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Kinematic analysis of beat-up mechanism used for handmade carpet looms

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Kinematic analysis and dimensional synthesis of a beat-up mechanism used for handmade carpet looms have been studied. The design criteria of the beat-up mechanism has been established according to the problem statement, followed by the selection of a crank-rocker type four-link mechanism for the beat-up mechanism to obtain many crank-rocker type mechanisms using dimensional synthesis method. On the basis of the design criteria, the most suitable beat-up mechanism is chosen and the dynamic analysis of the selected mechanism is performed. In the dimensional synthesis, the case studies have been done for four different crank rotation angles and the most proper dimensions according to design criteria are obtained at $\phi = 180°$. In the dynamic analysis of the mechanism, it is determined that the beat-up force of the mechanism is over 60 N. By designing such a suitable beat-up mechanism for handmade carpet looms, the weaver gets less tired, the handmade carpet production is increased and the faults caused by this process are decreased.

Keywords: Beat-up mechanism, Handmade carpet, Kinematic analysis, Loom

1 Introduction

The history of the carpet, as evaluated in the pile weaving group, is very old. It has been woven in different regions of Anatolia and Asia for thousands of years. People used to produce carpets on looms made of wood for a very long time. By means of the technological developments, the weaving processes were completely performed by machines[1,2]. As the use of machine for carpet manufacturing became widespread, the carpet weaving on handlooms decreased. The weaving machines then succeeded the handlooms. Now, most of the carpet manufacturing is performed on weaving machines and handmade woven carpets have a little proportion on whole. However, the handmade carpet production has not become an extinct craft by the technological developments, it is still an expensive and much demanded decoration product. Handmade carpets have more resilience, more durability and unlimited color choice. Although the handmade carpets have superior properties than machine carpets, the production technology of them has not been changed for centuries because of complex knot shape and necessity of individual knot formation[3-6].

The weaving process in a handmade carpet includes selecting pile yarn, knotting, shedding, picking, beat-up, and cutting operations. The most important ones of them are knotting and beat-up. The weaver gets tired and too much labor is required during these operations. Beat-up process is done for inserting the formed knots and weft yarn into the carpet structure by strongly beating on them. It provides tightness and compactness to the carpet structure. A smooth pile surface is obtained as a result of this process. The force exerted on the knots and weft yarns must have same intensity along the loom width. Otherwise, the variation in the intensity of the beat-up force not only deforms the carpet structure but also decreases carpet quality. Therefore, beat-up operation is an important weaving process and it requires attention and experience. If this operation is carried out by a suitable mechanism, the handmade carpet manufacturing rate will be increased and the faults caused by this operation will be overcome. Also, the weaver will be able to produce more carpets with less labor and time by using this mechanism.

Some studies were reposed on the beat-up operation of the power loom in available literature[7-12]. However, the study about the beat-up operation of the handmade carpet looms has not been encountered. In this study, a crank-rocker type four-bar mechanism is selected for beat-up mechanism. First, the design criteria of the mechanism have been established according to problem statement. On the basis of the design criteria, the dimensional synthesis of the

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mechanism has been performed by using graph-analytical method. Then, four case studies have been performed for different crank rotation angles and the most suitable dimensions of the mechanism are determined at the angle of $\phi = 180^{\circ}$. Finally, the dynamic analysis of the selected mechanism has been performed to determine the beat-up force and the loads on the joints. The position, velocity and acceleration of the beater have also been determined in the dynamic analysis.

2 Material and Methods

2.1 Methodology

2.1.1 Problem Statement

During the handmade carpet weaving, a row of knots is formed by knotting the every pile yarn on two warp yarns. After that process, two weft yarns (one of them is straight and the other one is cross) are passed between the warp yarns and then the knots and weft yarn are inserted into the carpet structure by beating on them via an instrument called beater. The beater is an instrument (Fig. 1) that is generally made of metal and resembles a comb.

