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Dynamic Performance Improvement of a Carpet Scrapping Machine

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Dynamic performance improvement like less vibration, smooth motor torque requirement, etc. of a carpet scrapping machine to enhance productivity and quality of Indian hand knotted carpets is presented. A complete dynamic analysis is carried out, along with optimum balancing of shaking force and shaking moment of the machine. To do this, its inertia properties are represented by dynamically equivalent systems, referred as equimomental systems, of point-masses to identify the design variables, and formulate the associated constraints. Mass redistribution and counterweights are suggested methods to improve dynamic performances of existing carpet scrapping machine.

Key words: Carpet Scrapping machine, Dynamic performances, Optimization, Shaking force, Shaking moment.

1 Introduction

Carpet weaving is facing a tough competition from other exporting countries of Asia-Pacific region due to market liberalization[1]. A project[1,2] with the aims to improve processes, tools and machines involved in the manufacturing of carpets was initiated by IIT Delhi in 2000. In the project, optimisation of a metallic loom[3] was carried out for its reduced weight and cost. A way to balance any mechanism is to trade-off between all the competing dynamic quantities[4-10]. Since shaking force, shaking moment, input-torque, etc., depend on the mass and inertias of each link, and its mass centre locations[8], it is required to optimally distribute the link masses for dynamic balancing. A convenient way to represent the inertia properties of the links is treating them as dynamically equivalent systems of point masses referred to as *equimomental system*[11]. Using the concept of equimomental system, Sherwood & Hockey[8] presented optimization of mass distribution in mechanisms. Using the two point-mass model, Wiederrich & Roth[9] presented momentum balancing of four-bar linkages. Optimum balancing of combined shaking force, shaking moment, and torque fluctuations in linkages was later reported in Lee & Cheng[10], where a two point-mass model was used. In this paper, concept of equimomental system is used to balance the carpet scrapping machine in order to minimize shaking force and shaking moment so that vibrations and fluctuation in driving torque are reduced. Two methods are presented; the first is for the design of new scrapping machine using mass redistribution moving links and the second for reducing the unbalance of an existing one using counterweights. The methodology is quite general and not restricted only to single-loop four-bar linkage as reported in Refs[9,10,13]. The dynamic analysis presented in Ref[13] is extended in this paper for Carpet scarping mechanism which is a multiloop mechanism.

2 Carpet scrapping machine

Carpet woven on handloom has been washed manually that causes a lot of fatigue[12]. To overcome the problems, a carpet scrapping machine (Fig. 1) has been conceived, designed and fabricated at IIT Delhi[12].

The machine generates a path like washer man. It has been conceived using Hoeken's and the Pantograph mechanisms (Fig. 2) which are suitable for this application. The machine works fairly well. However, it vibrates quite a lot due to the unbalanced shaking force and shaking moment transmitted to the frame of the machine.

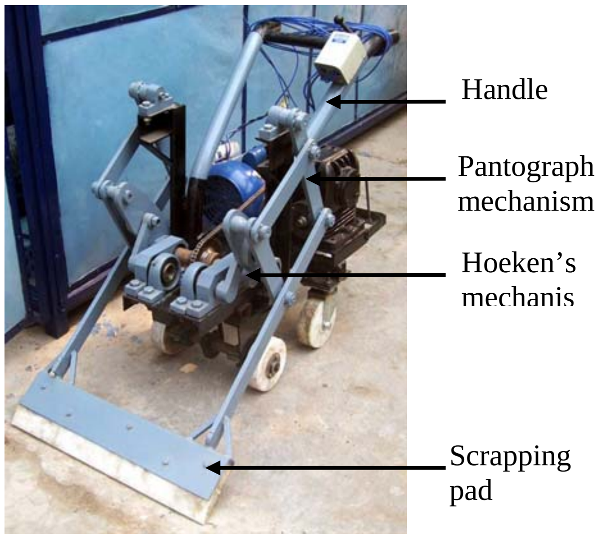
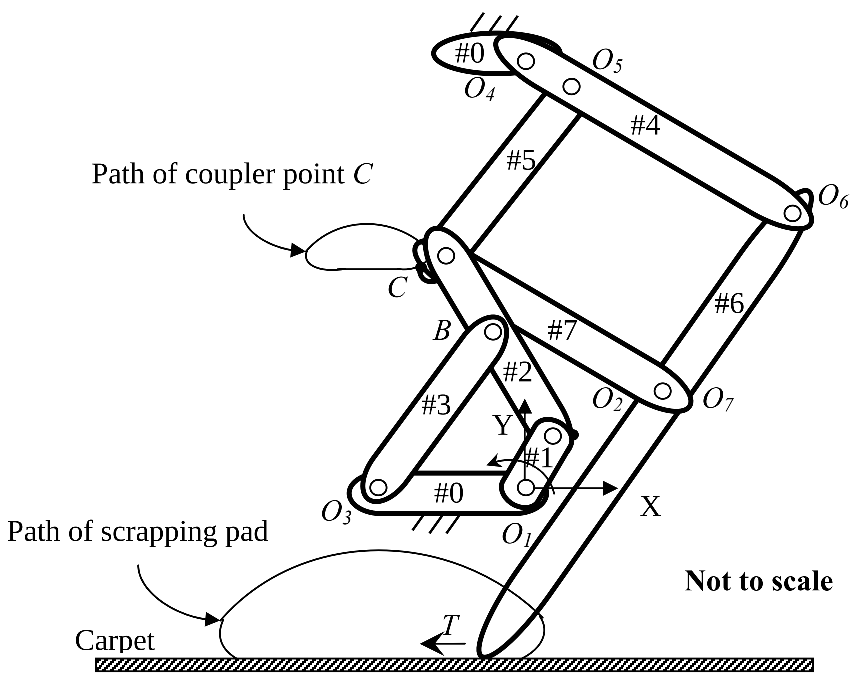


