Chapter 9
Dynamic Modeling of a Sheep Hair Shearing Device Using RecurDyn and Its Verification

Sasanka Sekhar Sinha and Subir Kumar Saha

Abstract This paper discusses a general procedure for creating a computer-aided design (CAD) model of an existing commercial sheep hair shearing device for simulation purpose. In this paper, simulation was carried out using the commercial software RecurDyn while the CAD models of the components of the device were created using SolidWorks software. Note that the mechanism in the device can be identified as an RCCR spatial four-bar linkage which was also modeled analytically from its kinematics point of view. The dynamic equations of motion were developed using the concept of the cut-joint approach and the Decoupled Natural Orthogonal Complement (DeNOC) matrices. The equations of motion were then used to simulate the mechanism in Matlab environment. The results were compared to those obtained using the CAD model in RecurDyn environment.

Keywords Sheep · Wool · Spatial · Four-bar · RCCR · RecurDyn · Lagrange multipliers

9.1 Introduction

A sheep hair shearing device is used to cut the woolen fleece of sheep. It is a power-driven machine-shear substitute for the traditional scissors to reduce the drudgery of operation. The device consists of a motor, handpiece, flexible drive, comb and cutter. The essential details of the device are shown in Fig. 9.1. From kinematic point of view, the device is a spatial four-bar mechanism housed in an ergonomic chamber called the barrel shown in Fig. 9.1a. Motor provides rotary torque input to the crank by means of a flexible shaft coupling as shown in Fig. 9.1b. A fork connects the crank to a toothed blade or cutter which is driven back and forth over the surface of a comb, causing the shearing of wool. The cutter constantly presses against the

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E. Zahariev, J. Cuadrado (eds.), *IUTAM Symposium on Intelligent Multibody Systems – Dynamics, Control, Simulation*, IUTAM Bookseries 33,
https://doi.org/10.1007/978-3-030-00527-6_9

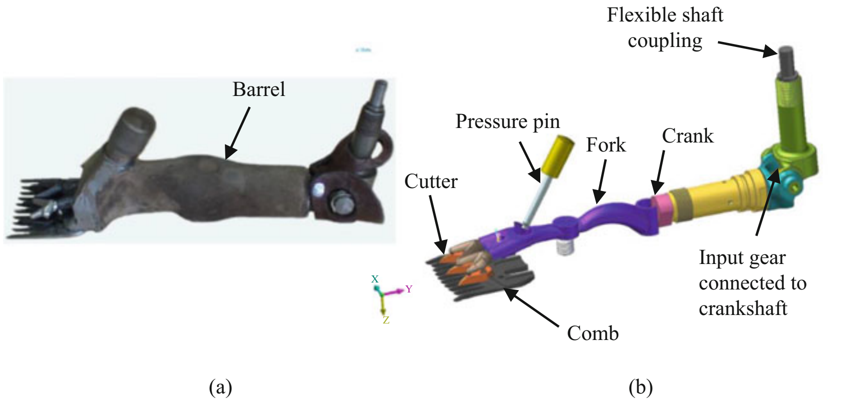

Fig. 9.1 (**a**) An actual handpiece, (**b**) CAD Model. Essential components of a sheep hair shearing device

comb and the pressure can be adjusted by means of a pressure adjustment pin. This has a direct impact on the cutting efficiency and the power consumption.

The device is manufactured by many companies in the world, e.g., Heiniger, Lister, Oster and others. Presently, it is imported at high costs in India. The Rural Technology Action Group (RuTAG) at IIT Delhi in India has been trying to develop an indigenous version since 2006. Presently, it is working on the mass scale manufacturing of the device. In order to choose appropriate materials for the components and processes to manufacture them, it was felt important that the complete dynamic analysis of an existing device be performed for deeper understanding of the interactions between the components. Therefore, a RecurDyn [1] model was attempted using the existing CAD models of the components.