Here, the problem includes designing a beat-up mechanism that will tighten the knots and weft yarn into carpet structure. The mechanism must have one degree of freedom and a beater must be designed for output link. A crank-rocker type mechanism is selected for beat-up process of the handmade carpet looms. The warp yarns, weft yarns, knots, the position of the beat-up mechanism and the trajectory of the mechanism are presented in Fig. 1. The link DC is crank (input link) and the link AB is the rocker (output link) of the mechanism. As the crank DC performs a full rotation, the rocker AB of the mechanism makes an oscillatory motion between two dead positions. The motion of the crank DC is transmitted to the rocker AB via the coupler link CB. The beater is joined to the rocker AB with a rigid connection. The beat-up mechanism is placed properly with regard to warp yarns. The mechanism is driven by a motor through the input link DC. As the output link AB of the mechanism oscillates between two limit positions following the dashed line (Fig. 1), the teeth of the beater placed on the output link insert between the warp yarns and tighten the weft yarn and knots into carpet structure. Also, there must be a slider mechanism which moves along the carpet width together with beat-up mechanism.

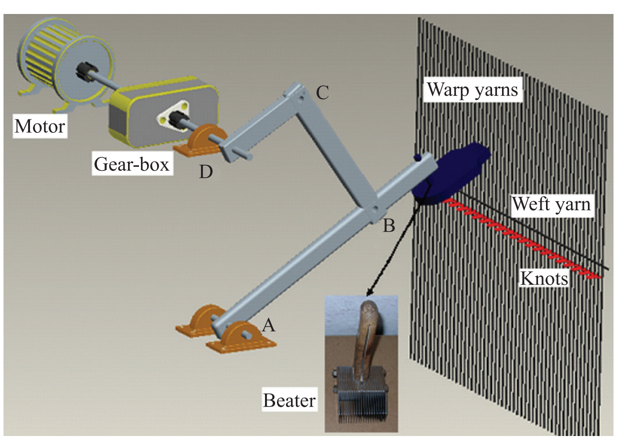

Fig. 1— Crank-rocker type beat-up mechanism placed in front of the handmade carpet loom

2.1.2 Design of Beat-up Mechanism

The swing angle is the angle between extended death position and folded death position of the mechanism. The trajectory followed by the weaver hand during beat-up operation is analyzed to determine a proper swing angle for the output link. An experienced weaver is observed to determine the path of the weaver hand during the beat-up process. The initial (P_1), the second (P_2) and the final (P_3) positions of the weaver hand are established on the trajectory as shown in Fig. 2. By applying the three point synthesis on the trajectory as given in Fig. 2, the swing angle of the output link is determined as $\psi = 30°$. It is required that the kinematic design of this crank-rocker beat-up mechanism satisfies the following mechanical criteria beside the swing angle:

(i) Optimum transmission angle— It provides the highest force transfer by exerting the least force on the joints. The torque applied to the input link is transmitted to the output link at maximum value when the transmission angle maximum approaches to 90°.

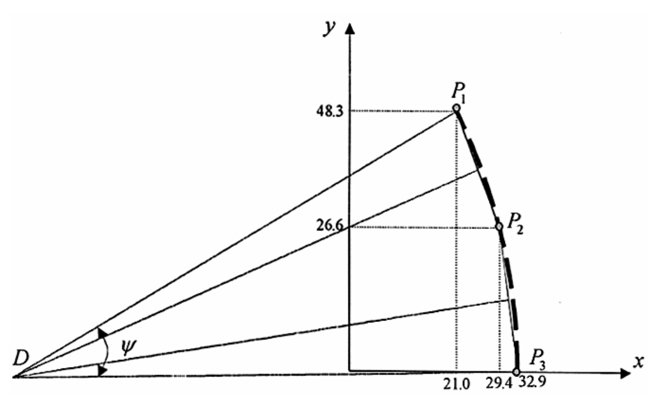

Fig. 2—Oscillation angle required for beat-up mechanism

In practice, it has been found that if the maximum deviation of transmission angle exceeds 40° or 50°, the mechanism will lock. Consequently, the transmission angle must satisfy the $90 - \mu_{\min} < 40°$ or the $90 - \mu_{\min} < 50°$ condition, except under special situation[13-15].

