# Errata Sheet Apr 2020

## DESIGN OF MECHANISMS WITH SOLIDWORKS MOTION ANALYSIS AND MATLAB/SIMSCAPE

| Page | Presently reads: | Change to |
|---|---|---|
| 1-5 | (Last line) If the **canter** of rotation …. | ….center…. |
| 1-31 | (Fourth line) … the link relative to: | … the link relative to $\mathbf{I_{z1z1}}$: |
| 2-2 | (First Table. Delete Step 3) Step **4** and Step **5** | Step **3** and Step **4** |
| 2-7 | (Fifth line) Complete the **velocity** polygon | Complete the **acceleration** polygon |
| 2-7 | ($10^{th}$ line) ….=3.91 rad/$s^2$ CW | ….=3.91 rad/$s^2$ **CCW** |
| 2-7 | ($2^{nd}$ velocity polygon) $\mathbf{a_{G3}=4989.4}$ | $\mathbf{a_{G3}=5028.8}$ |
| 2-9 | $\omega_4$ = 3.58 rad/sec **CW** | $\omega_4$ = 3.58 rad/sec **CCW** |
| 2-10 | This page has been updated (See below) | |
| 2-12 | (Table) $\alpha_3$=3.91 rad/sec^2 **CW** | $\alpha_3$=3.91 rad/sec^2 **CCW** |
| 2-13 | This page has been updated (See below) | |
| 2-16 | (Fifth line) ..link 2 **is** rotates with angular… | ..link 2 rotates with a **constant** angular…<br>(the angular acceleration of link 2 is zero) |
| 2-19 | The graph on this page has been updated (See below) | |
| 2-20 | The graph on this page has been updated (See below) | |
| 2-21 | (Mechanism sketch-labeling-) link **3** | link **4** |
| 2-23 | (Line $13^{th}$) …be written **in** as … | ….be written as…. |
| 2-26 | (E2.1-Line $3^{rd}$ line) .. angular acceleration of 50 rad/s^2 .. | .. angular acceleration of 50 rad/s^2 **CCW**.. |
| 4-2 | (Sketches labeling) $F_{41}$ | $F_{14}$ |
| 4-8 | (FBD of link 2) the direction of $\mathbf{F^1_{12}}$ should be reversed | |
| 4-8 | $F^1_{43} = \mathbf{8.8}\ lb$<br>$F^1_{23} = \mathbf{14.72}\ lb$ | $F^1_{43} = \mathbf{11}\ lb$<br>$F^1_{23} = \mathbf{18.4}\ lb$ |
| 4-9 | $T^1 = F^1_{32} \times d = 14.72 \times 2.52 = 37.1\ lb.in$ | $T^1 = F^1_{32} \times d = 18.4 \times 2.52 = 46.4\ lb.in$ |
| 4-10 | $T = T^1 + T^2 = 18.2 + 26.1 = 44.34\ lb.in$ | $T = T^1 + T^2 = 46.4 + 26.1 = 72.5 lb.in$ |
| 4-12 | ($2^{nd}$ row in the Table) $\omega_2$ | $\boldsymbol{\omega_3}$ |
| 4-13 | (FBD of link 2) $M_3$ | $\mathbf{M_{12\text{-}3}}$ |
| 4-18 | (Acceleration graph) $mm^2/S$ | $\mathbf{mm/S^2}$ |
| 4-19 | (Acceleration graph) $mm^2/S$ | $\mathbf{mm/S^2}$ |
| 4-25 | (Last line)..the **magnetite** of… | ..the **magnitude** of… |
| 4-35 | (Example 4.4).. With the Safety Factor of **2**: | ..With the Safety Factor of **1**: |
| 4-35 | (Last row in Table) **0.25%** | **25%** |
| 4-37 | Then, the maximum torque is<br>$T_t = J_{l-ref}\ \alpha = 1.516 \times 10^{-4} \times 3945 = 0.598\ [N.m]$ | Then, the total torque is<br>$T_t = J_{l-ref}\ \alpha + T_{l-ref} = 1.516 \times 10^{-4} \times 3945 + 0.0455 = \mathbf{0.644}\ [N.m]$ |
| 4-37 | (Unit of the angular acceleration) **[rda/sec²]** | **[rad/sec²]** |
| 4-38 | (Torque pattern graph) **0.598 N.m** | **0.644 N.m** |

