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 ①, ② and ③ with 6 mm thickness and the following lengths: L_1=100 mm, L_2=110 mm, L_3 = 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 $\varphi=20^o$, variable during mechanism movement between $20^o \div 105^o$. The mechanism is driven by beam ① with constant rotational velocity n_1=1 rot/min equivalent with angular velocity ω_1=0.105 rad/s which corresponds to 6 degree/second. Knowing that during 1 second the beam ① rotate with 6 degrees, for 105^o - 20^o = 85^o interval results the maximum time of the study equal with 85/6=14.17 seconds. The rigid angle $\alpha=60^o$ between beam ③ 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 m_1=49.81, m_2=54.49 and m_3=59.17 grams, respectively J_1=4.78E-05, J_2=6.24E-05 and J_3=7.97E-05 $kg \cdot m^2$. For gravitational acceleration g=9.8065 m/s2, the following weight results: G_1=0.4886, G_2=0.5345 and G_3=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.

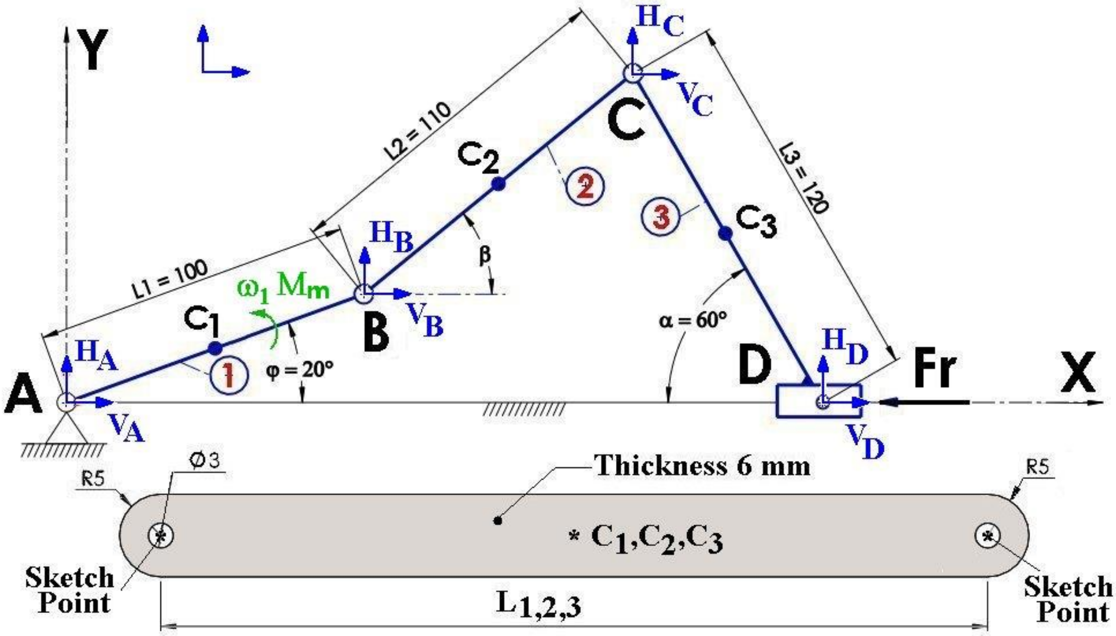

Figure 1. The shaker mechanism geometry

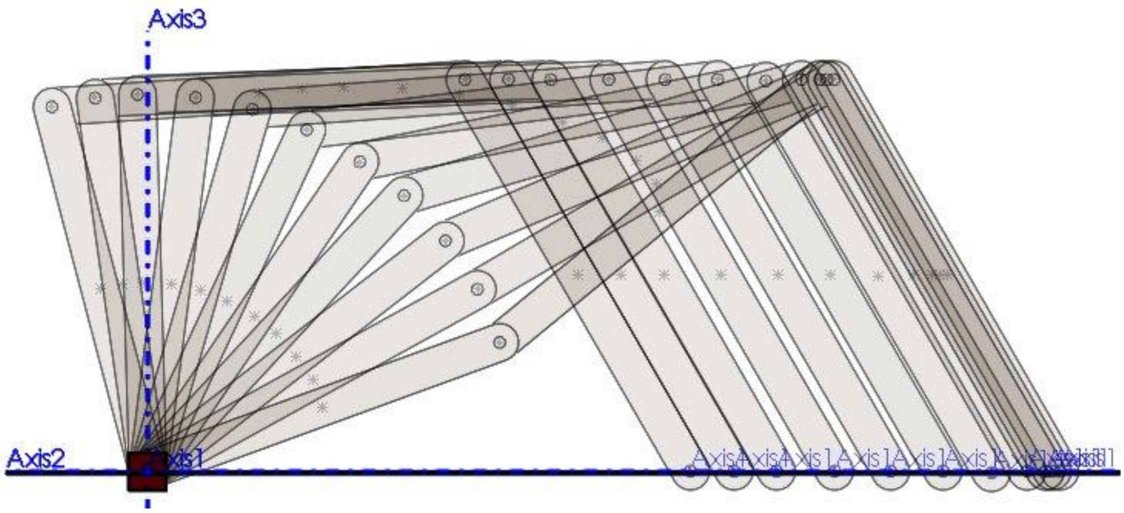

Figure 2. The successive positions of the shaker mechanism

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:

$$X_A = 0 \quad (1) \qquad Y_A = 0 \quad (2)$$

$$X_B = L_1 \cdot \cos(\varphi) \quad (3) \qquad Y_B = L_1 \cdot \sin(\varphi) \quad (4)$$

$$X_C = L_1 \cdot \cos(\varphi) + L_2 \cdot \cos(\beta) \quad (5) \qquad Y_C = L_1 \cdot sin(\varphi) + L_2 \cdot \sin(\beta) \quad (6)$$