(ii) Optimum crank/coupler ratio—The deviation degree of beat-up motion from simple harmonic motion has practical significance and the most important factor influencing this deviation is crank/coupler ratio (r / l). This ratio (r / l) is called as eccentricity of the beat-up mechanism, where r is the crank length and l, the coupler length. The higher the value of r / l ratio, the greater is the deviation from simple harmonic motion, and the higher acceleration values are obtained at around beat-up point. But high beat-up eccentricity causes the force acting on whole mechanism and bearings to increase. A high eccentricity ratio will therefore demand more robust loom parts and more rigid loom frame in order to prevent excessive vibration and wear. So, the loom will cost more. For this reason, most loom makers tend to avoid eccentricity ratios greater than about 0.3. Thus, a 0.3 r / l ratio is enough to provide adequate force at around beat-up point and it does not cause excessive force on bearings[16].

(iii) Grashof's condition—If $l + s < p + q$ (if the sum of the lengths of the shortest and the longest links is less than the sum of the two intermediate links), the linkage is Grashof and at least one link will be capable of making a full revolution with respect to the ground plane and the mechanism must not have toggle[17,18].

2.1.3 Dimensional Synthesis of Beat-up Mechanism

In this study, dimensional synthesis of beat-up mechanism is carried out according to the theory represented by Khare and Dave[13]. The graphical solution of a crank-rocker mechanism for ϕ is shown in Fig. 3. When the solution is made for ϕ, a, b, c show the dimensions of the links of the mechanism, as given below:

$$a = -\frac{\sin\alpha_1 \cos\beta_1}{\sin\alpha_2} \text{ and } b = \frac{\sin\alpha_1 \sin\beta_1}{\cos\alpha_2} \qquad \ldots(1)$$

where

$$\alpha_1 = \frac{\psi}{2},\ \alpha_2 = \frac{\phi}{2} - \frac{\psi}{2} \text{ and } \beta_1 = \frac{\phi}{2} + \beta \qquad \ldots(2)$$

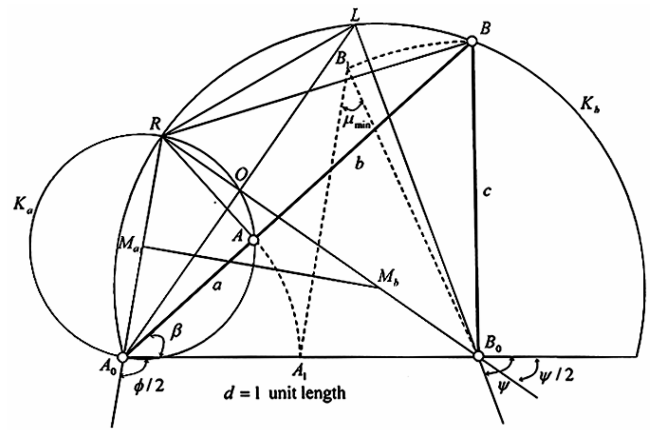

Fig. 3—Graphical solution of crank-rocker mechanism for ϕ

Applying the cosine law to the triangle A_0BB_0 as shown in Fig.3, the following relationship is obtained:

$$c^2 = (a+b)^2 + 1 - 2(a+b)\cos\beta \qquad \ldots(3)$$

Substitution for a and b in Eq. (3) and, then its simplification result in the following expression:

$$c^2 = K_1 + K_2\cos(\alpha_3 + 2\beta) + \frac{K_2^2}{2}\cos(2\alpha_3 + 2\beta) \qquad \ldots(4)$$

where

$$K_1 = 1 + K_2\cos\alpha_3 + \frac{K_2^2}{2},\ K_2 = \frac{2\sin\alpha_1}{\sin 2\alpha_2} \text{ and } \alpha_3 = \phi - \frac{\psi}{2} \qquad \ldots(5)$$

