The kinematic and kinetostatic study of the shaker mechanism with SolidWorks Motion

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Abstract. The objective of the paper is to calculate the kinematic and dynamic behaviour of the shaker mechanism and compare the theoretical with the following SolidWorks Motion results: the positional analysis, kinematic analysis of velocities, kinematic analysis of accelerations and kinetostatic analysis.

1. Introduction
The crank mechanism transforms the circular movement of the leading element into a translation of the driven element [1-3]. It has numerous applications, among which we just mention the actuation of devices used in structural analysis [4-6] and fatigue tests [7]. The positional parameters represent the linear displacements of the component’s specific points. The kinematic parameters of the mechanism are the linear velocities and accelerations. The kinetostatic analysis calculates the reaction forces and moments. If necessary, a fatigue analysis of the components can be accomplished [8].

2. The shaker mechanism geometry and main parameters
The shaker mechanism geometry presented in Figure 1 is composed from three beams identified as ◊, □ and △ with 6 mm thickness and the following lengths: L₁=100 mm, L₂=110 mm, L₃ = 120 mm. The specific points C₁, C₂ and C₃ represent the mass centre of the beams. The initial position of the mechanism is defined by the angle ϕ=20°, variable during mechanism movement between 20° ÷105°. The mechanism is driven by beam ◊ with constant rotational velocity n₁=1 rot/min equivalent with angular velocity ω₁=0.105 rad/s which corresponds to 6 degree/second. Knowing that during 1 second the beam ◊ rotate with 6 degrees, for 105° - 20° = 85° interval results the maximum time of the study equal with 85/6=14.17 seconds. The rigid angle α=60° between beam △ and X direction is constant. The beams are made from “Plan Carbon Steel”. The mass and the moments of inertia of the beams calculated by SolidWorks are m₁=49.81, m₂=54.49 and m₃=59.17 grams, respectively J₁=4.78E-05, J₂=6.24E-05 and J₃=7.97E-05 kg · m². For gravitational acceleration g=9.8065 m/s², the following weight results: G₁=0.4886, G₂=0.5345 and G₃=0.5805 N. The resistance force F_r=100 N acts on D point of the mechanism on opposite direction relative to the positive X axis. The successive positions of the shaker mechanism, in accordance to [6], are presented in Figure 2.
3. Theoretical background and numerical results
The positional analysis parameters, Table 1, represent the linear displacements of the component’s specific points, which can be calculated, in accordance to [5], with the analytical relations 1 to 16:

\begin{align}
X_A &= 0 \\
Y_A &= 0 \\
X_B &= L_1 \cdot \cos(\varphi) \\
Y_B &= L_1 \cdot \sin(\varphi) \\
X_C &= L_1 \cdot \cos(\varphi) + L_2 \cdot \cos(\beta) \\
Y_C &= L_1 \cdot \sin(\varphi) + L_2 \cdot \sin(\beta) \\
X_D &= L_1 \cdot \cos(\varphi) + L_2 \cdot \cos(\beta) + L_3 \cdot \cos(\alpha) \\
Y_D &= 0
\end{align}
\[ X_{c1} = L_1 \cdot \cos(\varphi) / 2 \]  
\[ Y_{c1} = L_1 \cdot \sin(\varphi) / 2 \]  
\[ X_{c2} = L_1 \cdot \cos(\varphi) + L_2 \cdot \cos(\beta) / 2 \]  
\[ Y_{c2} = L_1 \cdot \sin(\varphi) + L_2 \cdot \sin(\beta) / 2 \]  
\[ X_{c3} = L_1 \cdot \cos(\varphi) + L_2 \cdot \cos(\beta) + L_3 \cdot \cos(\alpha) / 2 \]  
\[ Y_{c3} = L_3 \cdot \sin(\alpha) / 2 \]  
\[ \beta = \arcsin \left( \frac{L_3 \cdot \sin(\alpha) - L_1 \cdot \sin(\varphi)}{L_2} \right) \]  

where \( \beta \in [0 \text{.. } 90^\circ] \)

