external loads. The method is a combination of mass redistribution and addition of two kinds of inertia counterweights, which are the geared inertia counterweights and the planetary-gear-train inertia counterweight. The design equations for complete force and moment balancing of crank-rocker and double crank mechanisms are given. The method is illustrated by a numerical example and results produced are better than that of GaoFeng's method.

Keywords: *Shaking force, shaking moment, four-bar mechanism*

1. Introduction

Shaking force and shaking moment balancing of planar mechanisms has been a challenging problemfor the mechanism and machine designers for the past five decades. The method of linearly independent mass vectors (Berkof R.S *et al*, 1969) has been the most efficient method for shaking force balancing of four- and six-bar planar mechanisms with revolute pairs. The authors (V.H.Arakelianetal, 1999; Gao Feng1990; Gao Feng1989, GaoFeng 1991) used planetary gears to balance shaking moment generated by links not directly connected to the frame. Berkof (1973) presented design equations and techniques, which allow an in-line four-bar linkage to be completely force and moment balanced, regardless of any variation of input angular velocity. The effect of such complete force and moment balancing on the input torque and the moment ground bearing forces was examined.

Though no inertia loads are transmitted to the surroundings it will cost a larger motor to supply the increased input torque, shorter life due to greater bearing forces, and the extra counterweight masses. Esat and Bahai (1999) demonstrated that the complete force balancing of planar linkages is possible using simple counterweights. Sherwood and Hokey (1969) presented the optimization of mass distribution in mechanisms using the concept of equimomental system. The method of principal vectors by Shchepetilnikov (1968) described the position of the mass center by a series of vectors that are directed along the links. These vectors trace the mass center of the mechanism at hand, and the conditions are derived to make the system mass center stationary. Tricamo and Lowen (1983) completely balanced shaking moment by inertia counterweight. Arakelian and Dahan (2001) presented a solution of the shaking force and shaking moment balancing of planar and spatial linkages.the conditions for balancing are formulated by the minimization of the root-mean-square value of the shaking moment. There are two cases considered: mechanism with the input link by constant angular velocity and mechanism with the input link by variable angular velocity. The method is realized by displacement of the axis of rotation of the input link connected with the counterweight. Kamenskii (1968) proved that complete moment balancing is also possible by a cam-actuated oscillating counterweight. Kochev(1990) developed a theory of optimal driving of symmetrical linkages. This theory is applicable if the specific requirements on the designed mechanism are geometrical in nature. In Kochev (1992) method dummy links like gears, pistons and dyads etc. are introduced to counter balance the shaking moments generated by the original linkage. Additional price is the complexity added to the original kinematic chain. Basically the method provides complete shaking moment balancing for any linkage, but attempts for generalization lead to unrealistic schemes. Ettefagh *et al* (2011) described the application of Genetic algorithm for force and moment balancing of crank-slider mechanism. This technique permits competing design objectives to be considered through the investigation of trade-offs between those objectives. The objective functions of the design parameters are determined and their values are minimized by adjusting the independent variables of the design and **the** limitation of design. The technique permits both partial force and moment balancing to be accomplished simultaneously while the desired constraints are satisfied. The forces are minimized with regard to the constraints of

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moments using genetic algorithm. One of the properties of genetic algorithm is binary genetic algorithm that uses the chromosomes as binary codes. Therefore binary genetic algorithm is selected to have good trade-off between the answers accuracy and convergence speed. Briot *et al* (2012) developed an innovative solution which is based on the optimal control of the robot links center of masses. Such a solution allows the reduction of the acceleration of the total mass center of many moving links and, consequently the considerable reduction in the shaking forces. The shaking force reduction reached up to 77%. Van der wijk *et al* (2012) aimed at low-mass and low-inertia dynamic balancing. The evaluation of a balanced rotatable link is found to be representative for a large group of balanced mechanisms. A rotatable link is balanced with duplicate mechanisms, with a counter mass and a separate counter rotation and with a counter-rotary counter mass. The equations for the total mass and the inertia are derived and compared analytically while the balancing principles are compared numerically. The results showed that the duplicate mechanism balanced link is the best compromise for low-mass and low-inertia but requires a considerable space. For the counter rotary counter mass balanced link and the separate counter rotation balanced link that are more compact, there is a trade-off between mass and inertia for which the counter-rotary counter mass-balanced link is the better of the two.