The study has been carried out considering four cases on the basis of following different experimental conditions:

(I) Case $\phi > 180°$

Grashof's criterion for the crank-rocker mechanism is $(l + s) \le (p + q)$. This condition is satisfied, if

$$L\hat{A}_0B_0 \ge \beta \ge 0 \text{ or } \left(\frac{\pi}{2} - \frac{\psi}{2}\right) \ge \beta \ge 0 \qquad \ldots(6)$$

Eq. (6) gives the upper and lower bounds on β, as shown in Fig. 3,

$$\cos\mu_{\min} = \frac{b^2 + c^2 - (1-a)^2}{2bc} \qquad \ldots(7)$$

The link length ratios *a, b* and *c* may then be obtained by using Eqs (1) and (4).

(II) Case $\phi < 180°$

The Grashof's condition for the crank-rocker mechanism is satisfied, if

$$\left(\frac{\pi}{2}-\frac{\psi}{2}\right) \geq \beta \geq (\pi-\phi) \qquad \ldots(8)$$

When the ϕ is less than 180°,

$$\cos\mu_{\min} = \frac{b^2+c^2-(1+a)^2}{2bc} \qquad \ldots(9)$$

The link length ratios *a, b* and *c* may be obtained by using Eqs (1) and (4).

(III) Case $\phi = 180° + \psi$

Unlike previous cases, the locus of the moving pivot of the rocker becomes a straight line rather than a circle. Referring Fig. 4, when the ground link is taken as unity, *a, b, c* links of the mechanism occur as shown below:

$$\beta = \pi - \frac{\phi}{2} \qquad \ldots(10)$$

$$a = \cos\beta = -\cos\frac{\phi}{2} \qquad \ldots(11)$$

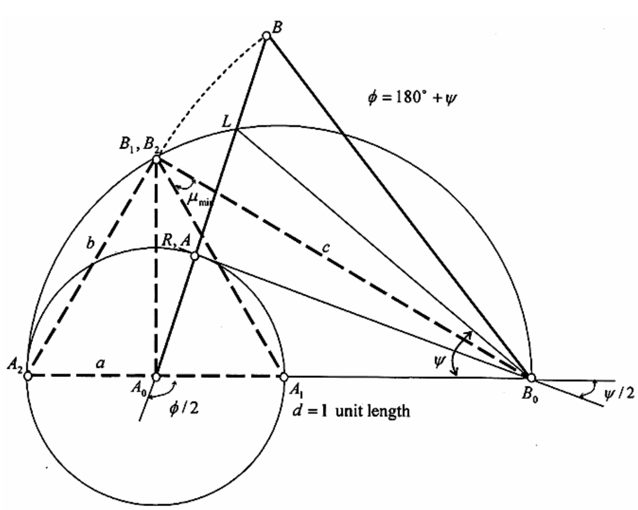

Fig. 4—Graphical solution of crank-rocker mechanism for $\phi = 180° + \psi$

From similar triangles $A_2B_2B_0$ and $A_1B_1A_0$, following relationship is obtained:

$$\frac{a}{b} = \frac{b}{(1+a)}$$

therefore;

$$b = \sqrt{[a(1+a)]} \qquad \ldots(12)$$

Also,

$$(1+a)^2 = b^2 + c^2 \text{ or } c = \sqrt{(1+a)} \qquad \ldots(13)$$

and

$$\cos\mu_{\min} = \frac{2\sqrt{a}}{(1+a)} \qquad \ldots(14)$$

(IV) Case $\phi = 180°$

This case is called as centric crank-rocker mechanism. In this situation, the mechanism has equal transmission angle $\mu_{\min}$ at both the position, when the crank is in line with the fixed link.