**Table 1.** The positional parameters

| \( \varphi \) (grd) | \( X_B \) (mm) | \( Y_B \) (mm) | \( X_C \) (mm) | \( Y_C \) (mm) | \( \beta \) (mm) | \( X_D \) (mm) | \( Y_D \) (mm) | \( X_{C1} \) (mm) | \( Y_{C1} \) (mm) | \( X_{C2} \) (mm) | \( Y_{C2} \) (mm) | \( X_{C3} \) (mm) | \( Y_{C3} \) (mm) |
|-------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 20                | 94.0           | 34.2           | 179.1          | 103.9          | 39.33          | 239.1          | 0              | 47.0           | 17.1           | 136.5          | 69.1           | 209.1          | 52.0           |
| 25                | 90.6           | 42.3           | 181.7          | 103.9          | 34.09          | 241.7          | 0              | 45.3           | 21.1           | 136.2          | 73.1           | 211.7          | 52.0           |
| 30                | 86.6           | 50.0           | 182.5          | 103.9          | 29.35          | 242.5          | 0              | 43.3           | 25.0           | 134.5          | 77.0           | 212.5          | 52.0           |
| 35                | 81.9           | 57.4           | 181.6          | 103.9          | 25.04          | 241.6          | 0              | 41.0           | 28.7           | 131.7          | 80.6           | 211.6          | 52.0           |
| 40                | 76.6           | 64.3           | 179.2          | 103.9          | 21.12          | 239.2          | 0              | 38.3           | 32.1           | 127.9          | 84.1           | 209.2          | 52.0           |
| 45                | 70.7           | 70.7           | 175.6          | 103.9          | 17.57          | 235.6          | 0              | 35.4           | 35.4           | 123.1          | 93.5           | 191.5          | 52.0           |
| 50                | 64.3           | 76.6           | 170.8          | 103.9          | 14.38          | 230.8          | 0              | 32.1           | 38.3           | 117.6          | 90.3           | 200.8          | 52.0           |
| 55                | 57.4           | 81.9           | 165.1          | 103.9          | 11.54          | 225.1          | 0              | 28.7           | 41.0           | 111.2          | 92.9           | 195.1          | 52.0           |
| 60                | 50.0           | 86.6           | 158.6          | 103.9          | 9.06           | 218.6          | 0              | 25.0           | 43.3           | 104.3          | 95.3           | 188.6          | 52.0           |
| 65                | 42.3           | 90.6           | 151.5          | 103.9          | 6.94           | 211.5          | 0              | 21.1           | 45.3           | 96.9           | 97.3           | 181.5          | 52.0           |
| 70                | 34.2           | 94.0           | 143.8          | 103.9          | 5.19           | 203.8          | 0              | 17.1           | 47.0           | 89.0           | 98.9           | 173.8          | 52.0           |
| 75                | 25.9           | 96.6           | 135.6          | 103.9          | 3.82           | 195.6          | 0              | 12.9           | 48.3           | 80.8           | 100.3          | 165.6          | 52.0           |
| 80                | 17.4           | 98.5           | 127.2          | 103.9          | 2.84           | 187.2          | 0              | 8.7            | 49.2           | 72.3           | 101.2          | 157.2          | 52.0           |
| 85                | 8.7            | 99.6           | 118.6          | 103.9          | 2.24           | 178.6          | 0              | 4.4            | 49.8           | 63.7           | 101.8          | 148.6          | 52.0           |
| 90                | 0.0            | 100.0          | 109.9          | 103.9          | 2.04           | 169.9          | 0              | 0.0            | 50.0           | 50.0           | 102.0          | 139.9          | 52.0           |
| 95                | -8.7           | 99.6           | 101.2          | 103.9          | 2.24           | 161.2          | 0              | -4.4           | 49.6       | 46.2           | 101.8          | 131.2          | 52.0           |
| 100               | -17.4          | 98.5           | 92.5           | 103.9          | 2.84           | 152.5          | 0              | -8.7           | 49.2           | 37.6           | 101.2          | 122.5          | 52.0           |
| 105               | -25.9          | 96.6           | 83.9           | 103.9          | 3.82           | 143.9          | 0              | -12.9          | 48.3           | 29.0           | 100.3          | 113.9          | 52.0           |

The kinematic parameters of the mechanism, depicted in Table 2, are the linear velocities and accelerations, which can be calculated in accordance to [3] with the analytical relations 17 to 34:
\[ a^X_c = \varepsilon_2 \cdot (X_C - X_B) - \omega^2 \cdot (Y_B - Y_A) - \omega^2 \cdot (Y_C - Y_B) = 0 \]  
\[ a^X_{c1} = -\omega^2 \cdot (X_{C1} - X_A) \]  
\[ a^X_{c2} = -[\varepsilon_2 \cdot (Y_{C2} - Y_B) + \omega^2 \cdot (X_B - X_A) + \omega^2 \cdot (X_{C2} - X_B)] \]  
\[ a^X_{c2} = \varepsilon_2 \cdot (X_C - X_B) - \omega^2 \cdot (Y_B - Y_A) - \omega^2 \cdot (Y_{C2} - Y_B) \]  
\[ a^X_{c3} = a^X_b = a^X_c \]  
\[ a^X_{c3} = a^X_b = a^X_c = 0 \]  