$$X_D = L_1 \cdot \cos(\varphi) + L_2 \cdot \cos(\beta) + L_3 \cdot \cos(\alpha) \quad (7) \qquad Y_D = 0 \quad (8)$$

$X_{C_1} = L_1 \cdot \cos(\varphi)/2$ (9) $Y_{C_1} = L_1 \cdot \sin(\varphi)/2$ (10)

$X_{C_2} = L_1 \cdot \cos(\varphi) + L_2 \cdot \cos(\beta)/2$ (11) $Y_{C_2} = L_1 \cdot sin(\varphi) + L_2 \cdot \sin(\beta)/2$ (12)

$X_{C_3} = L_1 \cdot \cos(\varphi) + L_2 \cdot \cos(\beta) + L_3 \cdot \cos(\alpha)/2$ (13) $Y_{C_3} = L_3 \cdot \sin(\propto)/2$ (14)

$$\beta = arcsin\frac{L_3 \cdot \sin(\alpha) - L_1.\sin(\varphi)}{L_2} \quad (15)$$ where $\beta \epsilon [0 \ldots 90^0]$ (16)

Table 1. The positional parameters

φ grd	X_B mm	Y_B mm	X_C mm	Y_C mm	β grd	X_D mm	Y_D mm	X_{C_1} mm	Y_{C_1} mm	X_{C_2} mm	Y_{C_2} mm	X_{C_3} mm	Y_{C_3} 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	87.3	205.6	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	55.0	102.0	139.9	52.0
95	-8.7	99.6	101.2	103.9	2.24	161.2	0	-4.4	49.8	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:

$$\omega_2 = \left|\frac{\omega_1.(X_B - X_A)}{X_C - X_B}\right| \quad (17) \qquad \varepsilon_2 = \frac{\omega_1^2 \cdot (Y_B - Y_A) + \omega_2^2 \cdot (Y_C - Y_B) - \varepsilon_1 \cdot (X_B - X_A)}{(X_C - X_B)} \quad (18)$$

$V_B^X = -\omega_1 \cdot (Y_B - Y_A)$ (19) $V_B^Y = \omega_1 \cdot (X_B - X_A)$ (20)

$V_C^X = -\omega_1 \cdot (Y_B - Y_A) + \omega_2 \cdot (Y_C - Y_B)$ (21) $V_C^Y = \omega_1 \cdot (X_B - X_A) - \omega_2 \cdot (X_C - X_B) = 0$ (22)

$V_D^X = V_C^X$ (23) $V_D^Y = V_C^Y = 0$ (24)

