

$$\textcircled{1} \quad M_{\ddot{\theta}} + C_{\dot{\theta}} + G = \tau + A^T [\lambda_1, \lambda_2, \lambda_3]^T$$



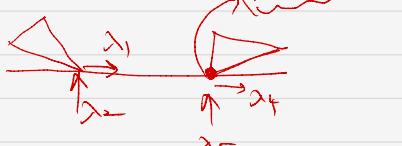
const:  $\text{ToeST}_x = 0$  ( $\lambda_1$ )  
 $\text{ToeST}_y = 0$  ( $\lambda_2$ )  
 $\text{HeelST}_y = 0$  ( $\lambda_3$ )  
 $\lambda_4 = 0, \lambda_5 = 0, \lambda_6 = 0$

Guard:  $\lambda_3 = 0$

$$\dot{\theta}_1 < 0$$

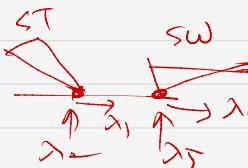
$$\textcircled{2} \quad ST \quad SW \quad \text{const.} \quad \text{ToeST}_x = 0 (\lambda_1) \quad \text{ToeST}_y = 0 (\lambda_2) \quad \lambda_3 = \lambda_4 = \lambda_5 = \lambda_6 = 0$$

Guard: impact (heel strike)



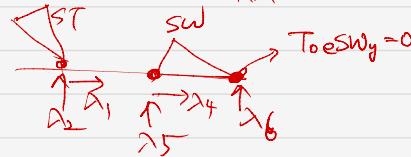
use impact dyn. to update velocity afterwards.

\textcircled{3}



const.  
 $\text{ToeST}_x = 0 (\lambda_1)$   
 $\text{ToeST}_y = 0 (\lambda_2)$   
 $\text{HeelSW}_x = 0 (\lambda_4)$   
 $\text{HeelSW}_y = 0 (\lambda_5)$   
 $\lambda_3 = \lambda_6 = 0$

Guard: impact (foot drop flat)



\textcircled{4}

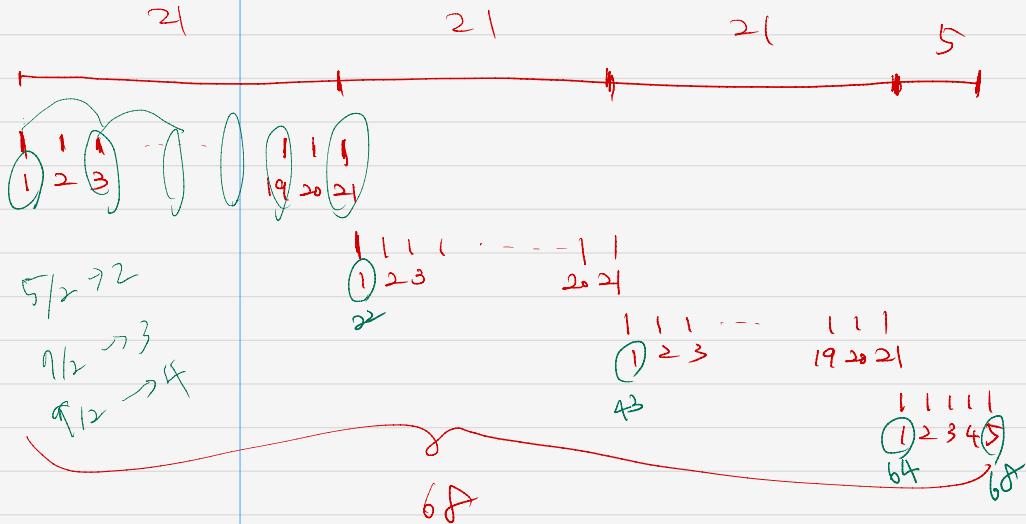
$$ST \quad SW \quad \text{const.} \quad \text{ToeST}_x = 0 (\lambda_1) \quad \text{ToeST}_y = 0 (\lambda_2) \quad \text{HeelSW}_x = 0 (\lambda_4) \quad \text{HeelSW}_y = 0 (\lambda_5) \quad \text{ToeSW}_y = 0 (\lambda_6)$$

Guard  $\text{ToeST}_y > 0, \lambda_2 = 0, \lambda_3 = 0$

# Dynamic constraints:  $9 + 6 = 15$  (1 ~ ④ 8)  
 $\text{unknown } \beta_1 \sim g_9, \lambda_1 \sim \lambda_6 : 15$

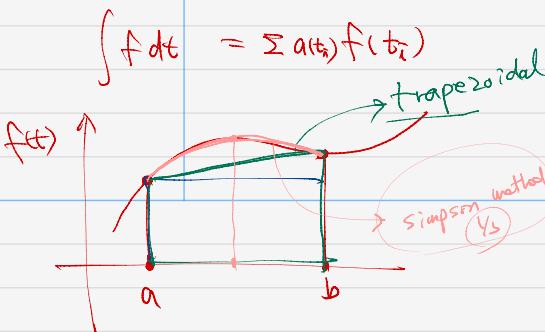
eq's ⑨ dyneq. + 6 const.  $\Delta \Sigma \text{ eq 4}$

$M_{\ddot{\theta}} + C_{\dot{\theta}} + G = B\dot{\theta} + A\ddot{x}$



Direct collocation.

