Actuator Sizing

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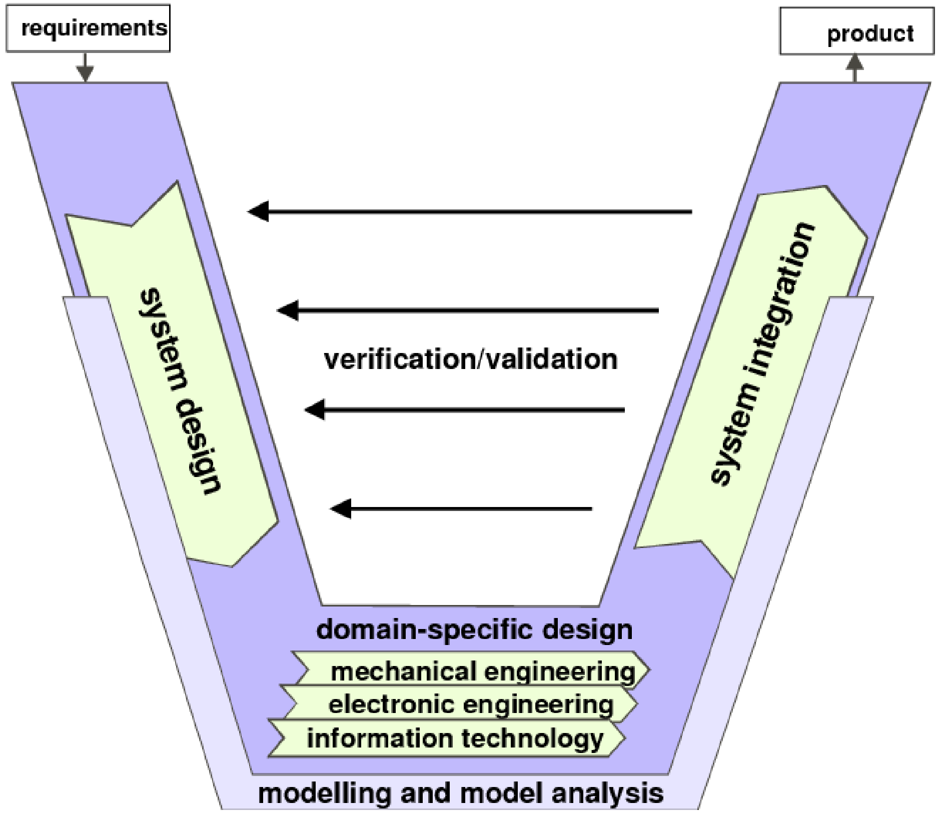
- **VDI 2206**
- **Assurance of Properties**
- **Actuator Sizing**

V-Shaped Model for Design of Mechatronic Systems

Requirements: Starting point is an individual design task. The task has been clarified/defined and described with the help of requirements. These requirements represent at the same time the measure for the evaluation of the later product.

System design: The object is to define a cross-domain solution concept which describes the essential physical and logical characteristics of the future product. The overall function of a system will be divided into sub-functions. Suitable working principles and/or solution elements are assigned to these sub-functions and the fulfilling of the functions regarding the overall system context is evaluated. In mechanical engineering this phase is called “conceptualisation”, but this term has not the same meaning within software and electronic engineering. Therefore “system design” has been chosen as a cross-domain term.