| | | |
|---|---|---|
| 4-38 | (TRMS calculation)<br>$T_{RMS} = \left(\frac{\mathbf{0.598^2} \times 0.2 + 0 \times 0.4 + \mathbf{0.598^2} \times 0.2 + 0 \times 0}{0.2 + 0.4 + 0.2 + 0}\right)^{\frac{1}{2}} = \mathbf{0.423}\ [\boldsymbol{N.m}]$ | $T_{RMS} = \left(\frac{\mathbf{0.644^2} \times 0.2 + 0 \times 0.4 + \mathbf{0.644^2} \times 0.2 + 0 \times 0}{0.2 + 0.4 + 0.2 + 0}\right)^{\frac{1}{2}} = \mathbf{0.455}\ [\boldsymbol{N.m}]$ |
| 4-41 | (9th line)<br>$T_{external} = T_{gravity} = \boldsymbol{T_{preload}} = 0$ | $T_{external} = T_{gravity} = 0$ |
| 4-41 | (Unit of the angular acceleration) **[rda/sec$^2$]** | **[rad/sec$^2$]** |
| 4-44 | (E4.3)..at angular acceleration of 400 rad/s$^2$… | at **the** angular acceleration of 400 rad/s$^2$ **CW**.. |
| 4-44 | (E4.4) this problem has been updated. See below | |
| 4-45 | (E4.5 3rd line)..**N=1/2**… | …**N=2**… |
| 4-46 | (E4.7 3rd line) .. are 100 **cm** in diameter, 160 **cm** long…the bely weighs **2000** kg | ..are 100 **mm** in diameter, 160 **mm** long.. the bely weighs **2** kg |
| 5-24 | Tutorial 5.**3** | Tutorial 5.**2** |
| 6-11 | (Example 6.7) P=[0,**1**,0] | P=[0,**-1**,0] |
| 6-15 | (Step 8) $\mathbf{A}_{i-1}^{i}$ | $\mathbf{T}_{i-1}^{i}$ |
| 6-15 | (Step 9)<br>$T_0^n = T_0^1\, T_1^2 \ldots . T_{n-1}^n$ | $T_n^0 = T_1^0\, T_2^1 \ldots . T_n^{n-1}$ |
| 6-17 | Change the direction of $x_1$ along $O_0O_1$<br>Change the direction of $x_3$ (parallel to $x_2$) | |
| 6-19 | $T_0^n = T_0^1\, T_1^2 \ldots . T_{n-1}^n$<br>$H = T_0^n = T_0^1\,(\mu_1) T_1^2(\mu_2) \ldots . T_{n-1}^n(\mu_n)$<br>$H = \begin{bmatrix} R & d \\ 0 & 1 \end{bmatrix} = T_0^n$ | $T_n^0 = T_1^0\, T_2^1 \ldots . T_n^{n-1}$<br>$H = T_n^0 = T_1^0\,(\mu_1) T_2^1(\mu_2) \ldots . T_n^{n-1}(\mu_n)$<br>$H = \begin{bmatrix} R & d \\ 0 & 1 \end{bmatrix} = T_n^0$ |