In the present work the planetary geared inertia counterweights mounted on the links not directly connected to the frame in earlier methods (V.H.Arakelianetal, 1999; Gao Feng1990; Gao Feng1989, GaoFeng 1991) are mounted on the base of the mechanism. The better results are produced than that of GaoFeng method. The paper is organized as follows: section 1 deals with introduction, section 2 presents articulation dyad. Dynamic balancing of four-bar linkage is presented in section 3.Numerical example and results are discussed in section 4.Conclusions and future scopes are given in section 5.

2. Articulation dyad

2.1 Complete shaking force and shaking moment balancing of an articulation dyad

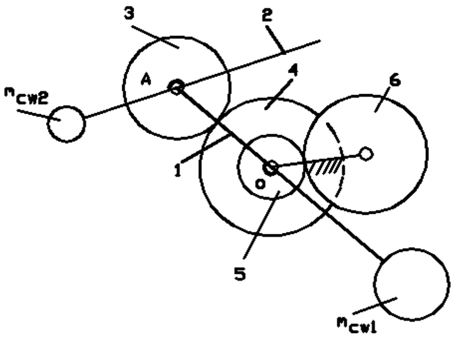

Fig.1 Complete shaking force and shaking moment balancing of an articulation dyad

An open kinematic chain of two binary links and one joint is called a dyad. When two links are articulated by a joint so that movement is possible that arrangement of links is known as articulation dyad.

The scheme of complete shaking force and shaking moment balancing of an articulation dyad (V.H.Arakelian *et al*, 1999; Gao Feng1990; Gao Feng1989, Gao Feng 1991) is shown in Fig.1.

To link 2 is added a counterweight which permits the displacement of the center of mass of link 2 to joint A. then, by means of a counter weight with mass m_{cw_1} [Fig.1] a complete balancing of shaking force is achieved. A complete shaking moment balance is realized through four gear inertia counter weights 3-6, one of them being of the planetary type and mounted on link 2.

2.2 Complete shaking force and shaking moment balancing of an articulation dyadby gear inertia counterweights mounted on the base

The scheme used in the present work [Fig.2] is distinguished from the earlier scheme by the fact that gear 3 is mounted on the base and is linked kinematically with link 2 through link $1'$.

To prove the advantages of such a balancing, the application of the new system with the mass of link $1'$ not taken into account is considered. In this case (compared to the usual method Fig.1), the mass of the counter weight of link 1 will be reduced by an amount

$$\delta m_{cw_1} = m_3 l_{OA} / r_{cw_1} \quad (1)$$

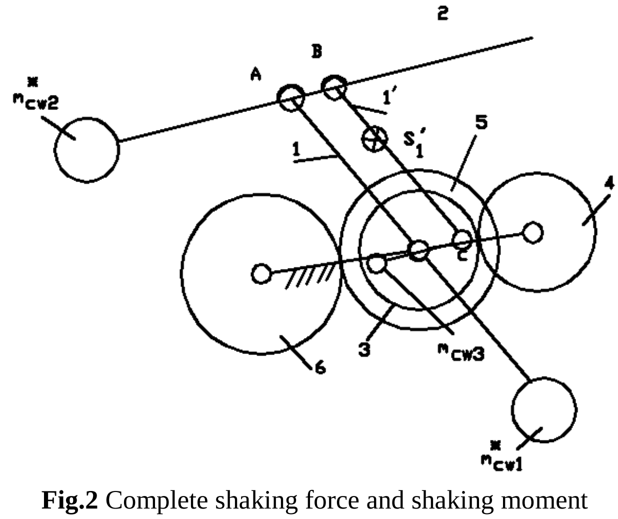

Fig.2 Complete shaking force and shaking moment balancing of an articulationdyad by gear inertia counterweights mounted on the base

Where,

m_3 is the mass of gear 3,

l_{OA} is the distance between the centers of hinges O and A,

r_{cw_1} is the rotation radius of the center of mass of the counter weight.