**Table 2. The kinematic parameters**

| \( \varphi \) (grd) | \( \omega_2 \) (gr/s) | \( \varepsilon_2 \) | \( V^X_B \) (mm/s) | \( V^Y_B \) (mm/s) | \( V^X_C \) (mm/s) | \( V^Y_C \) (mm/s) | \( a^X_b \) (mm/s²) | \( a^Y_b \) (mm/s²) | \( a^X_c \) (mm/s²) | \( a^Y_c \) (mm/s²) | \( a^X_{c1} \) (mm/s²) | \( a^Y_{c1} \) (mm/s²) | \( a^X_{c2} \) (mm/s²) | \( a^Y_{c2} \) (mm/s²) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 20 | 6.63 | 0.88 | -3.6 | 9.8 | 4.5 | 0 | -1.03 | -0.38 | -3.24 | 0 | -0.52 | -0.19 | -2.14 | -0.19 |
| 25 | 5.97 | 0.71 | -4.4 | 9.5 | 2.0 | 0 | -0.99 | -0.46 | -2.75 | 0 | -0.50 | -0.23 | -1.87 | -0.23 |
| 30 | 5.42 | 0.62 | -5.2 | 9.1 | -0.1 | 0 | -0.95 | -0.55 | -2.39 | 0 | -0.47 | -0.27 | -1.67 | -0.27 |
| 35 | 4.93 | 0.56 | -6.0 | 8.6 | -2.0 | 0 | -0.90 | -0.63 | -2.09 | 0 | -0.45 | -0.31 | -1.50 | -0.31 |
| 40 | 4.48 | 0.53 | -6.7 | 8.0 | -3.6 | 0 | -0.84 | -0.70 | -1.83 | 0 | -0.42 | -0.35 | -1.34 | -0.35 |
| 45 | 4.05 | 0.51 | -7.4 | 7.4 | -5.1 | 0 | -0.78 | -0.78 | -1.60 | 0 | -0.39 | -0.39 | -1.19 | -0.39 |
| 50 | 3.62 | 0.51 | -8.0 | 6.7 | -6.3 | 0 | -0.70 | -0.84 | -1.37 | 0 | -0.35 | -0.42 | -1.04 | -0.42 |
| 55 | 3.19 | 0.51 | -8.6 | 6.0 | -7.4 | 0 | -0.63 | -0.90 | -1.16 | 0 | -0.31 | -0.45 | -0.90 | -0.45 |
| 60 | 2.76 | 0.52 | -9.1 | 5.2 | -8.2 | 0 | -0.55 | -0.95 | -0.96 | 0 | -0.27 | -0.47 | -0.75 | -0.47 |
| 65 | 2.32 | 0.53 | -9.5 | 4.4 | -9.0 | 0 | -0.46 | -0.99 | -0.77 | 0 | -0.23 | -0.50 | -0.61 | -0.50 |
| 70 | 1.87 | 0.54 | -9.8 | 3.6 | -9.5 | 0 | -0.38 | -1.03 | -0.59 | 0 | -0.19 | -0.52 | -0.48 | -0.52 |
| 75 | 1.41 | 0.56 | -10.1 | 2.7 | -9.9 | 0 | -0.28 | -1.06 | -0.42 | 0 | -0.14 | -0.53 | -0.35 | -0.53 |
| 80 | 0.95 | 0.56 | -10.3 | 1.8 | -10.2 | 0 | -0.19 | -1.08 | -0.27 | 0 | -0.10 | -0.54 | -0.23 | -0.54 |
| 85 | 0.48 | 0.57 | -10.4 | 0.9 | -10.4 | 0 | -0.10 | -1.09 | -0.15 | 0 | -0.05 | -0.55 | -0.12 | -0.55 |
| 90 | 0.00 | 0.57 | -10.5 | 0.0 | -10.5 | 0 | 0.00 | -1.10 | -0.04 | 0 | 0.00 | -0.55 | -0.02 | -0.55 |
| 95 | 0.48 | 0.57 | -10.4 | -0.9 | -10.4 | 0 | 0.10 | -1.09 | 0.05 | 0 | 0.05 | -0.55 | 0.07 | -0.55 |
| 100 | 0.95 | 0.56 | -10.3 | -1.8 | -10.2 | 0 | 0.19 | -1.08 | 0.11 | 0 | 0.10 | -0.54 | 0.15 | -0.54 |
| 105 | 1.41 | 0.56 | -10.1 | -2.7 | -9.9 | 0 | 0.28 | -1.06 | 0.15 | 0 | 0.14 | -0.53 | 0.21 | -0.53 |