- **Calculate** $a_A^N$. Normal acceleration of point A on link 2 is determined as follows:

$$a_A^N = l_2\omega_2^2 = 3 \times 10^2 = 300\ \frac{in.}{s^2}$$

- **Calculate** $a_A^T$.Tangential acceleration of point A on link 2 is determined as follows:

$$a_A^T = l_2\alpha_2 = 3 \times 40 = 120\ \frac{in.}{s^2}$$

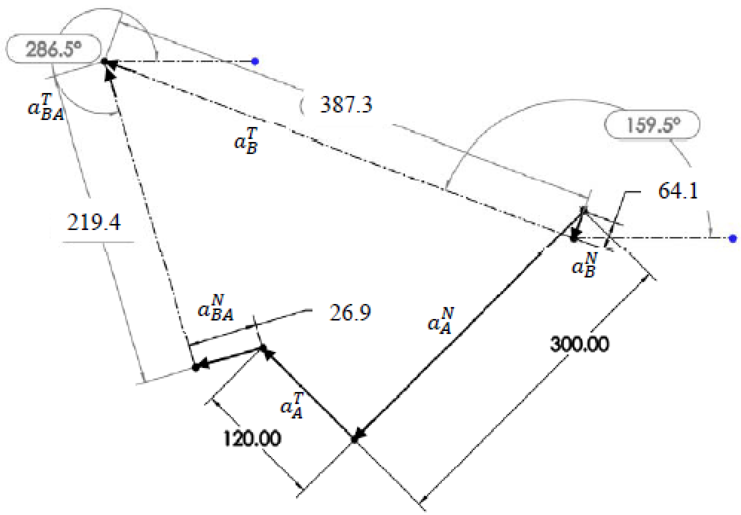
- **Calculate** $a_{BA}^N$. Normal acceleration of point B on link 3 is determined as follows:

$$a_{BA}^N = l_3\omega_3^2 = 9 \times 1.73^2 \cong 26.9\ \frac{in.}{s^2}$$

- **Calculate** $a_B^N$. Normal acceleration of point B link 4 is determined as follows:

$$a_B^N = l_3\omega_4^2 = 5 \times 3.58^2 \cong 64.1\ \frac{in.}{s^2}$$

- **Complete the velocity polygon.**
  Generate the acceleration polygon according to the accelration information. Add appropriate dimensions and notations as shown below.




- **Determine the angular acceleration of link 3 and link 4.**
  Then the angular acceleration of link 3 and link 4 can be determined as follows:

$$\alpha_3 = \frac{a_{BA}^T}{l_3} = \frac{219.4}{9} = 24.3\ rad/s^2\ \text{CCW} \qquad \alpha_4 = \frac{a_B^T}{l_4} = \frac{387.3}{5} = 77.5\ rad/s^2\ \text{CCW}$$

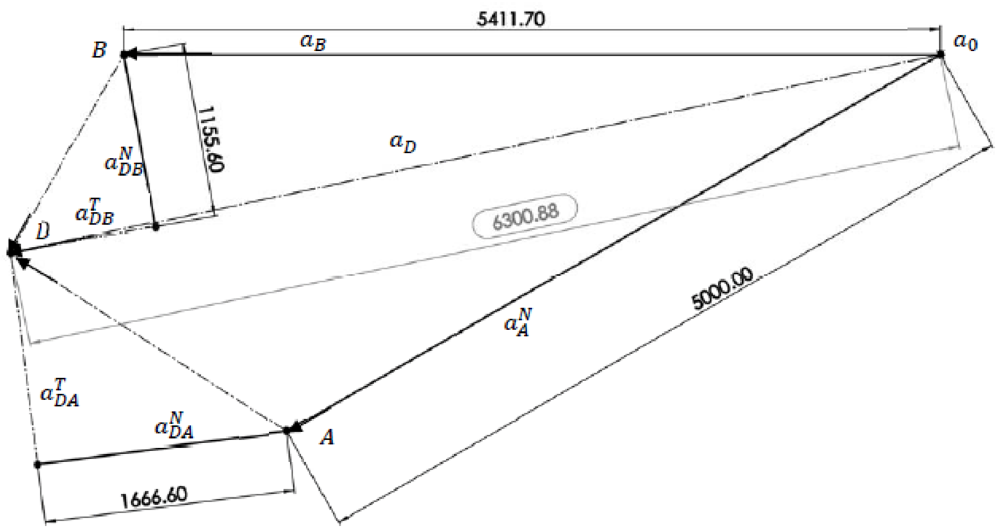
- Draw a line from the end of $a_A$ parallel to line AD as shown below. It represents the direction of $a_{DA}^N$.