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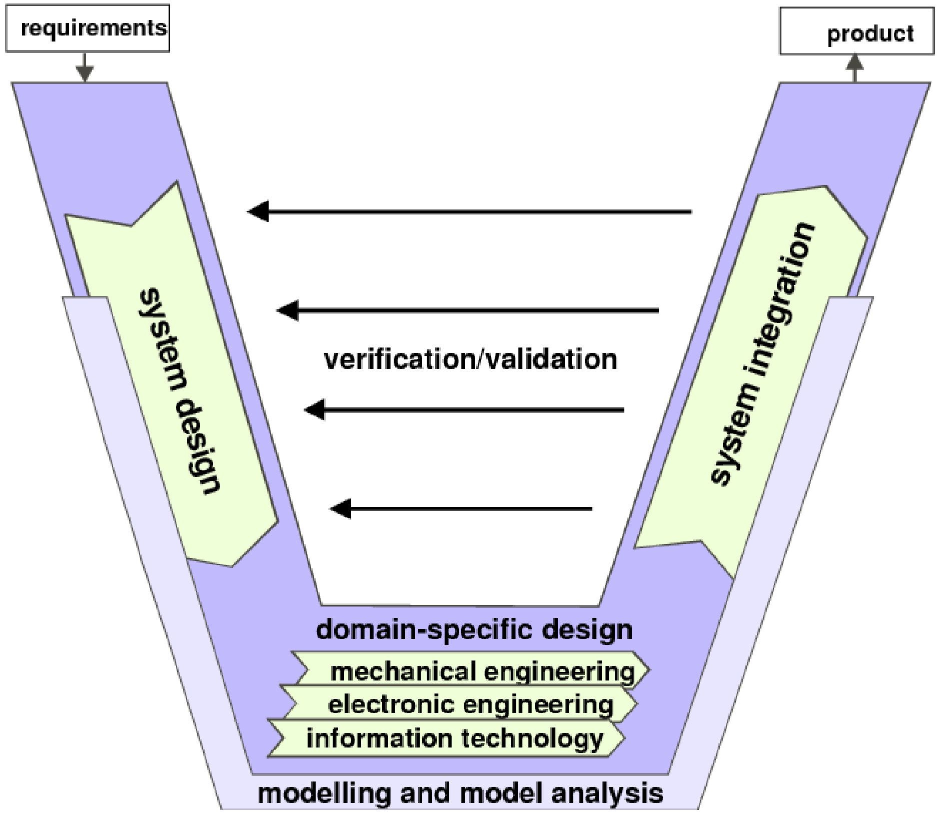
V-Shaped Model for Design of Mechatronic Systems

Domain-specific design: The solution concept which has been developed conjointly by the involved domains will be worked out in detail mostly separately in the concerned domains. Elaborate design and calculations are necessary in order to guarantee the functional performance, in particular that with critical functions.

System integration: The results from the specific domains are integrated to an overall system in order to analyse the interrelations.

Verification/validation: The design progress has to be checked continuously by means of the specified solution concept and the requirements. It is to be assured that the actual system characteristics match with those wanted.

Modelling and model analysis: The described phases are flanked by the modelling and analysis of the system characteristics with the aid of models and computer-aided tools for simulation.



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Verification	Validation
• Verification means checking whether the way in which something is realized and whether it coincides with the specification. • Verification is the answer to the question : Is a correct product being developed? For example, does a software program coincide with the specs of algorithms.	• Validation means testing whether the product is suitable for its intended purpose or achieves the desired value. • Validation is the answer to the question : Is a right product being developed?

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Actuator Sizing Algorithm:

1. Define the geometric relationship between the actuator and load. In other words, select the type of motion transmission mechanism between the motor and load (N=reduction ratio).
2. Define the inertia and torque\force characteristics of the load and transmission mechanisms, i.e. define the inertia of the tool as well as the inertia of the gear reducer mechanisms (J_l, T_l).
3. Define the desired cyclic motion profile in the load speed versus time ($\theta'_l(t)$).
4. Using the reflection equations developed above, calculate the reflected load inertia and torque/force (J_{eff}, T_{eff}) that will effectively act on the actuator shaft as well as the desired motion at the actuator shaft ($\theta'_m(t)$).
5. Guess a actuator/motor inertia from an available list (catalog) (or make the first calculation with zero motor inertia assumption), and calculate the torque history, $T_m(t)$, for the desired motion cycle. Then calculate the peak torque and RMS torque from $T_m(t)$.

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Actuator Sizing Algorithm Cont.:

6. Check if the actuator size meets the required performance in terms of peak and RMS torque, and maximum speed capacity (T_p, T_{rms}, θ'_{max}). If the above selected actuator/motor from the available list does not meet the requirements (i.e. too small or too large), repeat the previous step by selecting a different motor. It should be noted that if a stepper motor is used, the torque capacity of the stepper motor is rated only in terms of the continuous rating, not peak. Therefore, the required peak and RMS torque must be smaller than the continuous torque capacity of the step motor.
7. Most servo motor continuous torque capacity rating is given for $25^o C$. If ambient temperature is different than $25^o C$, the continuous (RMS) torque capacity of the motor should be derated using the following equation for a temperature,

$$T_{rms} = T_{rms}(25^o C)\sqrt{\frac{(155 - Temp^o C)}{130}}$$

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Example:

Consider a rotary motion axis driven by an electric servo motor. The rotary load is directly connected to the motor shaft without any gear reducer (Fig. 1). The rotary load is a solid cylindrical shape made of steel material, $d=75mm$, $l=50mm$, $\rho=7800kg/m^3$.The desired motion of the load is a periodic motion (Fig. 2).