Quadrature



$$\int_a^b \dot{x}(t) dt = \underline{x(b) - x(a)}$$

$$\approx \frac{1}{6} \cancel{\dot{x}(t)} (x_{k-1} + 4\dot{x}_k + \cancel{x_{k+1}})$$

$$x[1 \sim 9]$$

$$x[9 \sim 18]$$

$$x[19 \sim 21]$$

$$\left. \begin{array}{l} \text{ToeST}(x) = 0 \\ \text{ToeST}(y) = 0 \\ \text{HeelST}(y) = 0 \end{array} \right\} \xrightarrow{\frac{d}{dt}} \left. \begin{array}{l} (\text{ToeST})_{\text{Vel}}(x) = 0 \\ (\text{ToeST})_{\text{Vel}}(y) = 0 \\ (\text{HeelST})_{\text{Vel}}(y) = 0 \end{array} \right\}$$

$$\begin{array}{c} \overset{\circ}{\delta}_8 \rightarrow \overset{\circ}{\delta}_8 = 0 \\ \overset{\circ}{\delta}_9 \rightarrow \overset{\circ}{\delta}_9 = 0 \\ \overset{\circ}{\delta}_8 + \boxed{\quad} \xrightarrow{\frac{d}{dt}} \overset{\circ}{\delta}_9, \overset{\circ}{\delta}_1 = 0 \end{array}$$

$$\begin{array}{c} \overset{\circ}{\delta}_8 = J \overset{\circ}{g} = 0 \\ \overset{\circ}{\delta}_9 \rightarrow J \overset{\circ}{g} + f \overset{\circ}{g} = 0 \end{array}$$

Constraints for region 1.

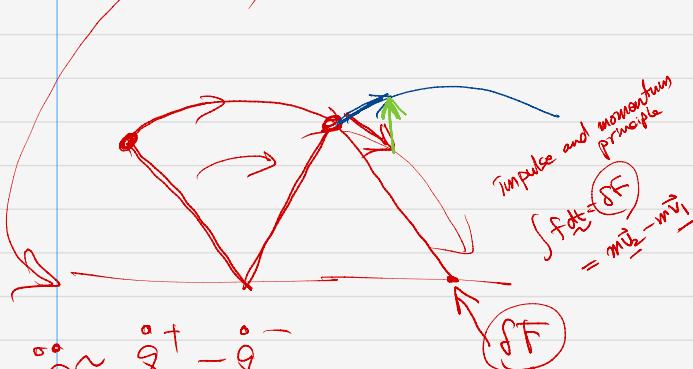
$$\text{Toest}_x \equiv 0 \Rightarrow \frac{d}{dt}(0) = 0 \Rightarrow \frac{d}{dt}(0) = 0$$

$$\text{TuST}_y \equiv 0$$

$$\text{HeelST}_y \equiv 0$$



$$D\ddot{\gamma} + \dot{c}\dot{\gamma} + g = c(J^T \delta F + J^T \dot{x})$$



$$\ddot{g} \approx \frac{\dot{g}^+ - \dot{g}^-}{dt}$$

$$\dot{g} \approx \frac{g^+ - g^-}{dt}$$

$$\left( D \frac{\dot{g}^+ - \dot{g}^-}{dt} + C \frac{g^+ - g^-}{dt} + G \right) dt$$

$$= C + J^T \lambda T^T S F$$

$$D(\dot{g}^+ - \dot{g}^-) + C(g^+ - g^-) + G dt$$

$$= (C + J^T \lambda) dt + T^T S F dt$$

$$[ D \dot{g}^+ ] - D \dot{g}^- = J^T S F dt$$

Heel SW Vel  $\Rightarrow 0 \Rightarrow J \dot{g}^+ = 0$

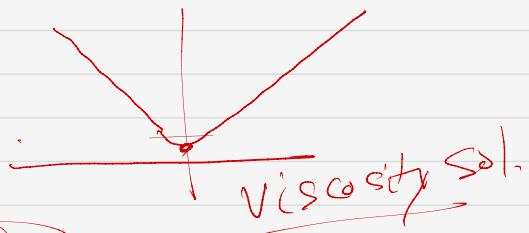
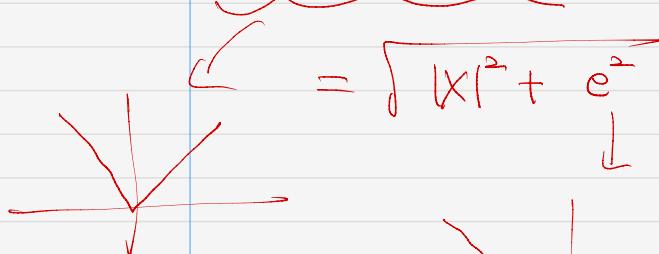
$$\begin{bmatrix} D & -J^T \\ J & 0 \end{bmatrix} \begin{bmatrix} \dot{g}^+ \\ SF dt \end{bmatrix} = \begin{bmatrix} D \dot{g}^- \\ 0 \end{bmatrix}$$

$$D\dot{g}^+ - D\dot{g}^- = J^T \delta F dt$$

$$\Rightarrow D\dot{g}^+ = D\dot{g}^- + J^T \delta F dt$$

$$\dot{g}^+ = \dot{g}^- + D^T J^T \delta F dt$$

$$|X| = \sqrt{|X|^2} \quad (\times)$$



$$\boxed{\begin{aligned} \mu N &\geq |S| \\ \mu N &\geq S \\ \mu N &\geq -S \end{aligned}}$$