The kinetostatic parameters of the mechanism, indicated in Table 3, result from the equations expressing the equilibrium of the mechanism under the reactions of the joints, the motor torque, the outside forces, the inertia forces and moments. These equations can be written independently for each mechanism component (classical) or may be embedded in a matrix equation (matrix method). The matrix equilibrium equations, see [9] for conformity, can be expressed through relations 36 to 40, where the unknown values are the components of the \{N\} vector, obtained from the equation:

\[
\{N\} = -[R]^{-1} \cdot \{F\}
\]

The matrix equilibrium equation is resolved in Microsoft Excel with VBA code, using \textit{MInverse} function to return the inverse of the matrix \([R]\) and \textit{MMult} function to return the product between \([-R]\)^{-1} and \{F\}.
\[ R \cdot \{N\} + \{F\} = \{0\}, \]

where:

\[
\begin{align*}
\{N\} &= \begin{bmatrix} H_A \\ V_A \\ Mm \\ H_B \\ V_B \\ H_C \\ V_C \\ V_D \\ M_D \end{bmatrix}, \\
\{F\} &= \begin{bmatrix} R_{1x} \\ R_{1y} \\ M_{1A} \\ R_{2x} \\ R_{2y} \\ M_{2A} \\ R_{3x} \\ R_{3y} \\ M_{3A} \end{bmatrix}, \\
\{R\} &= \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -Y_B & X_B & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & Y_C & -X_C & X_D & 1 \end{bmatrix}
\end{align*}
\]

Table 3. The kinetostatic parameters

| \(\varphi\) | \(H_A\) | \(V_A\) | \(H_B\) | \(V_B\) | \(H_C\) | \(V_C\) | \(H_D\) | \(V_D\) | \(M_m\) |
|---|---|---|---|---|---|---|---|---|---|
| 20 | 100 | 80.57 | -100 | -81.05 | -100 | -81.57 | 0.00 | -82.15 | 4.19 |
| 25 | 100 | 66.33 | -100 | -66.81 | -100 | -67.33 | 0.00 | -67.91 | 1.83 |
| 30 | 100 | 54.91 | -100 | -55.38 | -100 | -55.90 | 0.00 | -56.48 | -0.21 |
| 35 | 100 | 45.41 | -100 | -45.89 | -100 | -46.41 | 0.00 | -46.99 | -1.98 |
| 40 | 100 | 37.35 | -100 | -37.82 | -100 | -38.34 | 0.00 | -38.92 | -3.53 |
| 45 | 100 | 30.42 | -100 | -30.89 | -100 | -31.40 | 0.00 | -31.98 | -4.89 |
| 50 | 100 | 24.41 | -100 | -24.88 | -100 | -25.39 | 0.00 | -25.97 | -6.06 |
| 55 | 100 | 19.22 | -100 | -19.69 | -100 | -20.20 | 0.00 | -20.78 | -7.06 |
| 60 | 100 | 14.78 | -100 | -15.24 | -100 | -15.75 | 0.00 | -16.33 | -7.90 |
| 65 | 100 | 11.04 | -100 | -11.50 | -100 | -12.01 | 0.00 | -12.59 | -8.58 |
| 70 | 100 | 7.98 | -100 | -8.45 | -100 | -8.95 | 0.00 | -9.53 | -9.11 |
| 75 | 100 | 5.61 | -100 | -6.07 | -100 | -6.58 | 0.00 | -7.16 | -9.50 |
| 80 | 100 | 3.92 | -100 | -4.38 | -100 | -4.89 | 0.00 | -5.47 | -9.77 |
| 85 | 100 | 2.92 | -100 | -3.38 | -100 | -3.88 | 0.00 | -4.46 | -9.93 |
| 90 | 100 | 2.60 | -100 | -3.07 | -100 | -3.57 | 0.00 | -4.15 | -10.00 |
| 95 | 100 | 2.99 | -100 | -3.45 | -100 | -3.95 | 0.00 | -4.53 | -9.99 |
| 100 | 100 | 4.06 | -100 | -4.52 | -100 | -5.03 | 0.00 | -5.61 | -9.93 |
| 105 | 100 | 5.82 | -100 | -6.28 | -100 | -6.79 | 0.00 | -7.37 | -9.82 |
4. Creation of the parts geometry and assembly mechanism

The 3D assembly of the shaker mechanism is shown in Figure 3. The components were placed in the assembly with Insert Components command from Assembly toolbar. Then select a part or assembly from the Part/Assembly to Insert list or click Browse to open an existing document. Next, click in the graphics area to place the component or click to place the component origin coincident with the assembly origin. Only the Support component will be placed with the origin coincident with the assembly origin.