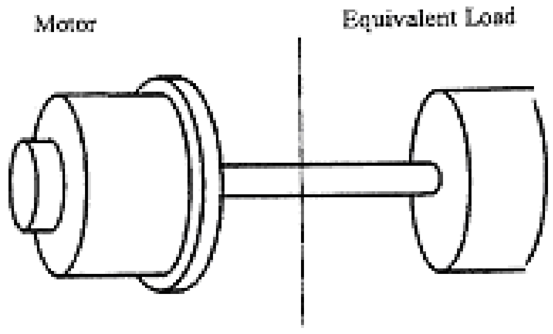

Fig. (1)

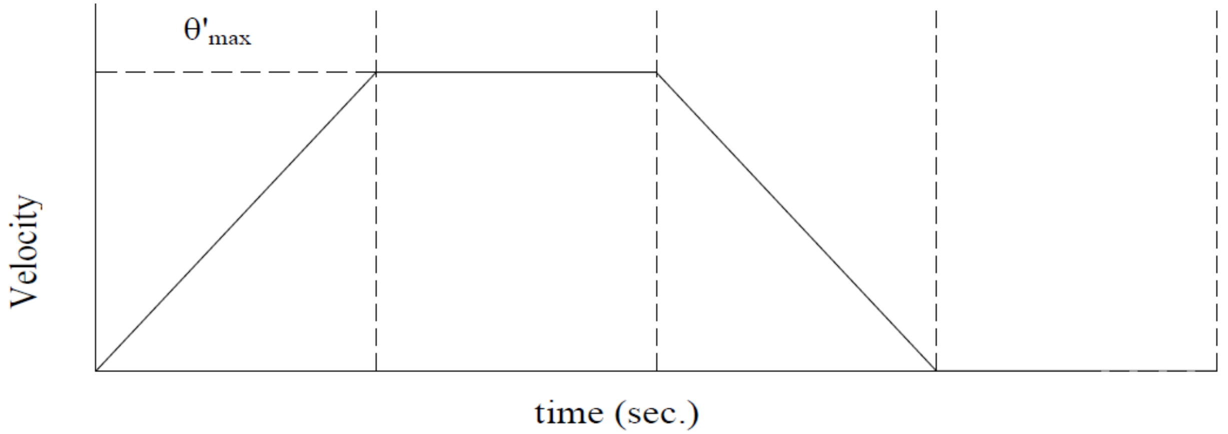

Fig.(2)

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Example (Cont.):

The total distance to be traveled is *1/4* of a revolution. *The period of motion* is t_{cyc}=250 *msec.*, and dwell portion of it is $t_{dw}=100$ *msec.*, and the remaining part of the cycle time is equally divided between acceleration, constant speed and deceleration periods, $t_a=t_r=t_d=50$ *msec*.

Determine the required motor size for this application.

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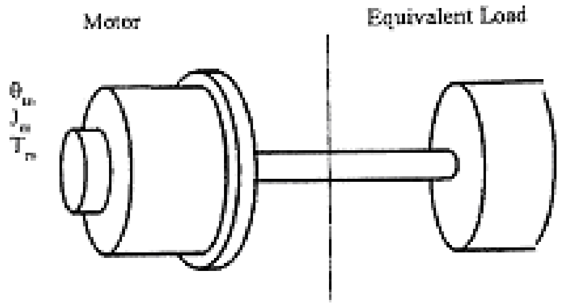
Solution:

1) Determine the Net inertia:



where:

J_{total}=the total inertia reflected on the motor axis.