Fig. 1 Carpet scrapping machine



Mechanisms: #0-#1-#2-#3: Hoeken's; #0-#4-#6-#7-#5: Pantograph

Fig. 2 The scrapping mechanism

3 Optimization of Carpet Scrapping Machine

Each rigid link of the mechanism is represented as a dynamic equivalent system of rigidly connected three point-masses. Shaking force and shaking moment are obtained from dynamic equations of motion of mechanism derived in terms of parameters of point-masses. These parameters are then treated as design variables to redistribute the link masses to minimize shaking force and shaking moment.

3.1 Equations of motion

Referring to the *i*th rigid link moving in a plane, Fig. 3(a), a set of three equimomental point-masses is defined as shown in Fig. 3(b).

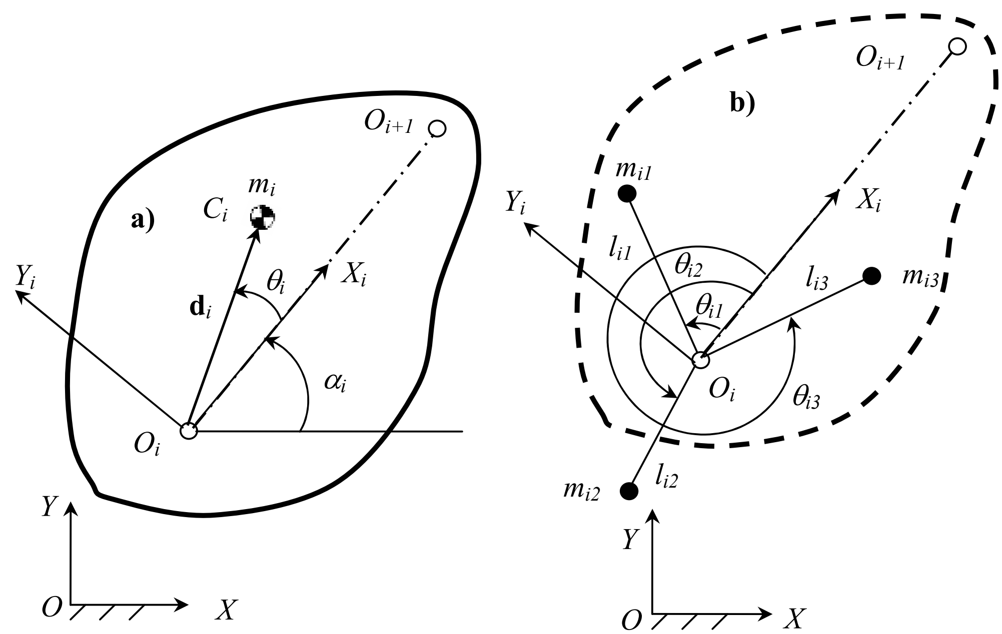


Fig. 3 The *i*th link: (a) Original link: (b) Its equimomental three point-masses system

The location of mass centre, C_i, is defined by vector $\mathbf{d}_i$ at an angle θ_i from the axis O_iX_i of local frame $O_iX_iY_i$ fixed to the link. Link's mass and mass moment of inertia about O_i are denoted as m_i and I_i, respectively. Point-masses (m_{i1}, m_{i2}, m_{i3}) are fixed in local frame, $O_iX_iY_i$, and their distances (l_{i1}, l_{i2}, l_{i3}) and angles (θ_{i1}, θ_{i2}, θ_{i3}) are defined from the origin O_i of link and axis O_iX_i, respectively. Axis O_iX_i is set along the line between two successive revolute joints, O_i and O_{i+1}, that is at angle α_i from axis OX of the fixed inertial frame OXY. Points O_i and O_{i+1} in the link are chosen as the point where *i*th link is joined to its surrounding links. All vectors are represented in fixed frame, OXY, unless stated otherwise.