In order to verify the RecurDyn results, an analytical model based on the kinematic architecture of the device which is an RCCR (revolute-cylindrical-cylindrical-revolute) spatial four-bar mechanism, was also developed. Compared to other spatial four-bar linkages like the well-known Bennett's linkage [2, 3] and the RSSR mechanisms [4] which have been studied extensively, there is not much work done on the kinematic and dynamic analysis of the RCCR mechanism to the best of the authors' knowledge. The dynamic equations of motion of the RCCR mechanism were generated using the cut-joint approach [5] and the concept of the DeNOC matrices [6]. The results were then compared to verify the outputs of RecurDyn software and the DeNOC-based dynamic model in Matlab environment.

Note that similar analyses have been reported in the literature for improved performance of a developed system. For example, Chaudhary et al. [7] developed a multiloop planar carpet scraping mechanism using a Hoeken's four-bar mechanism and a Pantograph. The cut-joint approach was used to develop the dynamic equations of motion. A comparison of the calculated driving torques was made with the values obtained from ADAMS (Automatic Dynamic Analysis of Mechanical Systems) software. Wang [8] simulated a high-speed cutting tool system in ADAMS environment and predicted any possible dynamic interference through analysis, which was later used for optimized design. Prior work on the sheep hair shearing device at IIT Delhi by Rane et al. [9] focused on the study of various kinematic and dynamic parameters, e.g., angle of fork oscillations, torque required at the crankshaft, etc. They had performed a simulation study in ADAMS but analytical expressions were derived only for the kinematics. So an analytical dynamic model was not available for comparison of the results and design optimization purpose. In this domain, one of the pioneering publications was made by Trevelyan [10] towards sensing and control of sheep-shearing robots.

The paper is organized as follows: Sect. 9.2 deals with solid modeling of various components of the sheep hair shearing device at hand. Section 9.3 discusses the model preparation and assembly details for the simulation performed in RecurDyn software. Section 9.4 delineates the simplified kinematic model chosen to replicate the behavior of the actual model. The dynamic formulation of the simplified RCCR model is also presented in this section. Lastly, Sect. 9.5 is concerned with the discussion of the results obtained from the study.

9.2 CAD Modeling of the Components

Each component of the device was scanned under a white light scanner and its shape was obtained as a point cloud of geometric samples on the surface. The measured data was devoid of any topological information. They were processed and modeled into a usable format. The level of sophistication proceeded as polygonal mesh models, NURBS surface models to editable feature-based solid models.

The first step of reconstruction to polygonal model involved finding and connecting adjacent points with straight lines in order to create a continuous surface. To do this, MeshLab was used. It is an open source, portable, and extensible system for the processing and editing of unstructured 3D triangular meshes [11]. Remeshing filters helped in surface reconstruction from points. Mesh Cleaning Filters aided removal of duplicated, unreferenced vertices, null faces, small isolated components and automatic filling of holes. MeshLab also converted .stl graphics to a normal .stl mesh file. White light scanned image and the polygonal mesh model for the comb are shown in Figs. 9.2 and 9.3, respectively.

The next step was to export into a CAD software to complete the model in CAD. Typical CAD software packages offer two basic methods for the creation of surfaces. First is the construction of curves (splines) from which the 3D surface is obtained through sweep or meshed through, and the second one is the direct creation of the surface with manipulation of the control points. Commercial CAD software SolidWorks [12] was used in the present simulation study. A combination of the geometric and freeform surfaces was used to render the mathematical identity. The end results were editable parametric CAD models for each component.

The objects and features of each created solid model were modifiable, and thereby, provided the scope for product improvement. The CAD model was then easily converted into the .step format. The G-codes can then be generated, if required, for subsequent CNC machining. The individual CAD files were assembled