J_{eff}=the load inertias reflected on the motor shaft ➔ $J_{eff} = J_L$

J_m=the motor rotor inertia.

$$J_{eff} = \frac{1}{2} m r^2 = \frac{1}{2} (\rho(\frac{\pi d^2}{4}) l) r^2$$

$$= \frac{1}{2} \times 7800 \times (\frac{\pi}{4} \times (75 \times 10^{-3})^2 \times 50 \times 10^{-3}) \times (\frac{75 \times 10^{-3}}{2})^2 = 0.0012 kg.m^2$$

The ratio of motor inertia to reflected load inertia should be between one-to-one and up to one-to-ten.

$$\frac{J_m}{J_{eff}} = \frac{1}{1} \sim \frac{1}{10}$$

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The one-to-one is considered the optimal match (an ideal case), where the motor drives a purely inertia load and this inertia ratio results in minimum heating of the motor. Let us assume that we will pick a motor which has a rotor inertia same as the load so that there is an ideal load and motor inertia match.

$$J_m = J_{eff} \quad = 0.0012 kg.m^2$$

$$\therefore \; J_{total} = J_m + J_{eff} \quad = 0.0024 kg.m^2$$

2) Determine the Net Torque:

$$\sum T(t) = T_{total}(t) = T_m(t) - T_R(t)$$

where:

$T_{total}(t)$=the total torque.

$T_m(t)$=the torque generated by the motor.

$T_R(t)$=the resistive load torques on the system, where $T_R(t)$ represent the sum of all external torques. If the load torque is in the direction of assisting the motion, it will be negative, and net result will be the addition of two torques. The $T_R(t)$ may include friction (T_f), and process related torque and forces (i.e. an assembly application may required the mechanism to provide a desired force pressure (T_R).

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$$\because T_R(t) = 0$$

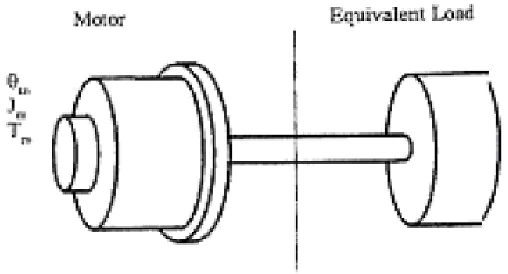
$$\therefore T_{total}(t) = T_m(t)$$

3) Fundamental Equations for torque calculation:

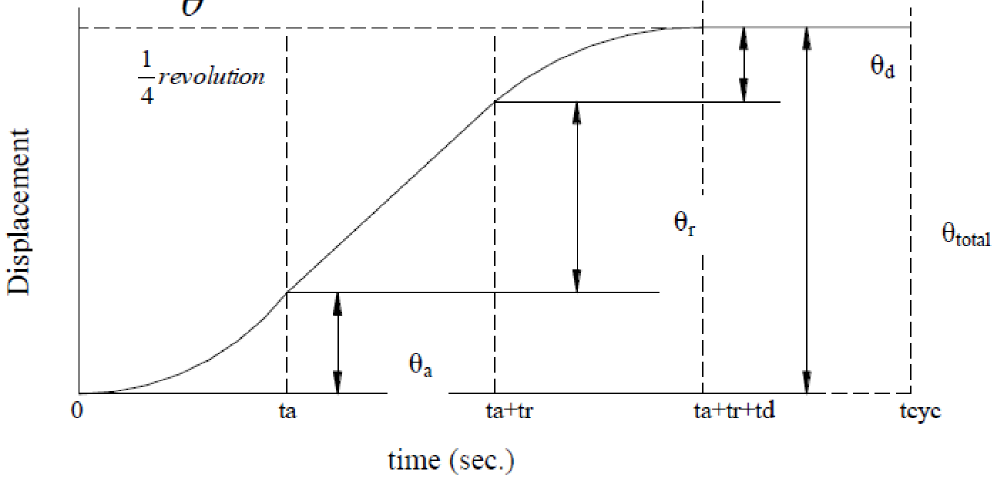
The torque and motion relationship is:

$$J_{total}\ddot{\theta} = \sum T$$

$$(J_m + J_{eff})\ddot{\theta} = T_m$$



The required torque to move the load through the desired cyclic motion given in the figure can be calculated if the value of $\ddot{\theta}$ calculated.



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4) Define the desired cyclic motion profile in the form of load (motor) speed versus time:

From the desired motion profile specification, we can determine the velocity and acceleration of the actuator can be deliver using the kinematic relations.

$$t_a = t_r = t_d = \frac{250 - 100}{3} = 50 m\sec.$$

where:

t_a=acceleration mode time.
t_r=constant speed mode time.
t_d=deceleration speed mode time.