` It is obvious that the moment of inertia of the links is correspondingly reduced. If the gear inertias are made in the form of heavy rims in order to obtain a large moment of inertia, the moments of inertia of the gear inertia counter weights may be presented as

$I = \frac{m_i D_i^2}{4}$ (i=3… 6).

Consequently, the mass of gear 6 will be reduced by an amount

$$\delta m_6 = 4(m_3 l_{OA}^2 + \delta m_{cw_1} r_{cw_1}^2)\frac{T_6}{D_6^2 T_5} \quad (2)$$

Where,

T_5 *and* T_6 are the numbers of teeth of the corresponding gears. Thus, the total mass of the system will be reduced by an amount

$$\delta m = \delta m_{cw_1} + \delta m_6 \quad (3)$$

Here the complete shaking force and shaking moment balancing of the articulation dyad with the mass and inertia of link $1'$ taken into account is considered. For this purpose initially, statically replace mass m_1' of link $1'$ by two point masses m_B and m_c at the centers of the hinges B and C

$$m_B = m_{1'} l_{CS_{1'}} / l_{BC}$$
$$m_C = m_{1'} l_{BS_{1'}} / l_{BC} \quad (4)$$

Where,

l_{BC} is the length of link 1,

$l_{CS_{1'}}$ and $l_{BS_1'}$ are the distances between the centers of joints C and B and the center of mass S_1' of link $1'$, respectively.

After such an arrangement of masses the moment of inertia of link $1'$ will be equal to

$$I_{S_1'}^* = I_{S_1'} - m_{1'} l_{BS_1'} l_{CS_1'} \quad (5)$$

Where,

i $I_{S_1'}$ s the moment of inertia of link $1'$ about the center of mass S_1' of the link.

Thus a new dynamic model of the system is obtained, where the link $1'$ is represented by two point masses m_B, m_C and has a moment of inertia $I_{S_1'}^*$.

This fact allows for an easy determination of the parameters of the balancing elements as follows:

$$m_{CW_2} = (m_2 l_{AS_2} + m_B l_{AB}) / r_{CW_2} \quad (6)$$

Where,

m_2 is the mass of link 2

l_{AB} is the distance between the centers of the hinges A and B

l_{AS_2} is the distance of the center of hinge A from the center mass of S_2 of link 2

r_{CW_2} is the rotation radius of the center of mass of the counterweight with respect to A and

$$m_{CW_1} = [(m_2 + m_{CW_2} + m_B) l_{OA} + m_1 l_{OS_1}] / r_{CW_1} \quad (7)$$

Where,

m_1 is the mass of link 1,

l_{OS_1} is the distance of the joint center O from the center of mass S_1 of link 1.

Also, $m_{CW_3} = m_C l_{OC} / r_{CW_3}$ (8)

Where,

$l_{OC} = l_{AB}$,

r_{CW_3} is the rotation radius of the center of mass of the counterweight.

Taking into account the mass of link $1'$ brings about the correction in Eq.(3) in this case,

$$\delta m = \delta m_{CW_1} + \delta m_6 - \delta m_1' \quad (9)$$

Where,

$\delta m_1'$ is the value characterizing the change in the distribution of the masses of the system links resulting from the addition of link $1'$.