For planar motion, equivalence of the system of three point-masses and original rigid link from dynamic motion point of view are: both will have (a) same total masses; (b) same centres of masses; and (c) same moments of inertia[11] as

$$\sum_{j=1}^{3} m_{ij} = m_i \tag{1}$$

$$\sum_{j=1}^{3} m_{ij} l_{ij} \cos(\theta_{ij} + \alpha_i) = m_i d_i \cos(\theta_i + \alpha_i) \tag{2}$$

$$\sum_{j=1}^{3} m_{ij} l_{ij} \sin(\theta_{ij} + \alpha_i) = m_i d_i \sin(\theta_i + \alpha_i) \tag{3}$$

$$\sum_{j=1}^{3} m_{ij} l_{ij}^2 = I_i \tag{4}$$

Note that the first subscript i denotes link number, and second subscript j=1, 2, 3, represents point-mass corresponding to *i*th link. Newton-Euler (NE) equations[13] of motion for *i*th rigid link undergoing a planar motion can be written as:

$$\mathbf{M}_i \dot{\mathbf{t}}_i + \mathbf{C}_i \mathbf{t}_i = \mathbf{w}_i \tag{5}$$

where 3-vectors, $\mathbf{t}_i, \dot{\mathbf{t}}_i$ and $\mathbf{w}_i$, are defined as twist, twist-rate and wrench of *i*th link with respect to the origin, O_i, as

$$\mathbf{t}_\mathrm{i} \equiv \begin{bmatrix} \omega_i \\ \mathbf{v}_i \end{bmatrix}; \dot{\mathbf{t}}_\mathrm{i} \equiv \begin{bmatrix} \dot{\omega}_i \\ \dot{\mathbf{v}}_i \end{bmatrix} \text{and } \mathbf{w}_\mathrm{i} \equiv \begin{bmatrix} n_i \\ \mathbf{f}_i \end{bmatrix} \tag{6}$$

in which ω_i and $\mathbf{v}_i$ are the scalar angular velocity about the axis perpendicular to the plane of motion, say, Z, and 2-vector of linear velocity of the origin of *i*th link, O_i, respectively. Accordingly, $\dot{\omega}_i$ and $\dot{\mathbf{v}}_i$ are time derivatives of ω_i and $\mathbf{v}_i$, respectively. Also, scalar, n_i, and 2-vector, $\mathbf{f}_i$, are resultant moment about O_i and resultant force at O_i, respectively. Moreover, 3×3 matrices, $\mathbf{M}_i$ and $\mathbf{C}_i$ are defined as

$$\mathbf{M}_i \equiv \begin{bmatrix} I_i & -m_i \mathbf{d}_i^T \mathbf{E} \\ m_i \mathbf{E} \mathbf{d}_i & m_i \mathbf{1} \end{bmatrix} \text{and } \mathbf{C}_i \equiv \begin{bmatrix} 0 & \mathbf{0}^T \\ -m_i \omega_i \mathbf{d}_i & \mathbf{O} \end{bmatrix} \quad (7)$$

where **1** and **O** are 2×2 identity and zero matrices, respectively, and **0** is 2-vector of zeros, and 2×2 matrix **E** is defined as

$$\mathbf{E} \equiv \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$$

Using equimomental conditions, [Eqs. (1)-(4)], 3×3 matrices, $\mathbf{M}_i$ and $\mathbf{C}_i$, [Eq. (7)], are re-written as

$$\mathbf{M}_i \equiv \begin{bmatrix} \sum_j \mathrm{m}_{\mathrm{ij}} l_{ij}^2 & -\sum_j m_{ij} l_{ij} S(\theta_{ij} + \alpha_i) & \sum_j m_{ij} l_{ij} C(\theta_{ij} + \alpha_i) \\ -\sum_j m_{ij} l_{ij} C(\theta_{ij} + \alpha_i) & \sum_j m_{ij} & 0 \\ \sum_j m_{ij} l_{ij} S(\theta_{ij} + \alpha_i) & 0 & \sum_j m_{ij} \end{bmatrix} \text{; and}$$

$$\mathbf{C}_i \equiv \begin{bmatrix} 0 & 0 & 0 \\ -\ \omega_i \sum_j m_{ij} l_{ij} C(\theta_{ij} + \alpha_i) & 0 & 0 \\ -\omega_i \sum_j m_{ij} l_{ij} S(\theta_{ij} + \alpha_i) & 0 & 0 \end{bmatrix} \quad (8)$$