$a_B^X = -\omega_1^2 \cdot (X_B - X_A)$ (25) $a_B^Y = -\omega_1^2 \cdot (Y_B - Y_A)$ (26)

$$a_C^X = -[\varepsilon_2 \cdot (Y_C - Y_B) + \omega_1^2 \cdot (X_B - X_A) + \omega_2^2 \cdot (X_C - X_B)] \quad (27)$$

$$a_C^Y = \varepsilon_2 \cdot (X_C - X_B) - \omega_1^2 \cdot (Y_B - Y_A) - \omega_2^2 \cdot (Y_C - Y_B) = 0 \quad (28)$$

$$a_{C_1}^X = -\omega_1^2 \cdot \left(X_{C_1} - X_A\right) \quad (29) \qquad a_{C_1}^Y = -\omega_1^2 \cdot \left(Y_{C_1} - Y_A\right) \quad (30)$$

$$a_{C_2}^X = -\left[\varepsilon_2 \cdot \left(Y_{C_2} - Y_B\right) + \omega_1^2 \cdot (X_B - X_A) + \omega_2^2 \cdot \left(X_{C_2} - X_B\right)\right] \quad (31)$$

$$a_{C_2}^Y = \varepsilon_2 \cdot \left(X_{C_2} - X_B\right) - \omega_1^2 \cdot (Y_B - Y_A) - \omega_2^2 \cdot \left(Y_{C_2} - Y_B\right) \quad (32)$$

$$a_{C_3}^X = a_D^X = a_C^X \quad (33) \qquad a_{C_3}^Y = a_D^Y = a_C^Y = 0 \quad (34)$$

Table 2. The kinematic parameters

φ grd	ω_2 (gr/s)	ε_2 gr/s^2	V_B^X mm/s	V_B^Y mm/s	V_C^X mm/s	V_C^Y mm/s	a_B^X mm/s^2	a_B^Y mm/s^2	a_C^X mm/s^2	a_C^Y mm/s^2	$a_{C_1}^X$ mm/s^2	$a_{C_1}^Y$ mm/s^2	$a_{C_2}^X$ mm/s^2	$a_{C_2}^Y$ mm/s^2
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, results 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:

$$\{N\} = -[R]^{-1} \cdot \{F\} \quad (35)$$

The matrix equilibrium equation is resolved in Microsoft Excel with VBA code, using *MInverse* function to return the inverse of the matrix $[R]$ and *MMult* function to return the product between $-[R]^{-1}$ and $\{F\}$.

$$\lfloor R \rfloor \cdot \{N\} + \{F\} = \{0\}, \quad (36)$$

where:

$$[R] = \begin{bmatrix} 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -Y_B & X_B & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & Y_B & -X_B & -Y_C & X_C & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & Y_C & -X_C & X_D & 1 \end{bmatrix} \quad (37)$$

$$\{N\} = \begin{bmatrix} H_A \\ V_A \\ M_m \\ H_B \\ V_B \\ H_C \\ V_C \\ V_D \\ M_D \end{bmatrix} \quad (38) \qquad \{F\} = \begin{bmatrix} R_{1x} \\ R_{1y} \\ M_{1A} \\ R_{2x} \\ R_{2y} \\ M_{2A} \\ R_{3x} \\ R_{3y} \\ M_{3A} \end{bmatrix} \quad (39) \qquad \{F\} = \begin{bmatrix} -m_1 \cdot a_{C_1}^X \\ -m_1 \cdot a_{C_1}^Y - G_1 \\ -R_{1x} \cdot Y_{C_1} + R_{1y} \cdot X_{C_1} \\ -m_2 \cdot a_{C_2}^X \\ -m_2 \cdot a_{C_2}^Y - G_2 \\ -J_2 \cdot \varepsilon_2 - R_{2x} \cdot Y_{C_2} + R_{2y} \cdot X_{C_2} \\ -m_3 \cdot a_{C_3}^X + F_R \\ -m_2 \cdot a_{C_2}^Y - G_3 \\ (R_{3x} - F_R) \cdot Y_{C_3} + R_{3y} \cdot X_{C_3} \end{bmatrix} \quad (40)$$

Table 3. The kinetostatic parameters

φ	H_A	V_A	H_B	V_B	H_C	V_C	H_D	V_D	M_m
grd	N	N	N	N	N	N	N	N	N·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 *Suport* ⓪ 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 ϕ3 mm, as shown in Figure 1.