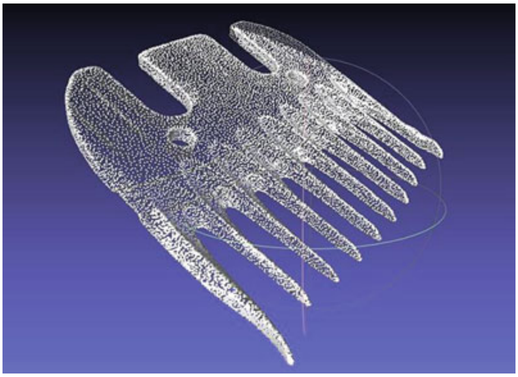

Fig. 9.2 White light scanned image of a comb

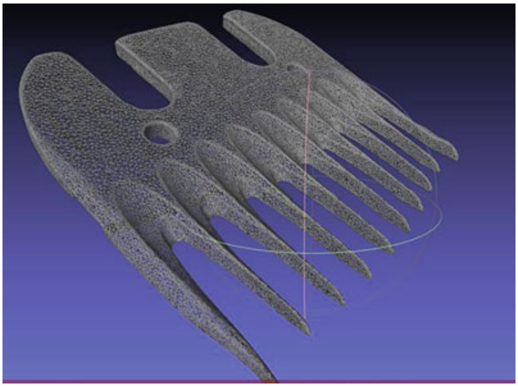

Fig. 9.3 Polygonal mesh model of the comb

together and the assembly of the handpiece is shown in Fig. 9.4. Once the CAD assembly of the handpiece was available, the sheep hair shearing device was subjected to motion analysis to check possible interference of the links during operation. Corrections were made and clearances were provided to accommodate free movement of the links by exploring the capabilities of the CAD software. It is much simpler to investigate a product in the CAD environment and incorporate changes before the real prototype is made. The model was then ready for the dynamic analysis, which can calculate the power consumption of the device for a prescribed angular velocity of the crankshaft, forces on the various components, etc.

9.3 Modeling in RecurDyn

RecurDyn has its own Modeler to create an analysis model. Alternatively, existing CAD files can also be imported in various formats. In our case, the assembly was imported in Parasolid format in RecurDyn V8R3. The joints were defined in the

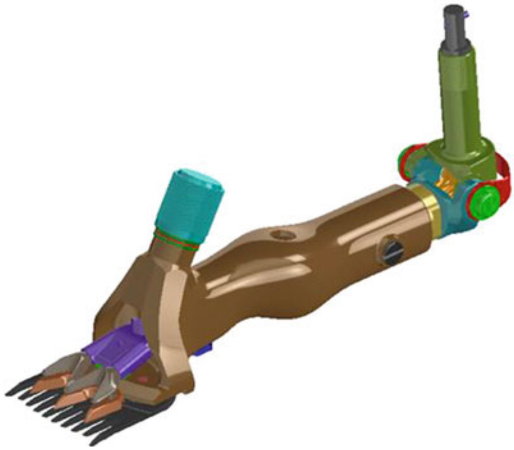

Fig. 9.4 CAD assembly of a handpiece

RecurDyn preprocessor environment. The crankshaft has one revolute joint with the barrel, which is ground for our analysis, and one cylindrical joint with the sliding ball. The fork has a cylindrical joint with the sliding ball and a revolute joint with the barrel. A spherical joint connects the pressure pin with the fork. RecurDyn is particularly efficient in handling contact problems. In the shearing device, there are quite a few places where contact modeling was required. For example, between the cutter and the comb, there is a contact which causes the rubbing action.

9.4 Inverse Dynamics

The model as shown in Fig. 9.4 is essentially a single degree-of-freedom (DoF) spatial four-bar mechanism which is shown in Figs. 9.5 and 9.6a. The joints at A and D are the revolute (R) joints with rotations θ_1 and θ_2, respectively. The joints at B and C are cylindrical (C) joints. The axes of the first two joints are parallel to each other, and so are the last two joints. The two sets of axes are perpendicular to each other. Using the cut-loop strategy for dynamic modeling as mentioned in [2], the two cylindrical joints were cut resulting in three serial open-loop subsystems. They are shown in Fig. 9.6b.

Two of the sub-systems are single-link planar serial manipulators while the third one consists of a floating body. The kinematic constraints lost due to the cut joints were recovered with the help of Lagrange multipliers. Let m_1 and m_2 be the masses, and I_{1zz} and I_{2zz} be the mass moment of inertia of the single-link subsystems. Also m_3 be the mass of the floating body of subsystem #3.The dynamic equations of motion for the first sub-system can be obtained easily as:

$$\mathbf{I}_I \ddot{\boldsymbol{\theta}}_I + \mathbf{C}_I \dot{\boldsymbol{\theta}}_I + \boldsymbol{\gamma}_I = \boldsymbol{\tau}_I + \mathbf{J}_I^T \boldsymbol{\lambda}_I \tag{9.1}$$