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5) Calculate the maximum speed $\dot{\theta}_{\max}$ required to define this profile from the motor:

From displacement motion profile:

$$\theta_{total} = \theta_a + \theta_r + \theta_d = \frac{1}{4} \times 2\pi = \frac{\pi}{2}$$

note that:

$$\theta(t) = \int \dot{\theta}(t)dt$$

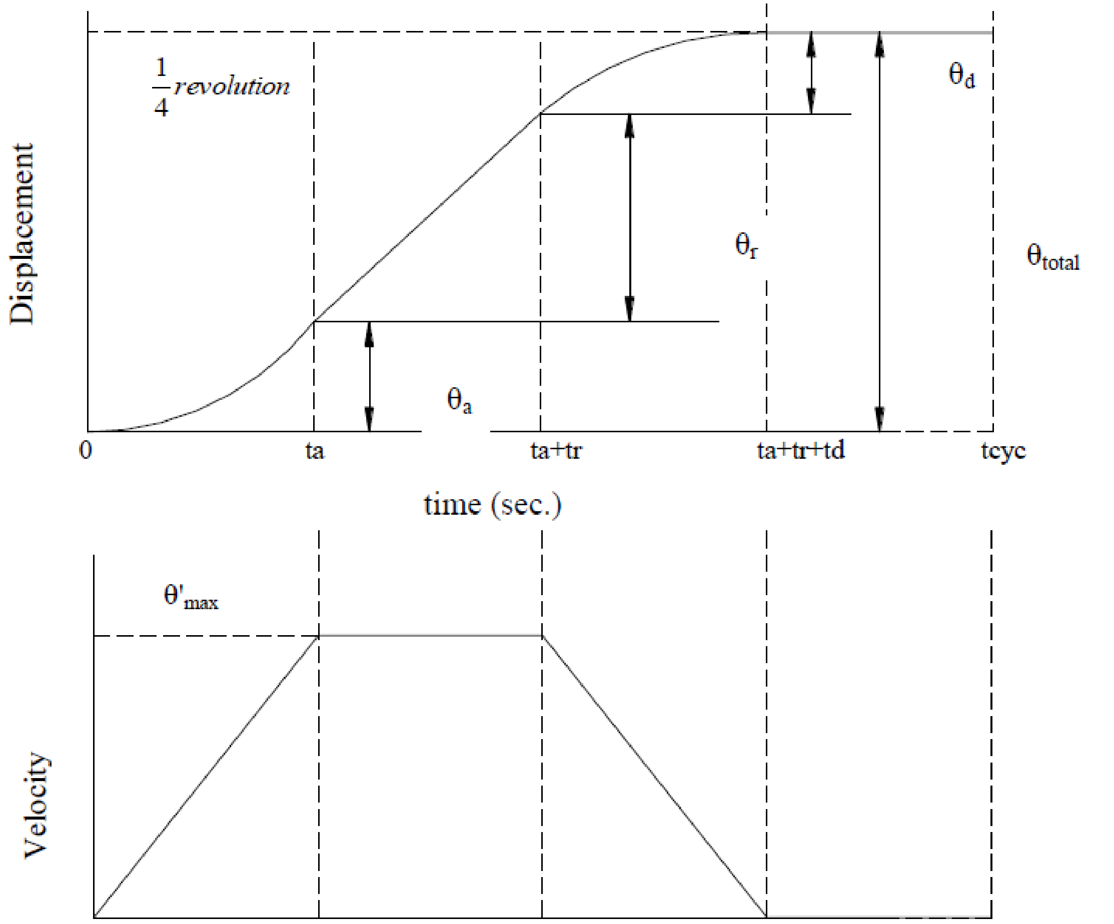
From velocity motion profile:

$$\theta_{total} = \frac{1}{2}\dot{\theta}_{\max} t_a + \dot{\theta}_{\max} t_r + \frac{1}{2}\dot{\theta}_{\max} t_d$$

$$\theta_{total} = \dot{\theta}_{\max} \left(\frac{t_a + 2t_r + t_d}{2}\right)$$

$$\therefore \dot{\theta}_{\max} = \frac{\pi}{150 \times 10^{-3}} = 20.9 rad/\sec$$