3. Dynamic Balancing of Four-bar mechanism

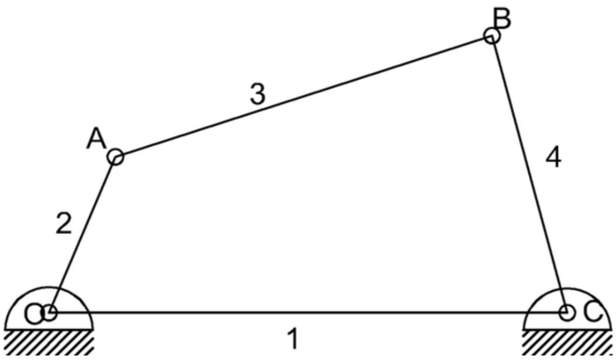

Fig.3 Four-bar mechanism

The four-bar mechanism is the simplest and the basic mechanism. It consists of four links, may be of different lengths, each link forms turning pair with the adjacent links. The applications of the four-bar mechanism are Beam engines, coupling rod of a locomotive and Watt's indicator mechanism etc. In the four-bar mechanism shown in Fig.3, link 1 is fixed link, link 2 is crank, link 3 is connecting rod, link 4 is output link, when this mechanism runs at high speeds shaking forces and shaking moments are developed ,these undesirable forces and moments are to be balanced. The balanced four-bar mechanism is shown in Fig.4. The shaking force and shaking moment balancing of four-bar mechanism is important as it helps in the design of new mechanisms, which in turn is useful to improve the performance of the mechanisms.

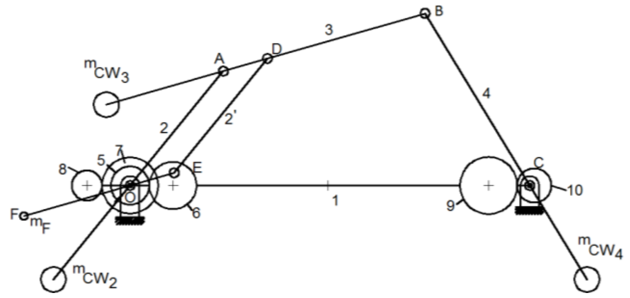

Fig.4 Balanced four-bar mechanism

3.1 Shaking force balancing of the mechanism

To balance shaking force of the four-bar mechanism, the coupler link is dynamically replaced by two point masses and then input and output links are considered. For link 3, shown in Fig.4, to be dynamically replaced by two point masses 'm_{B3}'*and* 'm_{P3}' the condition to be satisfied is$k_3^2 = l_{p_3s_3} l_{Bs_3}$; where '$l_{BS_3}$' is arbitrarily chosen and '$l_{P_3S_3}$' is obtained from the above condition.

$$m_{B3} = m_3 l_{p_3s_3} / (l_{p_3s_3} + l_{Bs_3})$$

$$m_{P3} = \text{m}_3 l_{Bs_3} / (l_{p_3s_3} + l_{Bs_3})$$

After link 3 is dynamically replaced by two point masses it is kinematically connected to its corresponding gear inertia counterweight 6 by link $2'$, moreover link is statically replaced by two point masses 'm_D' and $2'$ 'm_E'

$$m_D = m_{2'} l_{Es_2} / l_{ED}$$

$$m_E = m_{2'} l_{Ds_2} / l_{ED}$$

Counterweight against link 3 can be obtained as

$$m_{cw_3} = (m_3 l_{AS_3} + m_D l_{AD}) / r_{cw_3} \quad (10)$$

Where $r_{cw_3} = l_{p_3s_3} - l_{AS_3}$ is the radius of rotation of counterweight m_{cw_3}

Link 2 is dynamically replaced by two point masses m_{A2} and m_{P2} using the condition $k_2^2 = l_{p_2s_2} l_{AS_2}$

$$m_{A2} = m_2 l_{p_2s_2} / (l_{p_2s_2} + l_{AS_2})$$

$$m_{P2} = m_2 l_{AS_2} / (l_{p_2s_2} + l_{AS_2})$$

Counterweight against link 2 can be obtained as

$$m_{cw_2} = \frac{(m_3 + m_{cw_3} + m_D)}{r_{cw_2}} \quad (11)$$

Where $r_{cw_2} = l_{p_2s_2} - l_{AS_2}$ is the radius of rotation of counterweight m_{CW_2}