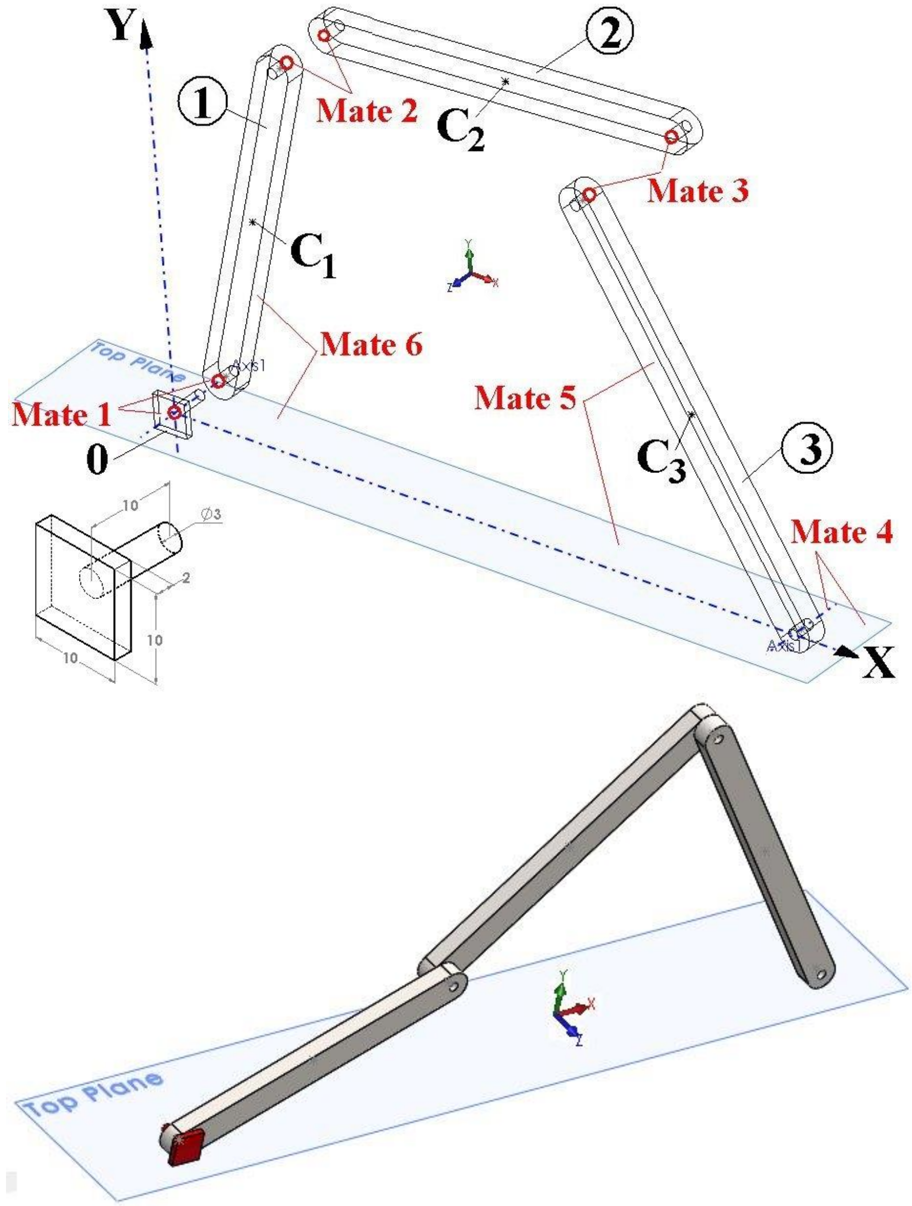

Figure 3. The 3D assembly of the shaker mechanism

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 ⓪; select *Constant speed* from *Motor Type list* and set 1 rpm value in the speed motor field; click ✓ 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 ③ 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 ✓ 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).