$$a_{DA}^N = DA\,\omega_3^2 = 360.56 \times 2.15^2 \cong 1666.6\,\frac{mm}{sec^2}$$

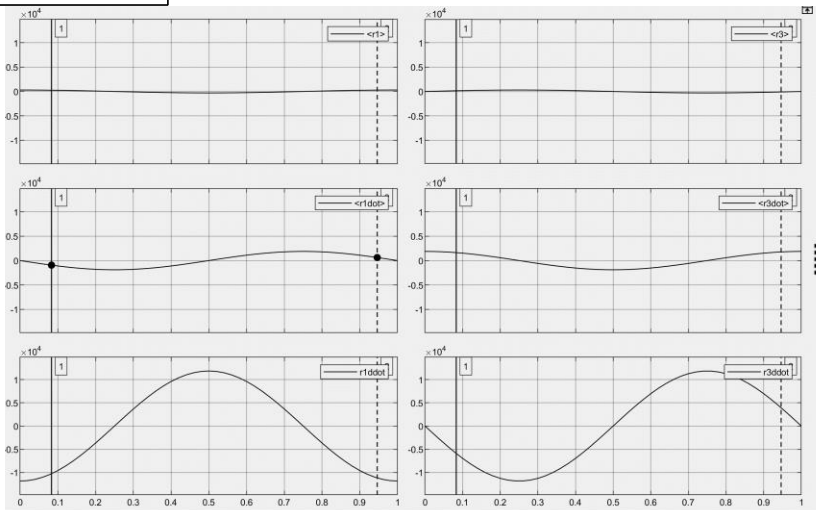
- Draw a line from the end of $a_{DA}^N$ perpendicular to line AD as shown below. It represents the direction of $a_{DA}^T$. the magnitude of this vector is unknown at this point.
- Draw a line from the end of $a_A^N$ parallel to line BD as shown below. It represents the direction of $a_{DB}^N$.

$$a_{DB}^N = DB\,\omega_3^2 = 250 \times 2.15^2 \cong 1155.6\,\frac{mm}{sec^2}$$

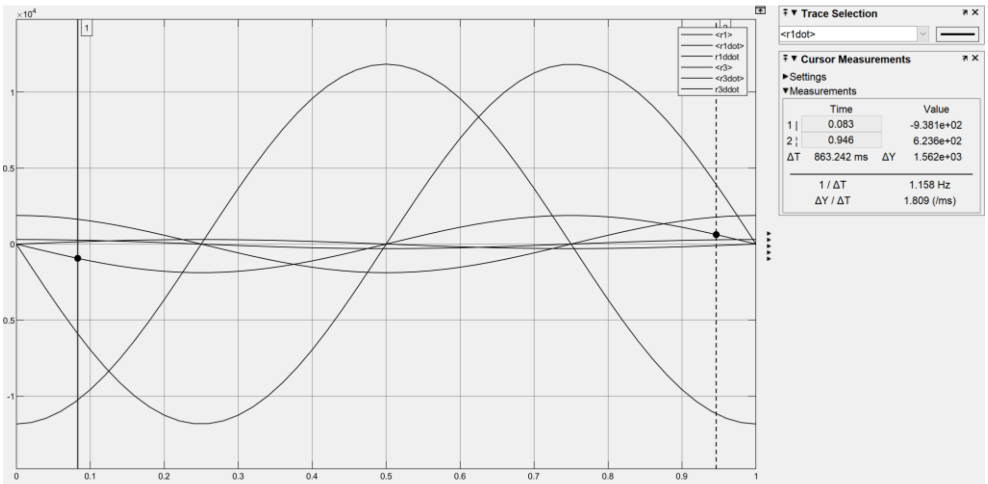
- Draw a line from the end of $a_{DB}^N$ perpendicular to line BD as shown below; showing the direction of $a_{DB}^T$. The magnitude of this vector is unknown at this point.
- Draw a line from $a_0$ to the the intersection of $a_{DA}^T$ and $a_{DB}^T$.
- Add appropriate annotations and arrows as shown below.
- Then $a_D$ = **6300.9 mm²/s**.