Link 4 is dynamically replaced by two point masses m_{B_4} and m_{p_4}using the condition $k_4^2 = l_{P_4S_4} l_{BS_4}$;where l_{BS_4} is arbitrarily chosen and $l_{P_4S_4}$ is obtained from the above condition

$$m_{B4} = m_4 l_{p_4S_4} / (l_{p_4S_4} + l_{BS_4})$$
$$m_{P4} = m_4 l_{BS_4} / (l_{p_4S_4} + l_{BS_4})$$

Counterweight against link 4 can be obtained as

$$m_{cw_4} = (m_4 l_{CS_4}) / r_{cw_4} \quad (12)$$

Where $r_{cw_4} = l_{p_4s_4} - l_{CS_4}$; is the radius of rotation of counterweight m_{CW_4}

Linear accelerations at points *A*, *B*, *C* are

$$A_A = ia\alpha_2 e^{i\theta_2} - a\omega_2^2 e^{i\theta_2}$$
$$A_{BA} = ib\alpha_3 e^{i\theta_3} - b\omega_3^2 e^{i\theta_3}$$
$$A_B = ic\alpha_4 e^{i\theta_4} - c\omega_4^2 e^{i\theta_4}$$

Total shaking force generated by the mechanism is given by

$$F = -(m_2(A_G)^2 + m_3(A_G)^3 + m_4(A_G)^4) \quad (13)$$

3.2 Shaking moment balancing of the mechanism

The shaking moment produced by the mechanism is balanced by geared inertia counterweights. The shaking moment generated by the linkage is balanced by gears 5 to 8. The total shaking moment generated by the mechanism is equal to the sum of shaking moments

$$M^{int} = M_2^{int} + M_4^{int} + M_3^{\text{int}} \quad (14)$$
$$M_2^{int} = (I_{S_2} + m_2 l_{OS_2}^2 + (m_D + m_{cw_3} + m_3) l_{OA}^2 + m_{cw_2} r_{cw_2}^2 + I_{S_{2'}}^* + m_{2'} l_{ES_2'}^2)\alpha_2$$

Changed mass moment of inertia $I_{S_{2'}}^* = \text{I}s_2' - m_{2'} l_{DS_2'} l_{ES_2'}$

$$M_3^{\text{int}} = 2m_E l_{OE}^2 \alpha_3$$
$$M_4^{int} = (I_{S_4} + m_4 l_{CS_4}^2 + m_{cw_4} r_{cw_4}^2)\alpha_4$$

Where

M_2^{int}, M_3^{int} M_4^{int} are the Shaking moments generated by links 2, 3 and 4 respectively
$I_{S_2}, I_{S_4}$are the mass moments of inertias of links 2 and 4 respectively
$I_{S_2}'^*$is the changed moment of inertia of links $2'$.
α_2, α_3, $\alpha_4$are the angular accelerations of links 2,3 and 4 respectively.

Table 1 Shaking force comparison of inversion-I of Four-bar mechanism

Crank angle(deg)	Shaking force generated in Proposed method 10^{11} N	Shaking force generated in GaoFeng's method 10^{11} N
0	18.5150	18.5160
30	50.2160	50.2170
60	16.7030	16.7040
90	2.2703	2.2713
120	0.0042	0.0052
150	1.0382	1.0392
180	-2.4026	-2.4032
210	3.3057	3.3067
240	4.3633	4.3644
270	-7.1841	-7.1851
300	13.1330	13.1340
330	7.1481	7.1492
360	18.5150	18.5160

Shaking force to be balanced for the mechanism in the Proposed method

$$F_{\text{Proposed}} = -(m_2 A_{G2} + m_3 A_{G3} + m_4 A_{G4} + m_2' A_{G2}')$$

Shaking moment to be balanced for the mechanism in the Proposed method

$$M_{proposed}^{\text{int}} = M_2^{\text{int}} + M_4^{\text{int}} + M_3^{\text{int}}$$