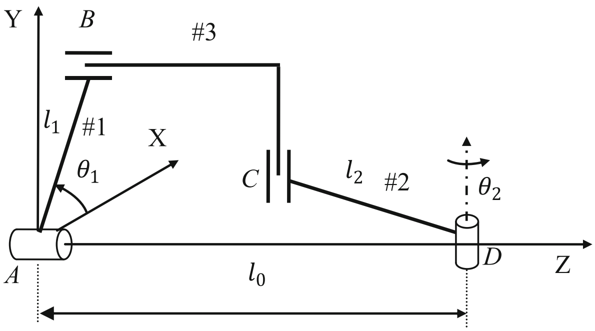

Fig. 9.5 Simplified model of sheep the hair shearing 4-bar mechanism

where the only term in the inertia matrix $\mathbf{I}_I$, i.e., scalar i_1 is $i_1 = m_1 r_1^2 + I_{1zz}$, $r_1$being the distance of the center of mass (COM) of the link from the revolute joint. The Coriolis and Centrifugal term in $\mathbf{C}_I \dot{\boldsymbol{\theta}}_I$ does not exist for the single-link manipulator. The joint torque of sub-system I is denoted as $\boldsymbol{\tau}_I = \tau_1$. The vector of Lagrange multipliers is $\lambda_I = [\lambda_{1x} \;\; \lambda_{1y}]^T$. It is to be noted that there is no λ_{1z} as the cylindrical joint offers no resistance in the sliding direction. The Jacobian matrix of the sub-system I is $\mathbf{J}_I = \begin{bmatrix} -l_1 \sin\theta_1 \; l_1 \cos\theta_1 \end{bmatrix}^T$. Similarly, for sub-system II the dynamic equations of motion are written as:

$$\mathbf{I}_{II} \ddot{\boldsymbol{\theta}}_{II} + \mathbf{C}_{II} \dot{\boldsymbol{\theta}}_{II} + \boldsymbol{\gamma}_{II} = \boldsymbol{\tau}_{II} + \mathbf{J}_{II}^T \boldsymbol{\lambda}_{II} \tag{9.2}$$

where $\mathbf{I}_{\text{II}}$ also has one term, i.e., scalar $i_2 = m_2 r_2^2 + I_{2zz}$, where r_2 is the distance of the COM of the link from the revolute joint. There is no Coriolis and Centrifugal term. The joint torque of the sub-system II is 0, i.e., $\boldsymbol{\tau}_{II} = \mathbf{0}$. The vector of Lagrange multipliers is $\boldsymbol{\lambda}_{II} = \begin{bmatrix} \lambda_{2x} \; \lambda_{2z} \end{bmatrix}^T$ with vanishing λ_{2y}. The coordinates of the point C can be written as $(l_2 \;\sin\theta_2, 0, l_0 + l_2 \cos\theta_2)$. Subsequently, the Jacobian matrix for the sub-system II is obtained as $\mathbf{J}_{II} = \begin{bmatrix} -l_2 \sin\theta_2 \; l_2 \cos\theta_2 \end{bmatrix}^T$. The Newton's equations of motion for the subsystem III are then expressed as:

$$m_3 \begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{bmatrix} = - \begin{bmatrix} \lambda_{1x} + \lambda_{2x} \\ \lambda_{1y} \\ \lambda_{2z} \end{bmatrix} \tag{9.3}$$

The floating body is in rotational equilibrium. So no Euler equations of motion were considered. The coordinates of the COM of the floating body can be written as $(l_1 \cos\theta_1, l_1 \sin\theta_1 + k_1, l_2 \cos\theta_2 + k_2)$, where k_1 and k_2 are constants. The angle θ_2 can be obtained from the loop-closure constraint in the x-direction as