$$n = \frac{60\dot{\theta}_{\max}}{2\pi} = 199.6 rpm$$



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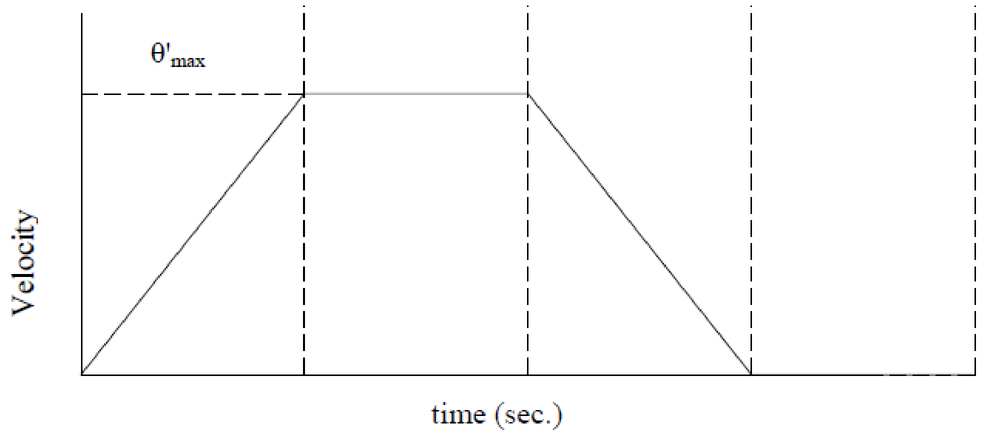
<u>6) Calculate the angular acceleration :</u>

<u>Note that:</u>

$$\ddot{\theta} = \frac{d\dot{\theta}}{dt}$$

From velocity motion profile:

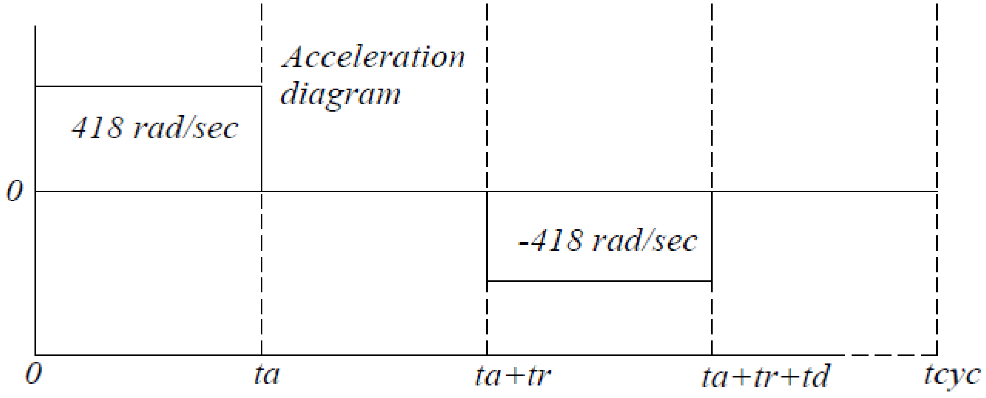


$$\ddot{\theta}_a = \frac{d\dot{\theta}_a}{dt} = \frac{\dot{\theta}_{\max} - 0}{t_a - 0} = \frac{\dot{\theta}_{\max}}{t_a} = \frac{20.9}{50 \times 10^{-3}} = 418 rad/\sec^2$$

$$\ddot{\theta}_r = \frac{d\dot{\theta}_r}{dt} = \frac{\dot{\theta}_{\max} - \dot{\theta}_{\max}}{(t_a + t_r) - t_a} = \frac{0}{t_r} = 0$$

$$\ddot{\theta}_d = \frac{d\dot{\theta}_d}{dt} = \frac{0 - \dot{\theta}_{\max}}{(t_d + t_r + t_a) - (t_r + t_a)} = \frac{-\dot{\theta}_{\max}}{t_d}$$

$$= \frac{-20.9}{50 \times 10^{-3}} = -418 rad/\sec^2$$



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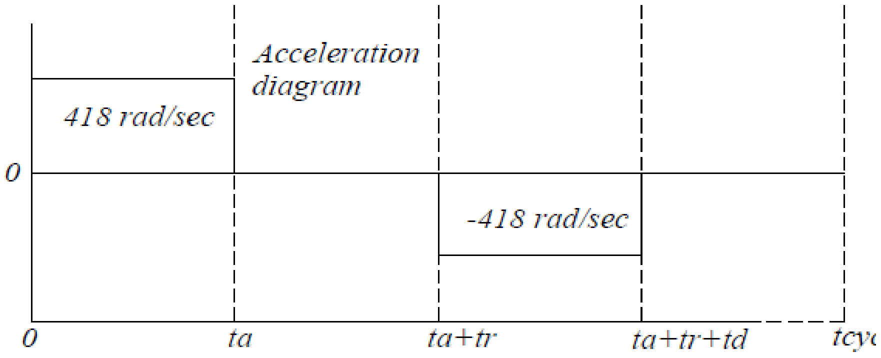
7) Use Fundamental equation for torque calculation at each mode:

$$(J_m + J_{eff})\ddot{\theta} = T_m$$

$$\therefore T_{m_a} = (J_m + J_{eff})\ddot{\theta}_a = 0.0024 \times 418 = 1.0032 N.m$$

$$\therefore T_{m_r} = (J_m + J_{eff})\ddot{\theta}_r = 0$$

$$\therefore T_{m_d} = (J_m + J_{eff})\ddot{\theta}_d = 0.0024 \times -418 = -1.0032 N.m$$

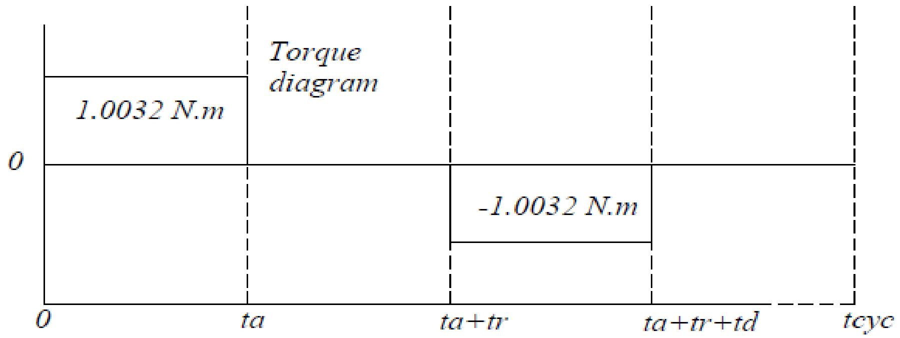


The torque diagram profile is shown in Fig

8) The Peak torque (maximum torque):

Hence, the peak torque requirement is

$$T_{max} = 1.0032 N.m$$



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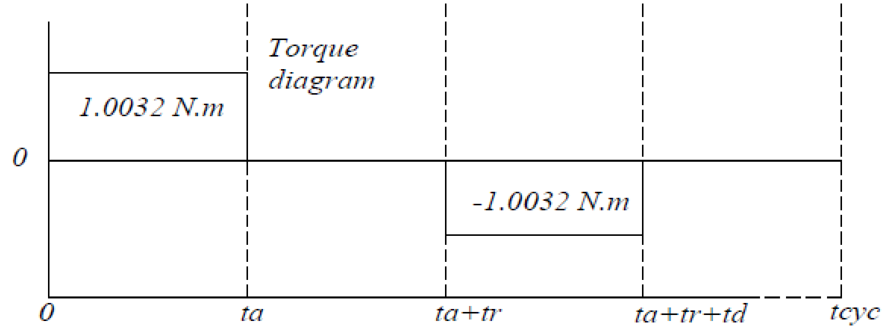
9) T_{rms} = root mean square torque over entire cycle:

$$T_{rms} = \sqrt{\frac{\int_0^{t_{cyc}} T_m(t)^2\, dt}{t_{cycle}}}$$

From torque diagram:



$$T_{rms} = \sqrt{\frac{T_{m_a}{}^2 t_a + T_{m_r}{}^2 t_r + T_{m_d}{}^2 t_d + T_H{}^2 t_{dw}}{t_a + t_r + t_d + t_{dw}}}$$

where : T_H=holding torque required in dwell mode=0

$$T_{rms} = \sqrt{\frac{(1.0032)^2 \times 50 \times 10^{-3} + 0 + (-1.0032)^2 \times 50 \times 10^{-3} + 0}{250 \times 10^{-3}}} = 0.6344\ N.m$$

Therefore, a motor which has rotor inertia of about *0.0012 kg.m²*, maximum speed capability of *20.9 rad/sec(199.6 rpm)*or better, peak and RMS torque rating in the range of *1.0032 N.m* and *0.6344 N.m* range would be sufficient for the task