Shaking force to be balanced for the mechanism inGaoFeng's method

$$F_{Gaofeng} = -(m_2 A_{G2} + m_3 A_{G3} + m_4 A_{G4} + m_{G6} A_{G6})$$

Shaking moment to be balanced for the mechanism inGaoFeng's method

$$M_{Gaofeng}^{\text{int}} = M_2^{\text{int}} + M_4^{\text{int}} + (I_{S6} + 2m_{G6} l_{OA}^2)\alpha_2$$

4. Numerical example

4.1 Inversion I: Crank-rocker mechanism

If the shortest link is adjacent to the fixed link crank-rocker mechanism is obtained. In the mechanism shown in Fig.3, link 'AB' is fixed to obtain the crank-rocker mechanism. The four-bar mechanism has the following parameters

$$l_{OA} = 2m, l_{AB} = 7m, l_{BC} = 6m, l_{OC} = 6m, m_2 = 2.5kg, m_3 = 4kg, m_4 = 3kg,$$
$$m_2' = 2.5kg, l_{DE} = 2m, l_{ES_2}' = l_{DS_2}' = 1m, l_{AD} = 1.5m, l_{AS_3=} = l_{BS_3} = 3.5m,$$
$$l_{BS_4} = l_{CS_4} = 3m, l_{OS_2} = l_{AS_2} = 1m, k_2 = 1.506m, k_3 = 4.055m, k_4 = 3.20m,$$
$$\omega_2 = 1000 rad/s, \alpha_2 = 10 rad/s^2, \theta_2 = 30^0$$

4.1.1 Comparison between the results of shaking force and shaking moment by GaoFeng's method and the Proposed method for Inversion I

The results of shaking force of the mechanism by the Proposed and GaoFeng's methods are shown in table 1, it is observed that the shaking force by proposed method is less than that of by GaoFeng's method. At every position of crank angle shaking force generated in proposed method is less than that of GaoFeng's method. The results of shaking moment by the Proposed and GaoFeng's methods are shown in table 2. From the shaking moment results it is observed that the shaking moment by proposed method is less than that of by GaoFeng's method. At crank angle 30, 60, 90,120,240,300,330 degrees the shaking moment by GaoFeng's method is slightly less than that of by the proposed method. Shaking force in proposed method is maximum, 50.216x10^{11} N, at 30^0 and minimum, 0.0042x10^{11} N, at 120^0. Shaking force in GaoFeng's method is maximum, 50.217x10^{11} N, at 30^0 and minimum, 0.0052x10^{11} N, at 120^0. Shaking moment in proposed method is maximum, 4.8387x10^7 N-m, at 30^0 and minimum, -0.0587x10^7 N-m, at 120^0. Shaking moment in GaoFeng's method is maximum, 4.6042x10^7 N-m, at 30^0 and minimum, -0.0416x10^7 N-m, at 120^0.

Shaking force in proposed method suddenly decreases from 30^0 to 120^0, and slightly increases at 150^0, and comes down to negative value at 180^0,again slightly increases from 210^0 to 240^0,again reaches negative value at 270^0, and gradually decreases from 300^0 to 330^0 of crank angle. Shaking moment in proposed method gradually decreases from 30^0 to 90^0, and gradually increases (negative value) gradually from 120^0 to 300^0, slightly decreases (negative) at 330^0, and suddenly reaches positive value at 360^0 of crank angle.

4.2 Inversion II: Crank-rocker mechanism

If the shortest link is adjacent to the fixed link, Crank-rocker mechanism is obtained. In the four-bar mechanism shown in Fig.3 link 'OC' is fixed to obtain the crank-rocker mechanism. The mechanism has the following dimensions: $l_{OA} = 2m, l_{AB} = 6m, l_{BC} = 6m, l_{OC} = 7m,$

4.2.1 Comparison between the results of shaking force and shaking moment by GaoFeng's method and the Proposed method for Inversion II

The results of shaking force generated for the crank rocker mechanism are shown in table 3. From the results of the