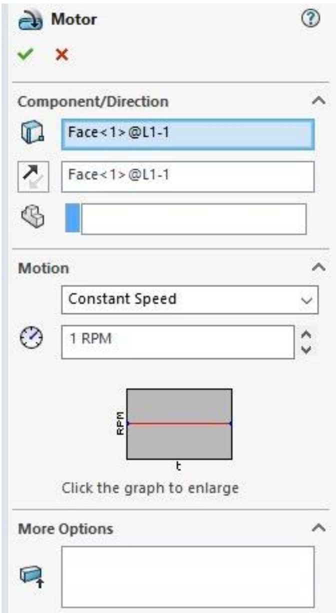

Figure 4. Motor

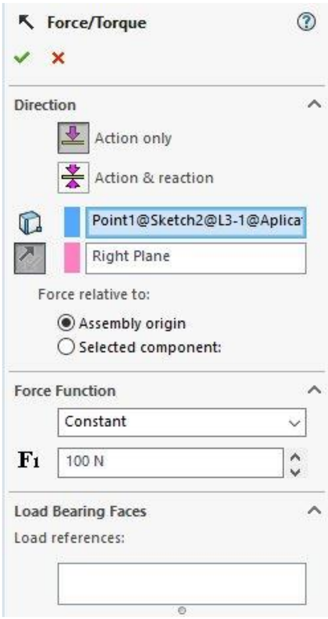

Figure 5. Force

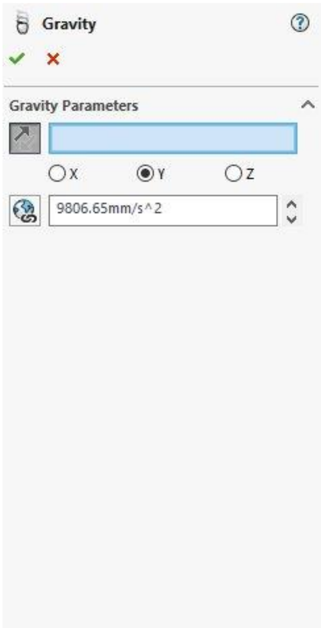

Figure 6. Gravity

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

Table 4. The mates applied to the shaker mechanism

Mate name	Mate type	Component 1	Component 2
Mate1	Coincident1	Support ⓪ edge	Beam ① bottom edge
Mate2	Coincident2	Beam ① top edge	Beam ② left edge
Mate3	Coincident3	Beam ② right edge	Beam ③ top edge
Mate4	Coincident4	Beam ③ bottom axis	Top Plane
Mate5	Angle1=60°	Top Plane	Beam ③ face
Mate6	Angle2=20°	Top Plane	Beam ① 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.