3.2 Shaking force and shaking moment

Appropriate reaction forces and moments due to the fixed link are indicated on the moving links to maintain the dynamic equilibrium (Fig.4). Shaking force is defined as the reaction of vector sum of all inertia forces associated with the mechanism, and shaking moment is the reaction of resultant of all inertia moments plus the moments of all inertia forces. By above definition, shaking force and shaking moment with respect to O_1, transmitted to the fixed link are given by

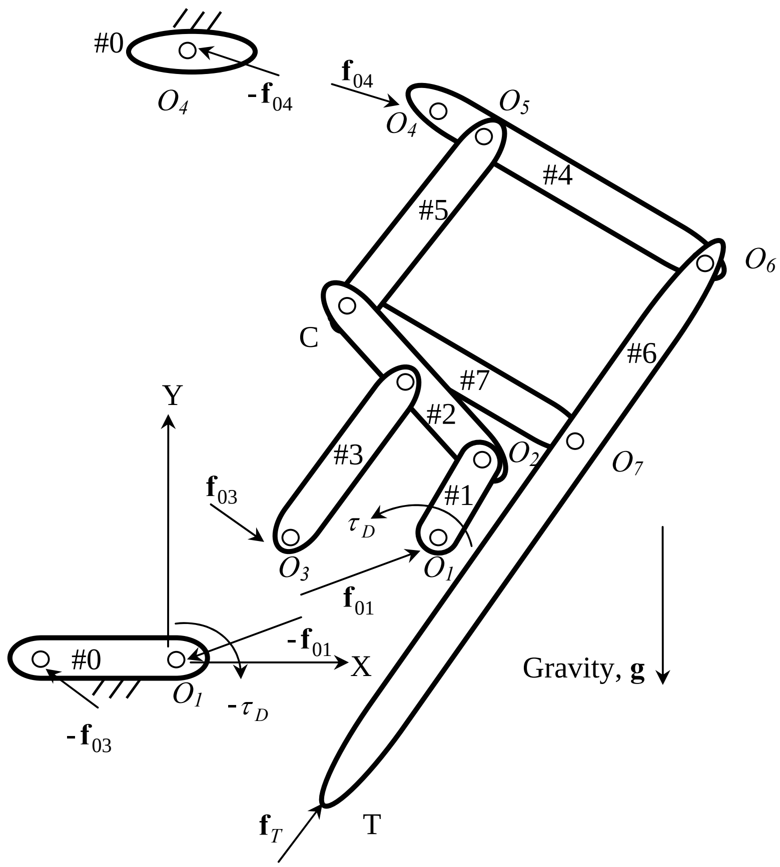


Fig. 4 Forces/moments transmitted to the fixed link in the scrapping mechanism

$$\mathbf{f}_{sh} = -\sum_{i=1}^{7} \mathbf{f}_i^* \tag{9}$$

$$n_{sh} = -\sum_{i=1}^{7} (n_i^* - \mathbf{a}_{1,i}^T \overline{\mathbf{E}} \mathbf{f}_i^*) \tag{10}$$

where n_i^* and $\mathbf{f}_i^*$ are the scalar inertia moment and 2-vector of inertia forces, respectively, acting about and at origin, O_i, of ith link. Note that the links move in parallel vertical planes. The inertia forces will therefore, produce additional moments about X and Y axes. These are assumed to be ignored. Moreover, 2-vector, $\mathbf{a}_{1,i}$, is defined from O_1 to origin of ith link. Substituting inertia forces and moments in terms of external force and moment, and reactions due to adjoining joints, Eqs. (9)-(10) yields

$$\mathbf{f}_{sh} = -(\mathbf{f}_{01} + \mathbf{f}_{03} + \mathbf{f}_{04} + \mathbf{f}_T) - (m_1 + \cdots + m_7)\mathbf{g} \tag{11}$$

$$n_{sh} = -\left[\tau_D - \mathbf{a}_{13}^T \mathbf{E}\mathbf{f}_{03} - \mathbf{a}_{14}^T \mathbf{E}\mathbf{f}_{04} - \mathbf{a}_{1,T}^T \mathbf{E}\mathbf{f}_T - \sum_{i=1}^{7} (\mathbf{a}_{1,i} + \mathbf{d}_i)^T \mathbf{E}(m_i \mathbf{g})\right] \tag{12}$$

where **g** is 2-vector of acceleration due to gravity defined as, $\mathbf{g} \equiv [0 \quad -g]^T$, and $\mathbf{f}_T$ is external force acting on link #6 due to carpet washing action, whereas $\mathbf{a}_{1,T}$ is 2-vector from O_1 to T.