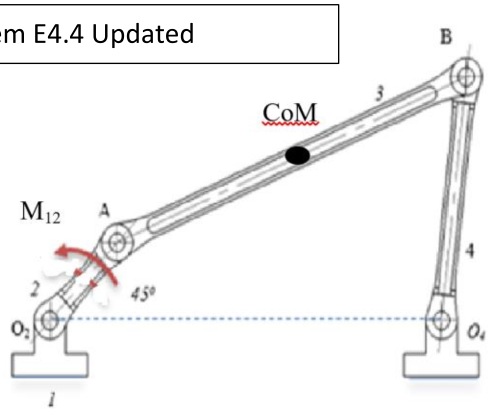
Page 2-19 Update




Page 2-20 Update



Problem E4.4 Updated




E4.4 For the mechanism shown on the right, determine the magnitude and direction of torque $M_{12}$ to be applied to link 2 from the base to overcome the effect of inertia of link 3. Assume $a_{G3}$=10 mm/s$^2$ at 179.4$^0$. The CoM of link 3 is located at the middle of link 3. Assume the mass and moment of inertia of link 3 are 10 kg and 20 kg.mm$^2$ respectively.

$L_2$=76.2 mm

$L_3$=228.6 mm

$L_4$=127 mm

$O_2O_4$=228.6 mm

$\alpha_3$=100 rad/s$^2$ CCW

$$T_{l-r} \quad = \frac{0.2 \times 6.2}{2\pi(0.1)} + \frac{24.5}{2\pi(0.1)(0.9)} = 45.5\ N.mm = 0.0455\ \ N.m$$

Step 3. Determine reflected load inertia ($J_{l-ref}$)

$$J_{l-ref} = J_{motor} + J_{coupling} + J_{screw} + J_{load\ and\ carriage-ref}$$

Lead screw inertia is calculated as follows:

$$J_{screw} = \frac{1}{2} m \left(\frac{D_B}{2}\right)^2 = \frac{1}{2} \rho\pi \left(\frac{D_B}{2}\right)^2 l_B \left(\frac{D_B}{2}\right)^2 = \frac{1}{2} \rho\pi l_B \left(\frac{D_B}{2}\right)^4$$

$$J_{screw} = \frac{1}{2}(7.9 \times 10^3)\pi \left(\frac{12 \times 10^{-3}}{2}\right)^4 (600 \times 10^{-3}) = 0.964 \times 10^{-5}\ \ [Kg.m^2]$$

The reflected inertia of load and carriage is calculated as follows:

$$J_{load\ and\ carriage-ref} = \frac{W_l + W_c}{g} \frac{1}{(2\pi P)^2 \epsilon} = 50 \frac{1}{\left(2\pi(0.1 \times 10^3)\right)^2 (0.9)} = 1.409 \times 10^{-4}\ [Kg.m^2]$$

Then, the total inertia on the motor side is calculated as follows:

$$J_{l-ref} = 380 \times 10^{-7} + 1.059 \times 10^{-6} + 1.409 \times 10^{-4} + 0.964 \times 10^{-5} = 1.516 \times 10^{-4}\ \ [Kg.m^2]$$

Step 4. Calculate the acceleration torque

The angular acceleration is calculated as follows:

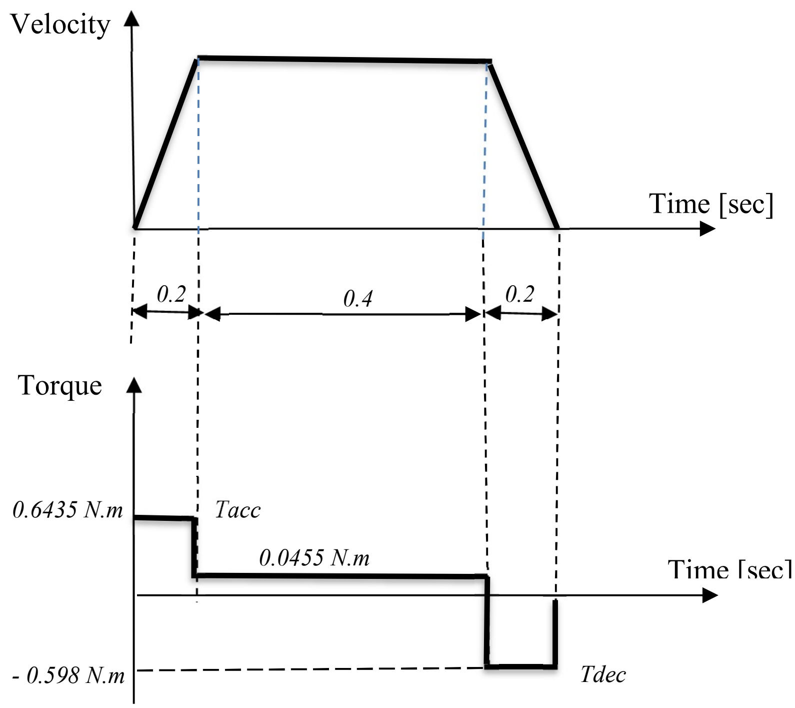
$$\alpha = \frac{\omega}{\Delta t} = \frac{789}{0.2} = 3945 \qquad [\frac{rad}{sec^2}]$$

Then, the maximum torque is

$$T_a = J_{l-re}\ \ \alpha + T_{l-ref} = \ 1.516 \times 10^{-4}\ \times 3945 + 0.0455 = 0.6435\ [N.m]$$

Step 5. Determine the torque pattern

The torque pattern is shown on the next page




Step 6. Calculate the magnitude of $T_{rms}$

$$T_{RMS} = \sqrt{\frac{1}{Cycle\ Time}\int_0^{t_{cycle}} T_m(t)^2\,dt} = \left(\frac{T_a^2\,t_a + T_r^2\,t_r + T_d^2\,t_d + T_{dw}^2\,t_{dw}}{t_a + t_r + t_d + t_{dw}}\right)^{\frac{1}{2}}$$

$$T_{RMS} = \left(\frac{0.6435^2 \times 0.2 + 0.0455 \times 0.4 + 0.598^2 \times 0.2 + 0 \times 0}{0.2 + 0.4 + 0.2 + 0}\right)^{\frac{1}{2}} = 0.4403 \ [N.m]$$

$$J_{parts} = 5\left(J_{part\ relative\ to\ its\ CoG} + m_{part}\left(\frac{D_p}{2}\right)^2\right)$$

$$J_{parts} = 5\left(0.5 \times 10^{-4} + 0.2\ \left(\frac{200\times10^{-3}}{2}\right)^2\right) = 0.0103\ \ [Kg.m^2)$$

Then, the total inertia as seen at output of the gearbox is

$$J_l = 0.606 + 1.860\ \times 10^{-5} + 0.0103 = 0.0709\ \ [Kg.m^2]$$

$$J_{l-ref} = 380 \text{ x } 10^{-7} + \frac{0.0709}{10^2\ \times 0.95} = 7.843 \times 10^{-4}\ \ [Kg.m^2]$$

Step 3. Determine maximum torque ($Ta$)

$$T_l = T_{external} + T_{gravity} + T_{friction} + T_{preload} + \cdots$$

No external and preload loads applied to the system. Also, the effect of gravity along the motion is zero. Then:

$$T_{external} = T_{gravity} = 0$$

We calculate both the friction and preload as follows:

$$T_{friction} = 0.05\ T_{inertia}$$

The angular acceleration is calculated as follows:

$$\alpha = \frac{\omega}{\Delta t} = \frac{4.53}{0.1} = 45.3\ \ [\frac{rad}{sec^2}] \qquad \text{or} \qquad \alpha_m = \alpha\ \times N = 453\ [\frac{rad}{sec^2}]$$