By default, the first part placed in an assembly is fixed and has a (f) before its name in the FeatureManager design tree. The other components: beam 1, beam 2 and beam 3 will be placed without this restriction. The A and D joints of the mechanism are placed in Top Plane of the assembly. Every beam was provided with sketch points C1, C2 and C3 which represent the mass centre. Also, sketch points were placed symmetrical in the holes with diameter $\phi 3$ mm, as shown in Figure 1.

![Figure 3. The 3D assembly of the shaker mechanism](image)
5. The stages of Motion Study
The stages of the study are as follows [10] and [11]:

- Activation of the SolidWorks Motion module;
- Creation and specification of the study’s options;
- Specify Rotary Motor;
- Specify Force;
- Specify Gravity;
- Specify Motion Mates;
- Running the design study.

To specify Rotary Motor click Motor to create a new rotary motor; select the face of the support \( \circ \); select Constant speed from Motor Type list and set 1 rpm value in the speed motor field; click \( \checkmark \) and the Rotary Motor1 branch will be created in the MotionManager design tree (Figure 4).

Click Force to create and apply a force \( F_R \); select Action only option; select the sketch bottom point of beam \( \circ \) as Point of force application; select Right Plane for direction; select Constant from Force Function list; set 100 N value in the Constant value field; click \( \checkmark \) and the Force1 branch will be created in the MotionManager design tree (Figure 5).

Click Gravity to create simulated gravitational forces on the mechanism; select Y axis as direction and 9806.65 mm/s\(^2\) as value (Figure 6).

The mates indicated in Table 4 will be applied in Motion Study between the assembly components.

| Mate name | Mate type     | Component 1          | Component 2          |
|-----------|---------------|----------------------|----------------------|
| Mate1     | Coincident1   | Support \( \circ \) edge | Beam \( \circ \) bottom edge |
| Mate2     | Coincident2   | Beam \( \circ \) top edge | Beam \( \circ \) left edge |
| Mate3     | Coincident3   | Beam \( \circ \) right edge | Beam \( \circ \) top edge |
| Mate4     | Coincident4   | Beam \( \circ \) bottom axis | Top Plane |
| Mate5     | Angle1=60\(^0\) | Top Plane | Beam \( \circ \) face |
| Mate6     | Angle2=20\(^0\) | Top Plane | Beam \( \circ \) face |
The mate Mate6 was only necessary to specify the initial position of the mechanism, but before the motion analysis calculation this mate must be suppresses.

6. Simulation and theoretical results comparison
The results are presented graphically in (Figure 1 ÷ Figure 11), where the SolidWorks Motion points are placed over the theoretical curves. Figure 7 ÷ Figure 8 show the positional parameters in X respectively Y direction: X_B, X_C, X_D, X_C1, X_C2, X_C3, Y_B, Y_C, Y_D, Y_C1, Y_C2, Y_C3. Figure 9 ÷ Figure 10 shows the kinematic parameters: velocity V_B^X, V_B^Y, V_C^X and accelerations a_Bx, a_By, a_Cx, a_Cy, a_C1x, a_C1y, a_C2x, a_C2y. Figure 11 show the kinetostatic parameters of the shaker mechanism: the reaction forces H_A, H_B, H_C, V_A, V_B, V_C and the moment M_m.
Figure 9. The kinematic parameters (velocity) of the shaker mechanism

Figure 10. The kinematic parameters (accelerations) of the shaker mechanism

Figure 11. The kinetostatic parameters of the shaker mechanism
7. Conclusions
We have presented the required steps to analyze the shaker mechanism and obtain the positional, kinematic and kinetostatic parameters through analytical equations and SolidWorks Motion software. The numerical values calculated by theoretical equations were compared graphically with the SolidWorks Motion results. The magnitudes of all results indicated excellent agreement with the values obtained by analysis in SolidWorks Motion software.

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