3.3 Optimality criterion

There are many possible criteria by which the shaking force and shaking moment transmitted to the frame of the mechanism can be minimized. For example, one criterion could be based on the root mean squares (RMS) values of the shaking force, shaking moment, and the required driving torque for a given motion, and/or the combination of these. Besides RMS values, there can be other criteria as well, namely, the largest values of shaking force and shaking moment during a cycle, and others. The choice of course depends on the requirements. Here, RMS value is preferred over others as it gives equal emphasis on the results of every time instances, and every harmonic component. In order to harmonize quantities of the force, the moment, etc., they are normalized[15] as:

$$\bar{f} \equiv |\mathbf{f}| / (m_r a_r \omega_{in}^2) \text{; and } \bar{n} \equiv n / (m_r a_r^2 \omega_{in}^2) \tag{13}$$

where a_r and m_r are length and mass of reference link for normalization, whereas ω_{in} is any input angular velocity. The terms $m_r a_r \omega_{in}^2$ and $m_r a_r^2 \omega_{in}^2$ have the unit of force and moment, respectively, and are used to make other forces and moments nondimensional. RMS values of normalized shaking force, $\bar{f}_{sh}$, and normalized shaking moment, $\bar{n}_{sh}$, for δ discrete positions of the mechanism are defined as

$$\tilde{f}_{sh} \equiv \frac{1}{\delta}\sqrt{\sum \bar{f}_{sh}^{2}} \text{ ; and } \tilde{n}_{sh} \equiv \frac{1}{\delta}\sqrt{\Sigma \bar{n}_{sh}^{2}} \qquad (14)$$

where $\tilde{f}_{sh}$ and $\tilde{n}_{sh}$ are RMS values of normalized shaking force and normalized shaking moment, respectively. Considering RMS values, $\tilde{f}_{sh}$ and $\tilde{n}_{sh}$, an optimality criterion is proposed as

$$z = w_1\tilde{f}_{sh} + w_2\tilde{n}_{sh} \qquad (15)$$

where w_1 and w_2 are weighting factors whose values may vary depending on an application. For example, w_1=1.0 and w_2=0 if the objective is to minimize shaking force only. Moreover, design variables and constraints depend on whether balancing is done through redistribution of link masses or attaching counterweights to the links.

3.3.1 Mass redistribution method

Since each link is modelled using three equimomental point-masses, there are nine parameters to specify them, which are put in the 9-vector, $\mathbf{x}_i$, as

$$\mathbf{x}_i \equiv [m_{i1} \quad m_{i2} \quad m_{i3} \quad l_{i1} \quad l_{i2} \quad l_{i3} \quad \theta_{i1} \quad \theta_{i2} \quad \theta_{i3}]^T \qquad (16)$$

Accordingly, 63-vector of point-mass parameters for the whole mechanism is given as

$$\mathbf{x} = \begin{bmatrix}\mathbf{x}_i^T & \cdots & \mathbf{x}_7^T\end{bmatrix}^T \qquad (17)$$

Now, all or some of the point-mass parameters can be used as design variables based on their influence on objective function of the optimization problem. For example, as evident from Eq. (4), angles, θ_{ij}, do not influence moment of inertia, however, distances, l_{ij}, do. Hence, angles, θ_{ij} are excluded from the set of design variables and given fixed values, namely,

$$\theta_{i1} = 0 \text{ ; } \theta_{i2} = 2\pi/3 \text{ ; } \theta_{i3} = 4\pi/3 \qquad (18a)$$

Furthermore, to reduce number of variables, distances of point-masses are assumed equal as

$$l_{i2} = l_{i3} = l_{i1} \tag{18b}$$

Hence, remaining four parameters, m_{i1}, m_{i2}, m_{i3}, and l_{i1}, for each link are variable that need to be optimized. They are defined as the *design variables (DV)*. For 7 links of the mechanism then the 28-vector, **x**, of the DVs is defined as

$$\mathbf{x} \equiv [m_{11}, m_{12}, m_{13}, l_{11}, \cdots, m_{71}, m_{72}, m_{73}, l_{71}]^T \tag{19}$$