Table 2 Shaking moment comparison of inversion-I of Four-bar mechanism

Crank angle(deg)	Shaking moment generated in Proposed method 10^7 N-m	Shaking moment generated in GaoFeng's method 10^7 N-m
0	2.7630	2.7899
30	4.8387	4.6042
60	2.8452	2.6533
90	1.1065	0.9768
120	-0.0587	-0.0416
150	-0.6042	-0.6879
180	-1.0243	-1.0899
210	-1.2994	-1.3265
240	-1.5908	-1.5528
270	-2.1125	-1.9722
300	-2.8440	-2.5587
330	-2.1358	-1.7853
360	2.7630	2.7899

Table 3 Shaking force comparison of inversion-II of Four-bar mechanism

Crank angle(deg)	Shaking force generated in Proposed method 1011 N	Shaking force generated in GaoFeng's method 1011 N
0	5.3901	5.3912
30	28.0850	28.0860
60	16.1350	16.1360
90	3.4207	3.4218
120	0.0313	0.0324
150	0.8990	0.9001
180	2.2865	2.2875
210	2.5892	2.5902
240	2.5519	2.5530
270	3.2691	3.2701
300	4.9892	4.9902
330	2.6579	2.6589
360	5.3901	5.3912

two methods it can be observed that the shaking force by the proposed method is less than that of by GaoFeng's method. The improved results are obtained by the proposed method over GaoFeng's method at every position of the crank angle. The results of shaking moment generated by the mechanism by two methods are shown in table 4. From table 4 it can be observed that the shaking moment by proposed method is less than that of by GaoFeng's method. The shaking moment generated by the mechanism by proposed method is slightly more at crank angles 30, 60,120,240,300,330 degrees than that of GaoFeng's method. The shaking force in the proposed method suddenly decreases from 30^0 to 120^0, and gradually increases from 150^0 to 180^0, and it almost remains constant at 240^0, and gradually increases from 270^0 to 300^0 of crank angle. The shaking moment in proposed method gradually decreases (positive) from 30^0 to 120^0, and gradually increases (negative) from 150^0 to 300^0, and slightly comes (negative) down at 330^0, and reaches positive value at 360^0 of crank angle.

4.3 III Inversion: Drag-link or Double crank mechanism

By fixing the shortest link as the frame, drag-link or double crank mechanism is obtained. In the four-bar mechanism shown in Fig.3 by fixing link 'OA' the drag-link mechanism is obtained. The four-bar mechanism has the following parameters:

$$l_{OA} = 7m, l_{AB} = 6m, l_{BC} = 6m, l_{OC} = 2m.$$

4.3.1 Comparison between the results of shaking force and shaking moment by Proposed and GaoFeng's method for Inversion III

The results of shaking force generated in the mechanism for inversion III are shown in table 5.The results in the table show that the shaking force by proposed method is less than that of by GaoFeng's method. At 30,60,90,120,150,180,210,240,270,300,330 degrees of the crank angle the shaking force generated in the mechanism by proposed method is less than that of GaoFeng's method. The shaking force in proposed method is maximum, $28.295x10^{11}$ N, at 330^0, and minimum, $0.0008x10^{11}$ N, at 240^0 of crank angle. The results of shaking moment generated by the mechanism are shown in table in 6. The shaking moment in proposed method is maximum, $3.6072x10^7$ N-m, at 330^0, and minimum, $0.2491x10^7$ N-m, at 240^0 of crank angle. While comparing the shaking moment values it can be observed that the shaking moment by proposed method is less than that of by GaoFeng's method at 0, 150, 210 degrees. The shaking

Table 4 Shaking moment comparison of inversion-II of Four-bar mechanism

Crank angle(deg)	Shaking moment generated in Proposed method 10^7 N-m	Shaking moment generated in GaoFeng's method 10^7 N-m
0	1.4326	1.5776
30	3.6071	3.4993
60	2.8096	2.6490
90	1.3801	1.2419
120	0.2491	0.1242
150	-0.5804	-0.7038
180	-1.0937	-1.2034
210	-1.2885	-1.3524
240	-1.3810	-1.3692
270	-1.6281	-1.5139
300	-2.0016	-1.7586
330	-1.5039	-1.1830
360	1.4326	1.5776