Therefore,

$$(1-a)^2 = b^2 + c^2 - 2bc\cos\mu_{\min}\text{ , and}$$

$$(1+a)^2 = b^2 + c^2 + 2bc\cos\mu_{\min}$$

Elimination of $\cos\mu_{\min}$ results in

$$c^2 = 1 + a^2 - b^2 \qquad \ldots(15)$$

When $\phi = 180°$ is substituted in Eq. (1), the lengths *a* and *b* are obtained using the following relationship:

$$a = \tan\frac{\psi}{2}\sin\beta \text{ and } b = \cos\beta \qquad \ldots(16)$$

Eq. (16) is substituted in Eq. (15), to obtain the following relationship:

$$c = \sec\frac{\psi}{2}\sin\beta \qquad \ldots(17)$$

Substituting *a, b* and *c* in Eq. (7) or Eq. (9) and simplifying, following relationship is obtained:

$$\cos\mu_{\min} = \frac{a}{bc} = \frac{\sin(\psi/2)}{\cos\beta} \qquad \ldots(18)$$

The range of the β value is calculated from the Eq. (6) or Eq. (8). The link length ratios *a, b, c* may then be obtained by using Eqs (16) and (17).

Many different crank-rocker type mechanisms are generated under five different cases (Case I, Case II, Case III, Case IV and Case V), as given below. These solutions are presented in Table 1.

Table 1—Parameters for different case studies

B, deg	*a*	*b*	*c*	*r/l*	μ_{min}, deg
		Case I			
75	0.2588	0.2588	1	1.00	0
72	0.2449	0.2720	0.9735	0.90	4.33
70	0.2353	0.2804	0.9556	0.84	4.66
67	0.2203	0.2923	0.9285	0.75	4.13
64	0.2047	0.3034	0.9015	0.67	2.78
60	0.1830	0.3170	0.8660	0.58	0
		Case II			
70	0.2473	0.3062	0.9632	0.81	25.08
65	0.2340	0.3513	0.9208	0.67	31.53
57	0.2089	0.4177	0.8427	0.5	34.97
55	0.2019	0.4331	0.8225	0.47	35.06
53	0.1948	0.4479	0.7997	0.43	34.92
43	0.1555	0.5136	0.6848	0.30	31.08
35	0.1207	0.5550	0.5912	0.22	24.27
30	0.0977	0.5755	0.5359	0.17	18.04
		Case III			
70	0.2518	0.3420	0.9728	0.74	40.82
67	0.2467	0.3907	0.9530	0.63	48.52
55	0.2195	0.5736	0.8481	0.38	63.18
50	0.2053	0.6428	0.7931	0.32	66.26
48	0.1991	0.6691	0.7694	0.30	67.24
47	0.1960	0.6820	0.7572	0.29	67.70
40	0.1722	0.7660	0.6655	0.22	70.25
35	0.1537	0.8192	0.5940	0.19	71.58
10	0.0465	0.9848	0.1798	0.05	74.76
		Case IV			
70	0.2559	0.5157	1.0332	0.50	42.97
67	0.2532	0.6680	1.0624	0.38	44.23
66	0.2521	0.7184	1.0735	0.35	44.02
60	0.2441	1.0157	1.1521	0.24	40.20
50	0.2250	1.4848	1.3135	0.15	31.40
40	0.1990	1.9088	1.4878	0.10	23.33
30	0.1670	2.2749	1.6533	0.07	16.44
25	0.1490	2.4326	1.7278	0.06	13.36
10	0.0889	2.7905	1.9025	0.03	05.07
		Case V			
75	0.2589	0.5708	1.122	0.45	36.06

Case study I

$\phi = 120^\circ$, $\psi = 30^\circ$, $75^\circ \geq \beta \geq 60^\circ$. The upper and lower bounds on the β may be obtained by using Eq. (8).