Once any rigid link converted into a dynamically equivalent system of point-masses, the parameters of the rigid link can be expressed completely by the parameters of point-masses. Hence, the allowable values of link's parameters can be constrained. For example, minimum mass of *i*th link is, $m_{i,\min}$, and maximum mass is , $m_{i,\max}$, which are dictated by strength of links, etc. Similarly, limits on parameters, l_{i1}, are decided based on limiting values of moments of inertias, etc. Considering suitable constraints, optimization problem is finally posed as

$$\text{Minimize } z(\mathbf{x}) = w_1 \tilde{f}_{sh} + w_2 \tilde{n}_{sh} \tag{20a}$$

$$\text{Subject to } m_{i,\min} \le m_i \le m_{i,\max} \tag{20b}$$

$$l_{i1,\min} \le l_{i1} \le l_{i1,\max} \tag{20c}$$

$$d_{i,\min} \le d_i \le d_{i,\min} \tag{20d}$$

$$m_i d_i^2 \le I_i \tag{20e}$$

for *i*=1, …,7 , where $m_{i,\min}$, $m_{i,\max}$, $l_{i1,mi}$, and $l_{i1,\max}$ are the lower and upper bounds on m_i and l_{i1}, respectively, and $m_i = m_{i1} + m_{i2} + m_{i3}$.

3.3.2 Counterweight method

When mass distribution of each link through redesigning is not allowed but dynamic performances of an existing machine have to be improved, counterweight balancing can be adopted. Here, counterweights are attached to the moving links of existing machine such that shaking force and shaking moment transmitted to the frame of machine are minimum. Assume that counterweight mass m_i^b, whose mass centre is located at (d_i^b, θ_i^b), is attached to *i*th link (Fig. 5). Note that original mass and its mass centre of *i*th link are m_i^o and (d_i^o, θ_i^o). Optimization problem as stated in Eqs. (20a-e) is accordingly modified as

$$\text{Minimize } z(\mathbf{x}) = w_1 \tilde{f}_{sh} + w_2 \tilde{n}_{sh} \quad (21a)$$

$$\text{Subject to } m_{i,\min}^b \le m_i^b \le m_{i,\max}^b \quad (21b)$$

$$l_{i,\min}^b \le l_i^b \le l_{i,\max}^b \quad (21c)$$

$$d_{i,\min}^b \le d_i^b \le d_{i,\max}^b \quad (21d)$$

$$m_i^b (d_i^b)^2 \le I_i^b \quad (21e)$$

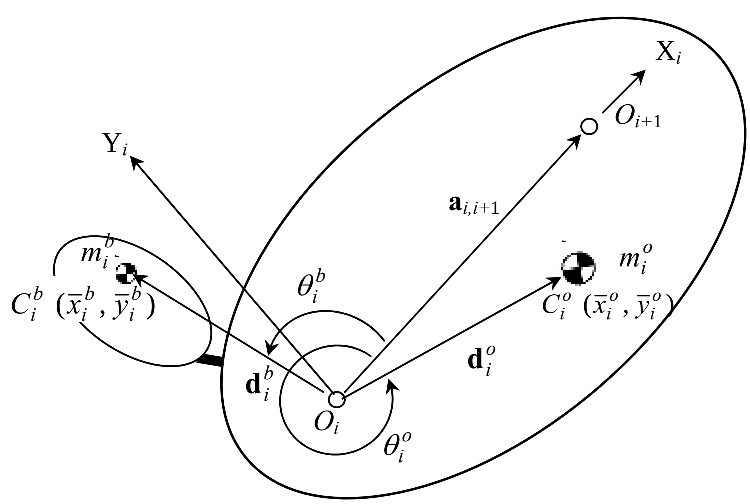


Fig. 5 Counterweight to the *i*th link

4 Results and Discussion

4.1 Numerical example

Input motion is provided to link # 1 by an electric motor (Fig. 2), which is a constant rotational speed of 45 *rpm* (4.712 *rad/s*). Fixed frame, *XYZ*, is located at joint O_1, where axis Z is orthogonal to the plane of this page. Joints O_3 and O_4 are located at (-0.089*m*, 0) and (0.038*m*, 0.410*m*), respectively. Note that joint between #2 and # 3 is located at the mid of link #2. Moreover, joint at O_5 is on link #4 from joint O_4 at 0.096*m*. Other geometries, masses, and inertias of the links are given in Table 1.

Table 1 Link parameters of the original scrapping machine

Link, *i*	Link length a_i (m)	Total link mass m_i^o	Mass centre location d_i^o (m)	θ_i^o (deg)	Moment of inertia I_i^o (kg-m^2)×10^{-3}
#1	0.0381	0.3263	0.0057	0.00	0.19
#2	0.2304	2.3178	0.1089	0.00	40.02
#3	0.1152	0.6393	0.0474	0.00	2.76
#4	0.3346	1.7060	0.1714	0.00	68.24
#5	0.2390	1.4119	0.1195	0.00	23.35
#6	0.2390	4.6232	0.4182	0.00	1086.60
#7	0.2390	1.4119	0.1195	0.00	23.35
		12.4364[+]			