$$l_1 \cos\theta_1 - l_2 \sin\theta_2 = 0 \tag{9.4}$$

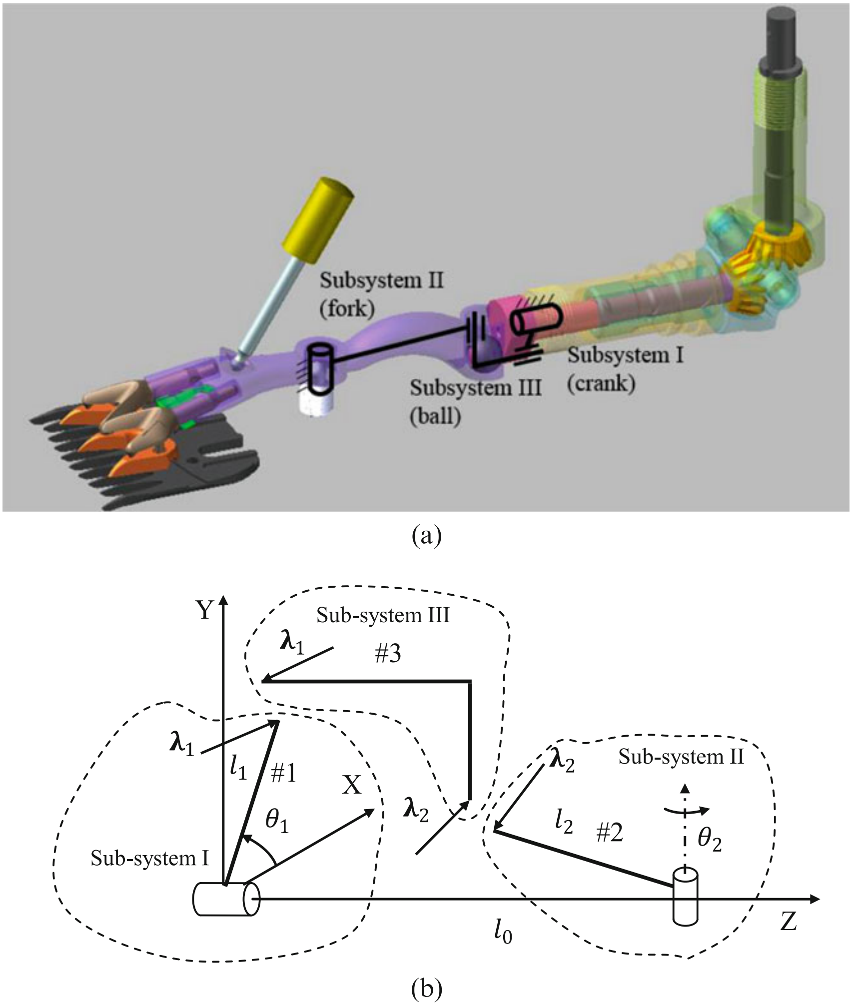

Fig. 9.6 Three cut-open subsystems

Since we have only one equation to solve for θ_2, it yields to

$$\theta_2 = \begin{cases} \pi - \sin^{-1}\left(\frac{l_1 \cos\theta_1}{l_2}\right), if\ \cos\theta_1 \geq 0 \\ \pi + \sin^{-1}\left(\frac{-l_1 \cos\theta_1}{l_2}\right), otherwise \end{cases} \tag{9.5}$$

Equations (9.1–9.3) are now rewritten in a compact form as

$$\begin{bmatrix} \varphi_I \\ \varphi_{II} \\ m_3\ddot{x} \\ m_3\ddot{y} \\ m_3\ddot{z} \end{bmatrix} = \begin{bmatrix} 1 & \mathbf{J}_I(1,1) & \mathbf{J}_I(2,1) & 0 & 0 \\ 0 & 0 & 0 & \mathbf{J}_{II}(1,1) & \mathbf{J}_{II}(2,1) \\ 0 & -1 & 0 & -1 & 0 \\ 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} \tau_1 \\ \lambda_{1x} \\ \lambda_{1y} \\ \lambda_{2x} \\ \lambda_{2z} \end{bmatrix} \tag{9.6}$$

where φ_I and φ_{II} are the terms appearing on the left-hand sides of Eqs. (9.1) and (9.2), respectively. Equation (9.6) can be evaluated to get the input torque required to drive the crank.

9.5 Results and Discussion

The crank is given a constant angular velocity of 3000 rpm. The structural and mass-inertia parameters of the model are enumerated in Table 9.1.