Case study II

$\phi = 160^\circ$, $\psi = 30^\circ$, $75^\circ \geq \beta \geq 20^\circ$. The upper and lower bounds on the β may be obtained by using Eq. (8).

Case study III

$\phi = 180^\circ$, $\psi = 30^\circ$, $75^\circ \geq \beta \geq 0^\circ$. The upper and lower bounds on the β may be obtained by using Eq. (6) or Eq. (8).

Case study IV

$\phi = 200^\circ$, $\psi = 30^\circ$, $75^\circ \geq \beta \geq 0$. The upper and lower bounds on the β may be obtained by using Eq. (6).

Case study V

$\phi = 210^\circ$, $\psi = 30^\circ$. Since $\phi = 180^\circ + \psi$, it is special condition and the equations in *Case III* are used.

2.1.4 Dynamic Analysis

Dimensional synthesis is performed to determine the functional dimensions. After the dimensions of the mechanism are determined, the forces acting on the links and joints must be analyzed in dynamic analysis. Dynamic analysis can be performed by obtaining the dynamic equations from Newton-Euler approach or Lagrange formulation[19-23]. These equations can be solved using programs such as Turbo Pascal, Fortran and C. On the other hand, dynamic analysis of even very complex mechanisms can be performed easily by using programs such as Working Model, Pro-Engineer, Ch Mechanism Toolkit 2.0 and Solid Works. In this study, since the beat-up mechanism is a simple crank-rocker type mechanism, the dynamic equations are obtained by Newton method and they are solved in turbo pascal program.

The dimensions selected as optimum solution are scaled with 0.3 m. It is assumed that each link of the mechanism is made of cast iron with a density of 7210 kg/m^3. The width of each link is 0.03 m and the thickness is 0.01 m. The mechanical properties [mass

(m) and mass moment of inertia (J)] of the mechanism are given below:

$AD = 0.3$ m
$DC = 0.0597$ m
$m_{DC} = 0.129$ kg
$J_{DC} = 4.073\times10^{-5}$ kg.m^2

$CB = 0.2007$ m
$m_{CB} = 0.434$ kg
$J_{CB} = 0.0015$ kg.m^2

$AE = 0.3001$ m
$m_{AE} = 0.649$ kg
$J_{AE} = 0.0049$ kg.m^2

It is assumed that the mechanism has an input velocity of 15.5 rad/s and the beater has a 2.5 kg weight. The results shown in Figs 6 and 7 are obtained for two full rotation of the crank link.

3 Results and Discussion

In the dimensional synthesis, the solutions of the crank-rocker mechanisms are obtained by using graph-analytical method for swing angle (ψ = 30°) and crank rotation angles (ϕ = 120°, 160°, 180°, 200° and 210°). Five case studies, as given in Table 1, are performed and results are obtained by using related formulas according to ϕ value. In each case study, the link length ratios are calculated for each β value and the optimum β value at which $\mu_{\min}$ (transmission angle) least deviates from 90° is determined. The least deviation of $\mu_{\min}$ angle from 90° is obtained at (ϕ = 180°. The solution of β = 48° is selected as the most suitable one for ϕ = 180°, since the design requirements, such as r/l = 0.3 and 90 – $\mu_{\min}$ < 40°, are satisfied.

Consequently, the dimensions of the links of the crank-rocker mechanism that could perform the beat-up operation for handmade carpet loom are calculated and presented on the beat-up mechanism (Fig. 5).

After the dimensions of the mechanism are determined on the basis of the design criteria, the dynamic analysis is performed. As a result of dynamic analysis, the position, velocity and acceleration of the beater are shown in Figs 6 (a)-(c) respectively and the total force on the beater is given in Fig. 6 (d). The loads on the joints C and B are given in Fig. 7.