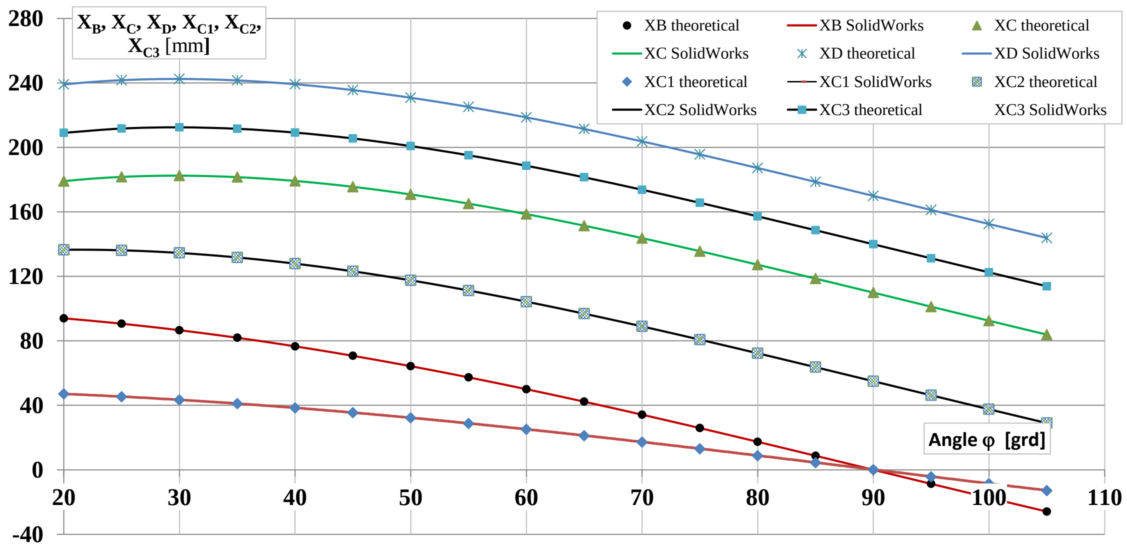

Figure 7. The positional parameters of the shaker mechanism in X direction

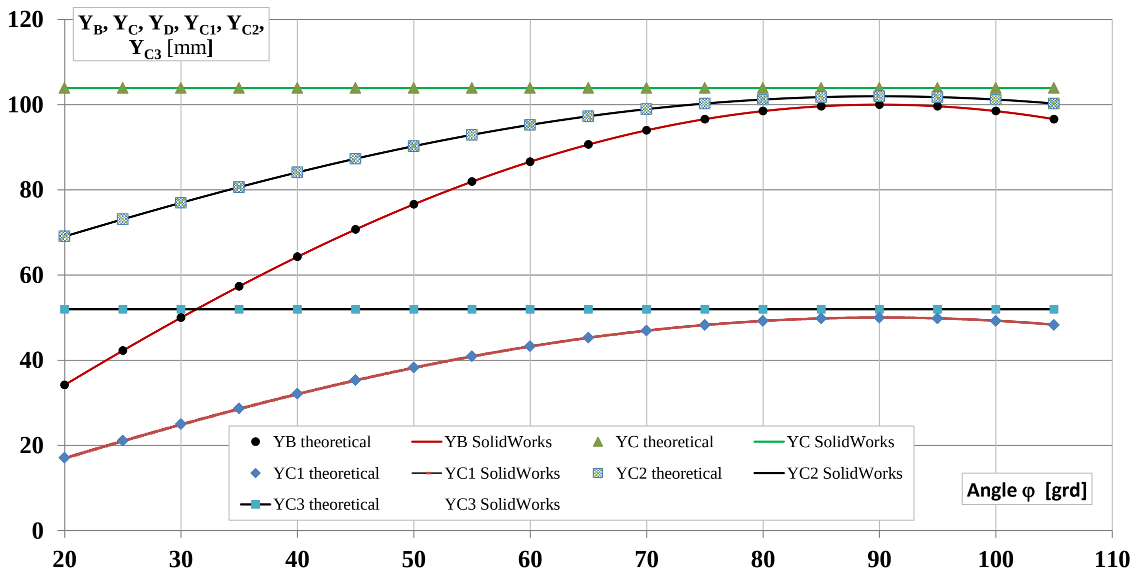

Figure 8. The positional parameters of the shaker mechanism in Y direction

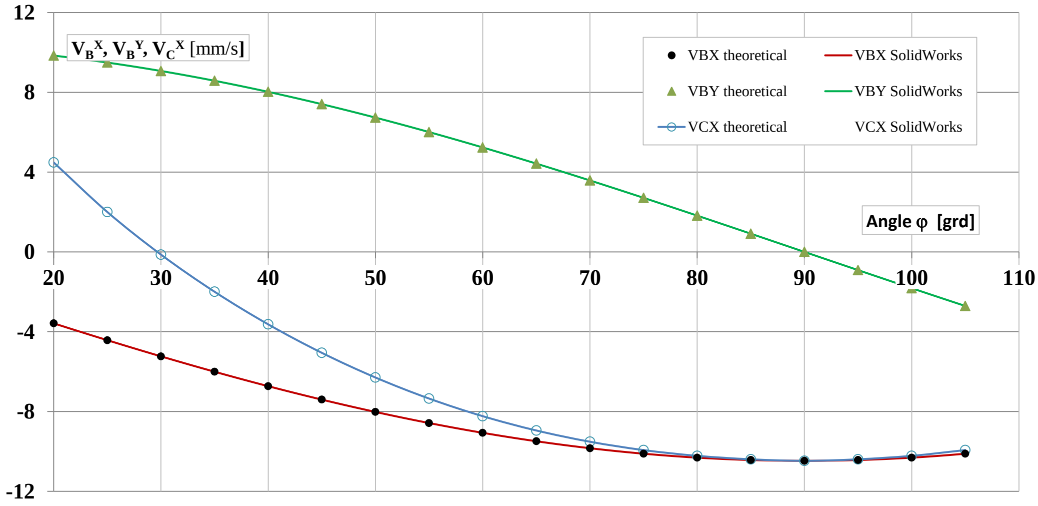

Figure 9. The kinematic parameters (velocity) of the shaker mechanism