Corresponding angular displacement of the fork is plotted in Fig. 9.7. The no-load torque at the crank calculated using Eq. (9.6) is plotted in Fig. 9.8. This torque is well within the specified torque limits of the motor used, i.e., 1800 Nmm. For mechanical design calculations of the components, one can account for the

Table 9.1 Structural and mass-inertia parameters for the RCCR model

Component	m_i (kg)	l_i (mm)	r_i (mm)	I_i $(kgmm^2)$
Crank	6.402e–2	7.794	0.5	1.639
Fork	0.115	57.8	10	280
Ball	5.06e-3	–	–	–

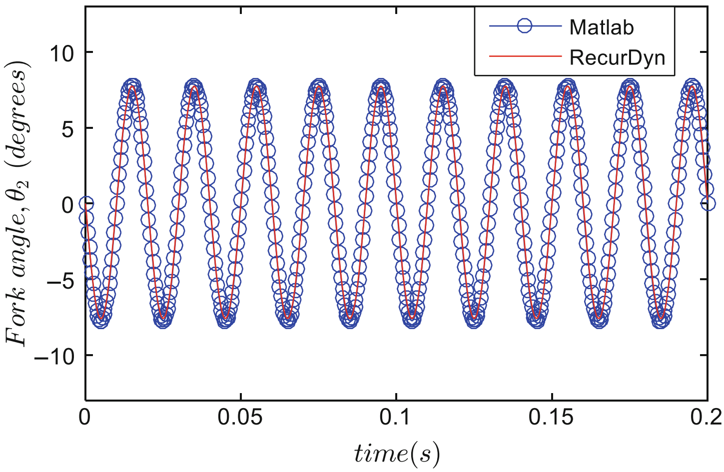

Fig. 9.7 Output motion at the fork end

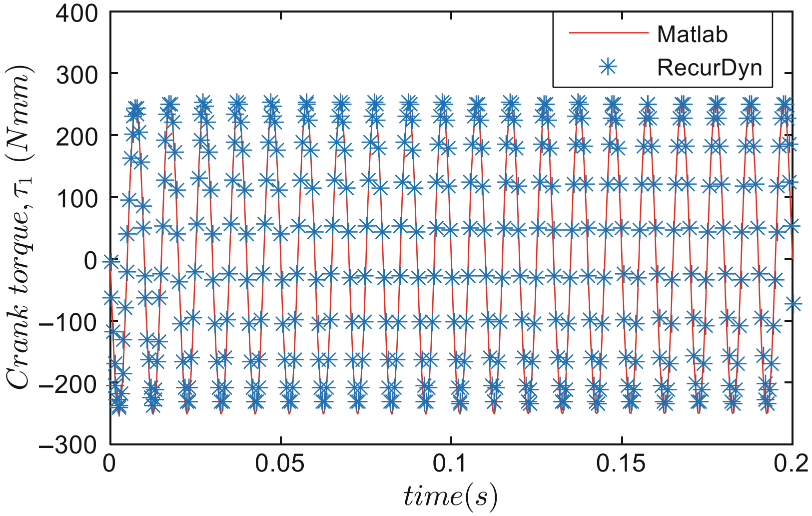

Fig. 9.8 Torque requirement at the crank

assumption of no friction considering a safety factor of 3–4 which yields the maximum required torque to be around 1000 Nmm. The fork completes one complete cycle of oscillation for every rotation of the crank leading to a gear ratio of 1.

9.6 Conclusions

The paper proposes the dynamic simulation of a sheep hair shearing device using commercial software, RecurDyn. It was also shown that the basic mechanism used for the device is a four-bar one-DoF spatial mechanism. Its dynamics modeling is also proposed using the cut-joint approach which provided the required joint-torque at the crank that is same as obtained using RecurDyn. The in-house or RecurDyn model can be easily adapted for further design improvement of the device which will be taken up in future.

Acknowledgments The work presented in this paper was carried out under Project No. RP03164 at Indian Institute of Technology (IIT) Delhi in India. It was funded by the Central Wool Development Board of India. The objective of the project was "Dissemination of low-cost sheep hair shearing device by IIT Delhi." The authors would like to thank the members of Rural Technology Action Group (RuTAG) IIT Delhi for their much-extended help and support.

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