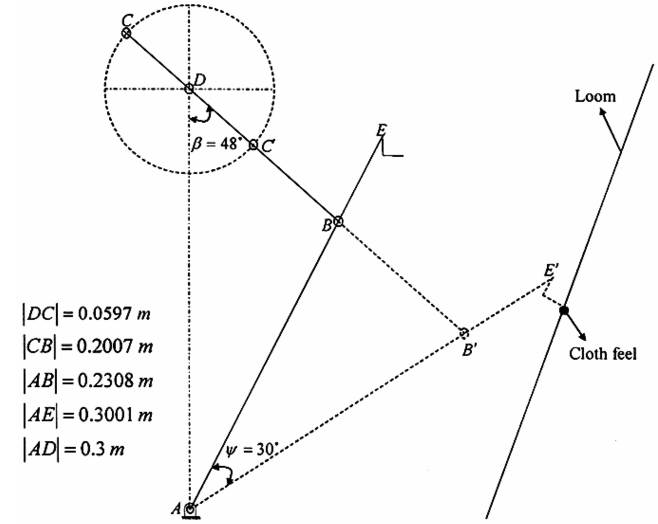

Fig. 5—Dimensions of links and motion of beat-up mechanism

The beater reaches its maximum velocity at about beating point. The peaks shown in Fig.6 (b) are obtained when the mechanism is at about the beat-up position. After the beat-up position, the velocity of the beater decreases sharply. The beater has minimum velocity [Fig. 6 (b)] at folded and extended dead centers of the beat-up mechanism. The beater reaches its maximum acceleration value at the beating points as given in Fig. 6 (c). The acceleration attains a value of 25 m/s^2 during the beat-up operation. There are two peaks in the graphic for two rotation of the crank link. The beater acceleration decreases after the beat-up operation.

As shown in Fig. 6 (d), the force sharply increases up to about the beat-up point and it reaches the maximum value (over 60 N) at the beating point, then the force sharply decreases after performing beat-up process. The peak points in the graphic represent the beat-up positions of the mechanism. The force on joints C and B are represented in Fig. 7. The force applied to the joints reaches the maximum value at the beat-up position of the mechanism. High loads on the joints can cause deformation of the mechanism and high vibration. Hence, the strong materials are to be used with increased cost. Optimum length ratio ($r/l = 0.3$) is selected not to create high loads on joints. In the construction of the mechanism, proper joints must be selected such that it can resist loads.