O_6T=0.8365 m; [+]Total mass of the original mechanism, Σm_i^o

In order to evaluate forces and moments acting on links using dynamic equations of motion, magnitude of force acting along link #6 during scrapping action is taken as 250 N. The value of shaking force and shaking moment is evaluated at δ positions of the mechanism. The positions of mechanism are defined at equal time interval of period of crank as $\delta = T/\Delta t$. In the numerical examples, time period of crank, T = 4/3 sec, and equal time step, Δt = 0.01 sec. Hence, δ=133. However, one can take any other time step. Moreover, lower and upper limits on m_i, l_{i1}, and d_i in mass redistribution method are chosen as $m_i^o \le m_i \le 5m_i^0$, $0.5l_{i1}^o \le l_{i1} \le 1.5l_{i1}^o$, and $0 \le d_i \le a_i$, respectively, whereas limits on m_i^b, l_{i1}^b, and d_i^b in counterweight method are taken as $0 \le m_i^b$, $0.25l_{i1}^o \le l_{i1}^b \le 1.5l_{i1}^o$, and $0 \le d_i^b \le a_i$, respectively. Furthermore, for practical solution, links connected to frame are considered for attaching counterweights. Shaking force and shaking moment transmitted to the frame, #0, are computed from Eqs (11) and (12). Finally, optimization is carried out using Eqs (20) and (21) and optimization toolbox of MATLAB software[14]. The optimization toolbox of MATLAB is used to solve the optimization problems. Using, "fmincon" function, which based on the Sequential Quadratic Programming (SQP) method [16], finds a minimum of the function z.

Numerical results are obtained by applying different weighting factors, w_1 and w_2. It is observed that for (w_1 , w_2)= (0.5, 0.5), shaking force and shaking moment are minimum simultaneously, as expected. Optimized masses, their mass centres locations, and moments of inertia of links are calculated (Table 2) from the optimized point-masses using Eqs (1)-(4). RMS values of the dynamic quantities of the optimized mechanism are compared (Table 3) with those corresponding to the original mechanism. The results show a significant improvement in shaking force and shaking moment, which will ultimately reduce overall vibration of the machine. In mass redistribution method, reductions are observed in RMS values of shaking force (73%) and shaking moment (26%), whereas reductions in counterweight method are 11% and 15%, respectively. Figs 6 and 7 show comparison between dynamic performances of the original and optimized mechanisms. Mass centre locations of optimized links are given in Fig. 8.

Table 2 Link parameters of the balanced crapping mechanism

Link, *i*	Link/counterweight mass	Mass centre location		Moment of inertia
Mass redistribution method				
	m_i^* [kg]	d_i^* [m]	θ_i^* [deg]	I_i^* [kg-m^2]
1	0.326	0.036	-19.30	0.0004
2	5.274	0.115	156.99	0.1544
3	0.639	0.099	-68.88	0.0062
4	8.530	0.120	-158.10	0.1224
5	1.412	0.193	-7.53	0.0525
6	4.623	0.239	-49.14	0.4521
7	1.412	0.193	-1.72	0.0525
	22.216[1]			
Counterweight method[3]				
	m_i^{b*} [kg]	d_i^{b*} [m]	θ_i^{b*} [deg]	I_i^{b*} [kg-m^2]
1	0.660	0.0363	59.77	0.0009
3	0.000	0.000	0.00	0.0000
5	11.288	0.05	-130.46	0.0282
	11.948[2]			

[1]Total mass of the balanced mechanism, $\Sigma\, m_i^*$; [2]Total mass of counterweight $\Sigma\, m_i^{*b}$

[3]Links *i*=1, 3, and 5 are considered for counterweights only.

Table 3 RMS values for the scrapping mechanism

Method	Sh. force $\tilde{f}_{sh}$ (N)	Sh. moment $\tilde{n}_{sh}$ (Nm)
Original	49.99	6.90
Mass redistribution method w_1=0.5;w_2=0.5	13.61(73)	5.13(26)
Counterweight method w_1=0.5;w_2=0.5	44.74(11)	5.84(15)

The values in parentheses denote round-off percentage decrease over the corresponding values for the original mechanism