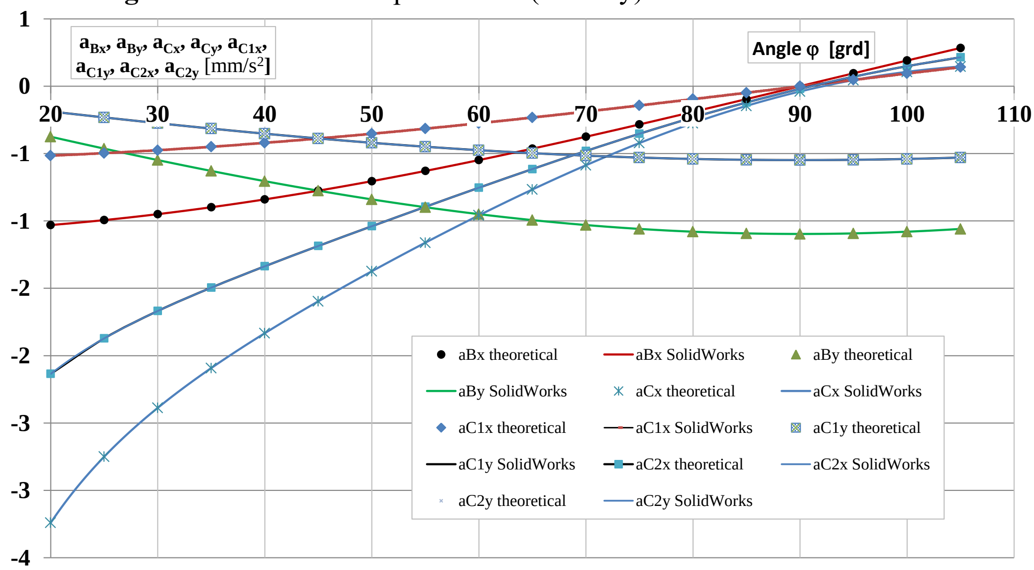

Figure 10. The kinematic parameters (accelerations) of the shaker mechanism

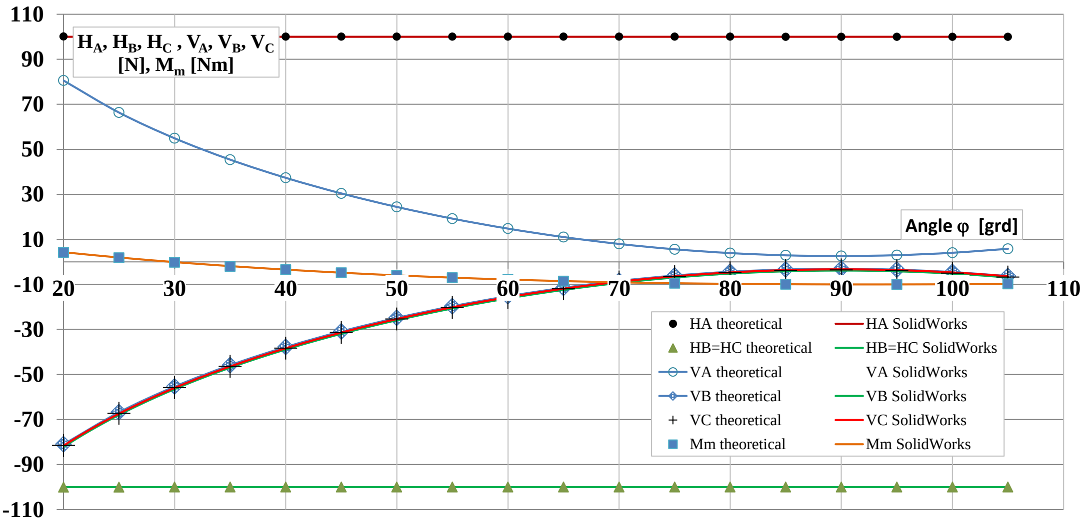

Figure 11. The kinetostatic parameters of the shaker mechanism

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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