Table 5 Shaking force comparison of inversion-III of Four-bar mechanism

Crank angle(deg)	Shaking force generated in Proposed method 10^{11} N	Shaking force generated in GaoFeng's method 10^{11} N
0	5.3912	5.3949
30	1.2898	1.2935
60	2.2145	2.2182
90	4.3847	4.3884
120	4.4585	4.4622
150	3.9996	4.0033
180	2.2865	2.2902
210	0.3941	0.3978
240	0.0008	0.0040
270	1.3412	1.3449
300	11.8800	11.8830
330	28.2950	28.2990
360	5.3912	5.3949

Table 6 Shaking moment comparison of inversion-III of Four-bar mechanism

Crank angle(deg)	Shaking moment generated in Proposed method 10^7 N- m	Shaking moment generated in GaoFeng's method 10^7N-m
0	1.4328	1.5777
30	-1.5037	-1.1829
60	-2.0015	-1.7585
90	-1.6280	-1.5138
120	-1.3810	-1.3691
150	-1.2884	-1.3524
180	-1.0936	-1.2034
210	-0.5804	-0.7037
240	0.2491	0.1245
270	1.3801	1.2420
300	2.8096	2.6491
330	3.6072	3.4994
360	1.4328	1.5777

moment by proposed method at other crank angular positions is slightly more than that of GaoFeng's method.

When the shaking forces and shaking moments generated by the inversions of four-bar mechanism are compared both by Proposed and GaoFeng's methods, it is observed that for inversion I both shaking forces and shaking moments are less by proposed method. At very few angular positions of the crank shaking moment by proposed method is slightly more than that of by GaoFeng's method. For inversion II, it can be observed that shaking forces and shaking moments are less by proposed method, at very few angular positions of the crank shaking moment is slightly more than that of GaoFeng's method. For inversion III, i.e., double crank mechanism, shaking forces by proposed method are less at all angular positions of the crank, where as shaking moments are slightly more than that of by GaoFeng's method.

When the shaking forces and shaking moments of three inversions are compared it is observed that proposed method has produced less shaking forces and shaking moments. Comparison of shaking forces and shaking moments of three inversions of four-bar mechanism proves that the proposed method has produced improved results over GaoFeng's method. For the three inversions of four-bar linkage shaking forces and shaking moments are determined by proposed and GaoFeng's method.

For crank-rocker mechanism shaking force is maximum, 50.2160x1011N, at 30^0 and minimum, $0.0042x10^{11}$ N, at 120^0 by proposed method. Shaking force gradually decreases from $50.2160x10^{11}$ at 30^0 to -$2.4020x10^{11}$at 180^0 and again gradually increases to $18.5150x10^{11}$ at 360 degrees. The shaking moment is maximum, $4.8387x10^7$ N-m, at 30^0 and minimum, $0.0587x10^7$ N-m, at 120^0. From minimum value shaking moment gradually increases to maximum at 360^0.

In drag link or double rocker mechanism shaking force is maximum,$28.2950x10^{11}$ N, at 330^0 and minimum,$0.0008x10^{11}$ N, at 240^0.Shaking force gradually increases from 30 to 120 degrees and from 180^0 gradually decreases to minimum at 240^0.Shaking moment in drag link mechanism is maximum,$3.6072x10^7$ N-m, at 330^0 and minimum, $0.5804x10^7$ N-m, at 210^0. Shaking moment of drag link mechanism gradually decreases from 60^0 to 240^0 .From the shaking forces and shaking moments of three inversions of four-bar linkage it can be concluded that improved results are produced by proposed method over GaoFeng's method.

Conclusions

Shaking force is balanced by method of redistribution of mass and shaking moment by geared inertia counterweights. In the three types of Four-bar mechanisms the results produced by the proposed method are better than that of the previous method. All the geared inertia counterweights required for balancing the shaking moment are mounted on the frame of the mechanism, which is constructively more efficient and makes the balanced mechanism compact.

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