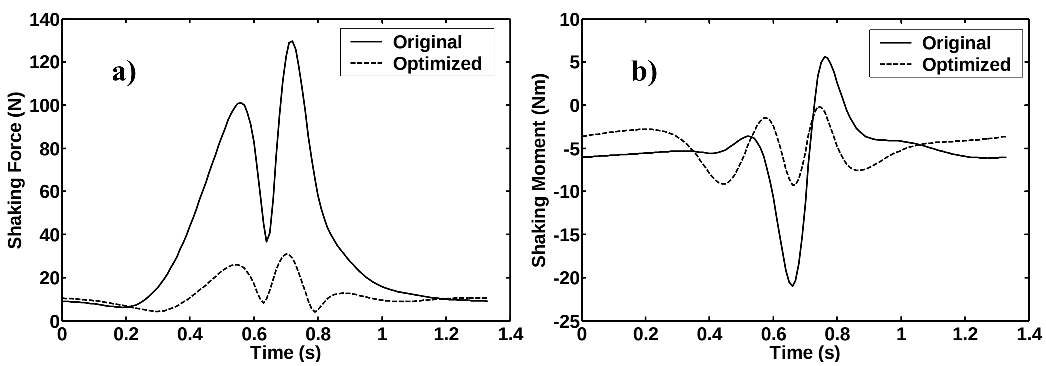


Fig. 6 Dynamic performances of the carpet scrapping mechanism using mass redistribution method: a) shaking force; b) shaking moment

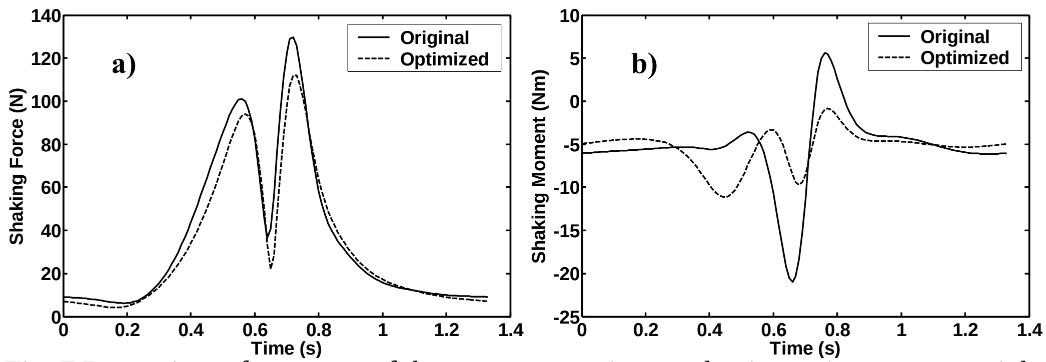


Fig. 7 Dynamic performances of the carpet scrapping mechanism using counterweight method: a) shaking force; b) shaking moment

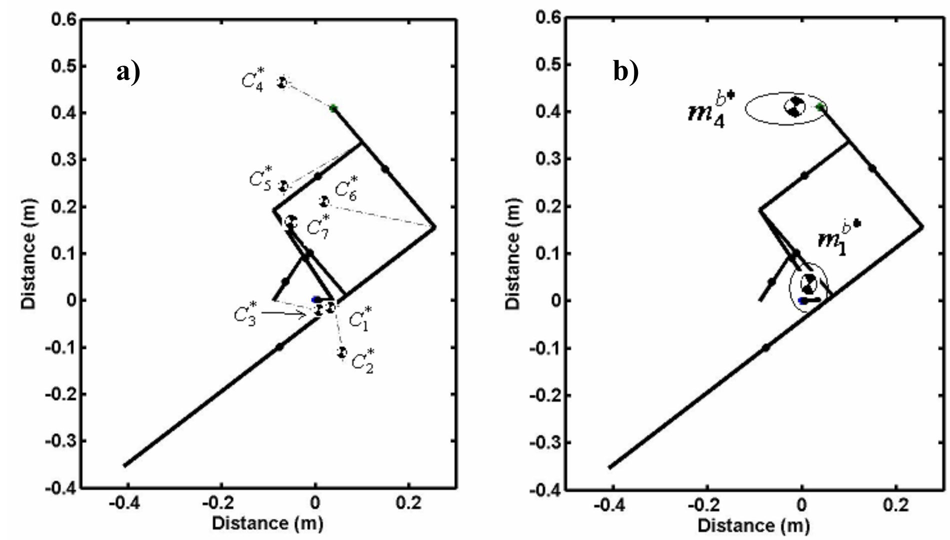


Fig. 8 Locations of link mass centres: a) Mass redistribution of all links; b) Counterweights to link 1 and 4

5. Conclusions

A mathematical formulation is presented to improve vibration and other dynamic performance characteristics of a carpet scrapping machine developed to help the carpet washers. Concept of equimomental system of point-masses to represent a rigid link moving in a plane is used to formulate the optimization problem. Mass distribution and counterweight methods are used to minimize shaking force and shaking moment that effectively will reduce vibration in existing machine. Counterweight method can be immediately implemented in the real machine. Practical problem faced by rural carpet industries of India is solved using the most advanced tools of dynamics and optimization that are frequently applied in robotics, vehicle dynamics, and other popular areas.

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