Then, $T_a$ at the output shaft of the gearbox is

$$T_a = [J_{l-ref}\alpha + 0.05 \times J_{l-ref}\alpha] \times 2$$

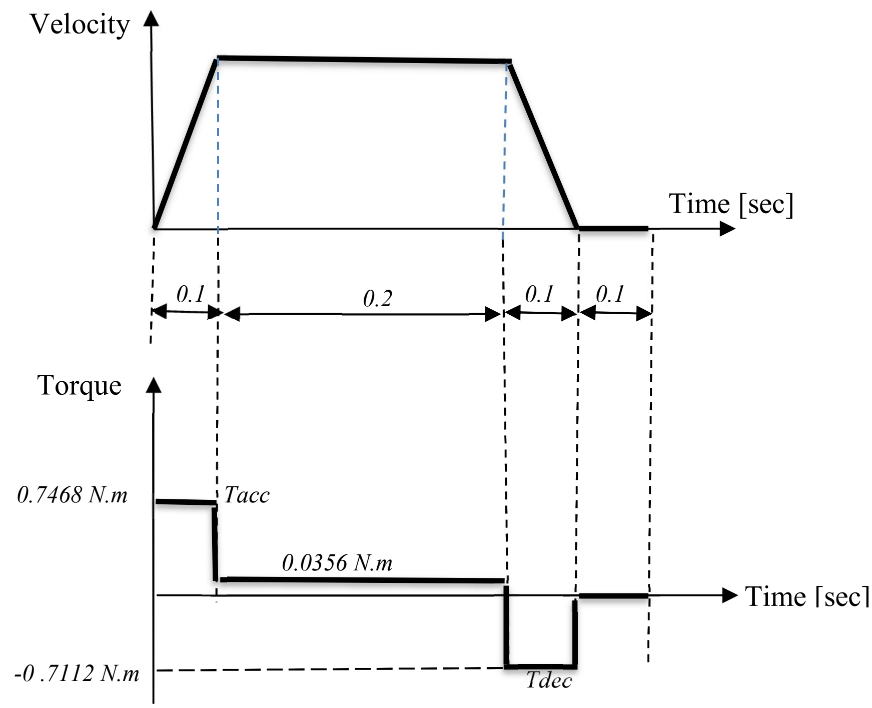
$$T_a = [(7.843 \times 10^{-4}\ ) \times 453 + 0.05 \times (7.843 \times 10^{-4}\ ) \times 453] \times 2 = 0.7468\ N.m$$

$$T_r = [0.05 \times (7.843 \times 10^{-4}\ ) \times 453] \times 2 = 0.0356\ N.m$$

$$T_a = -[(7.843 \times 10^{-4}\ ) \times 453] \times 2 = -0.7112\ N.m$$

Step 5. Determine the torque pattern

The torque pattern is shown on the next page.




Step 6. Calculate the magnitude of $T_{rms}$

$$T_{RMS} = \sqrt{\frac{1}{Cycle\ Time}\int_0^{t_{cycle}} T_m(t)^2\,dt} = \left(\frac{T_a^2\ t_a + T_r^2\ t_r + T_d^2\ t_d + T_{dw}^2\ t_{dw}}{t_a + t_r + t_d + t_{dw}}\right)^{\frac{1}{2}}$$

$$T_{RMS} = \left(\frac{0.7468^2\ \times 0.1 + 0.0356^2\ \times 0.2 + 0.7112^2\ \times 0.1 + 0 \times 0.1}{0.1 + 0.2 + 0.1 + 0.1}\right)^{\frac{1}{2}} = 0.4671\ \ [N.m]$$