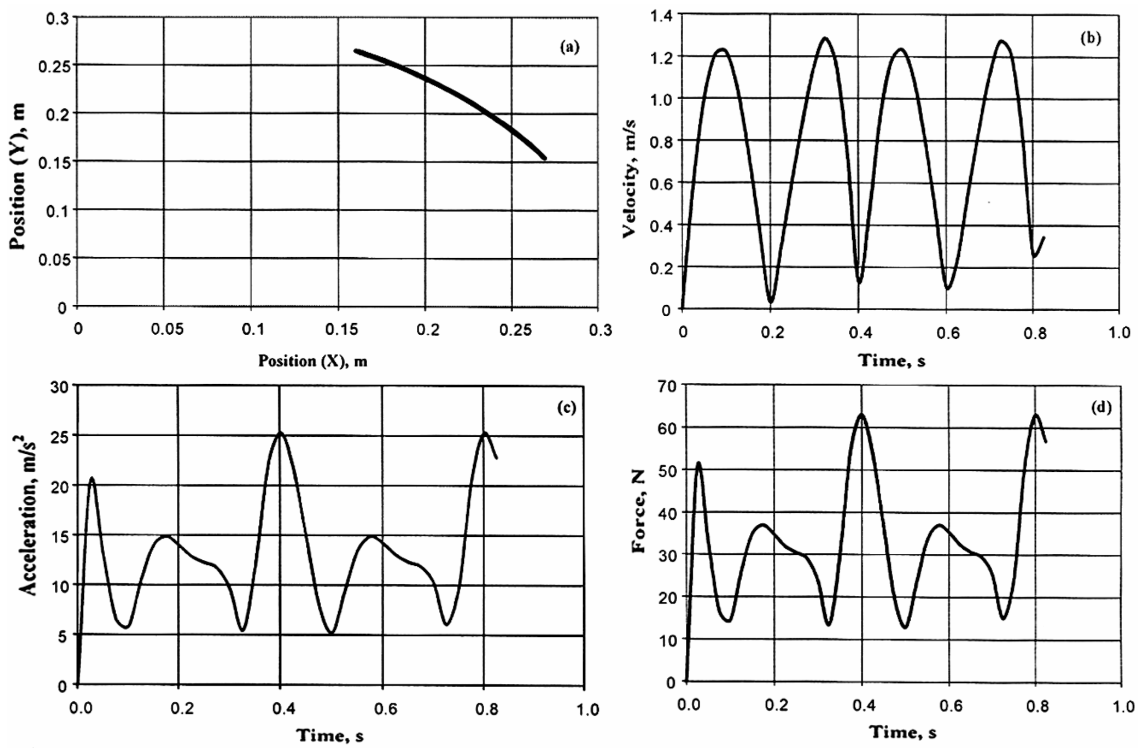

Fig. 6—Kinematics and dynamic analysis of the beater

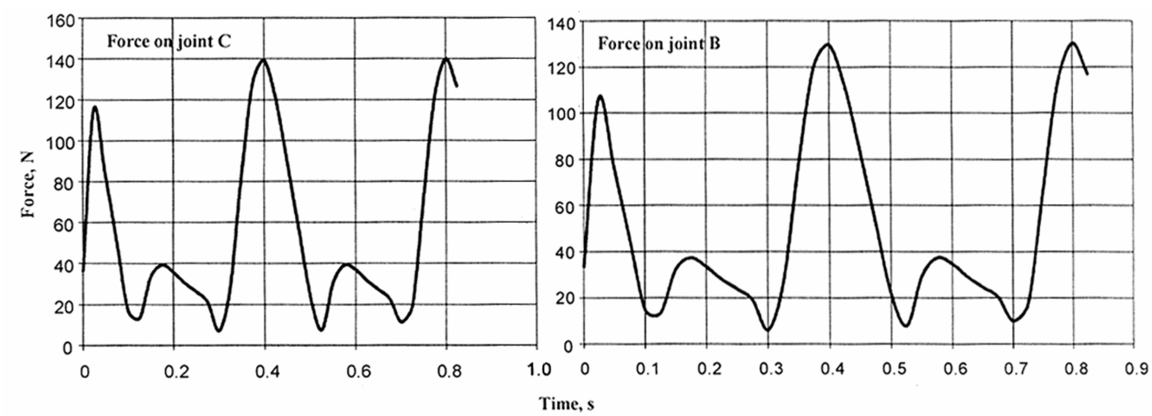

Fig. 7—Loads on pin joints C and B

4 Conclusions

A kinematic analysis is introduced for the design of four-bar beat-up mechanism for handmade carpet looms. In all, 32 alternative mechanism solutions are generated in five different cases by using dimensional synthesis method. After selecting one of them on the basis of the design criteria, its dynamic analysis is performed.

In the further studies, other operations such as shedding, picking, letting-off and taking-up can be performed mechanically by designing suitable mechanisms. These mechanisms may be synchronized by using a computer control and they work in a required sequence.

Industrial Importance: Since all of the weaving operations of the handmade carpets are performed by the weaver, the production speed of the handmade carpet could be increased and the performance of the weaver may be improved by using this mechanism. As the beat-up force during the operation is judged by the weaver, many weaving faults may potentially occur. By using this mechanism, weaving faults may be decreased, the carpet quality could be retained and the repair cost may be decreased.

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