Théorie des goupilles de raquette

Théorie avancée des goupilles de raquette

Cas d'un glissement entre spiral et goupille

Caractéristiques du spiral avec une spire externe semi-circulaire

Référence :E:\Résonateur (TA)\Data\Bal_spiral plat (ex num).mcd(R)

Dimensions $ép = 0.03\,mm$ $ha = 0.15\,mm$ $S = 4.5 \times 10^{-3}\,mm^2$

$d2_{sp} = 4.52\,mm$ $d1_{sp} = 1.1\,mm$ $p_{sp} = 0.135\,mm$ $n_{sp} = 12.667$

$L_{sp} = 11.182\,cm$ $\psi_0 := 2\cdot\pi\cdot n_{sp}$ $\psi_0 = 4.56 \times 10^3\,deg$ $E = 2.093 \times 10^{11}\,m^{-2}N$

Position du piton $r_P := 0.5\cdot d_{piton}$ $\alpha_P := 0$ $x_P := r_P\cdot cos(\alpha_P)$ $y_P := r_P\cdot sin(\alpha_P)$

$x_P = 2.55\,mm$ $y_P = 0\,mm$ $z_P := x_P + i\cdot y_P$

Position du point d'attache à la virole $r_V := 0.5\cdot d1_{sp}$ $\alpha_V(\theta) := \psi_0 + \theta$ $x_V(\theta) := r_V\cdot cos(\alpha_V(\theta))$ $y_V(\theta) := r_V\cdot sin(\alpha_V(\theta))$

Position du point de raccordement sur le spiral $\alpha_A := 180\cdot deg$ $r_A := 0.5\cdot d2_{sp}$ $z_A := r_A\cdot e^{i\cdot\alpha_A}$

Spire externe formée d'un demi-cercle $R_0 := r_P$ $x_{0t}(\alpha_t) := R_0\cdot cos(\alpha_t)$ $y_{0t}(\alpha_t) := R_0\cdot sin(\alpha_t)$ $z_{0t}(\alpha_t) := R_0\cdot e^{i\cdot\alpha_t}$

$s_t(\alpha_t) := R_0\cdot\alpha_t$ $l_t := s_t(\alpha_A)$ $l_t = 8.011\,mm$

Forme initiale du spiral

$a := \dfrac{p_{sp}}{2\cdot\pi}$ $r_s(\alpha) := r_A - a\cdot(\alpha - \alpha_A)$ $x_{0s}(\alpha) := r_s(\alpha)\cdot cos(\alpha)$ $y_{0s}(\alpha) := r_s(\alpha)\cdot sin(\alpha)$

$s_s(\alpha) := \dfrac{1}{2\cdot a}\cdot\left(r_A^{\,2} - r_s(\alpha)^2\right)$ $s_s(\alpha) := r_A\cdot(\alpha - \alpha_A) - \dfrac{a}{2}\cdot(\alpha - \alpha_A)^2$ $L_t := s_s(\psi_0 + \alpha_A) + l_t$

$L_t = 11.983\,cm$

Position angulaire des goupilles par rapport au piton:

$\varepsilon := 0.023$ $s_g := \varepsilon\cdot L_t$ $s_g = 2.756\,mm$ $\alpha_g := \dfrac{s_g}{R_0}$ $\alpha_g = 61.927\,deg$

Amplitude stationnaire du balancier $\theta_0 = 270\,deg$

Position radiale de la goupille pour une élongation de contact donnée

Première approximation de la déformée de la spire externe entre piton et goupille $\theta_1 := 20\cdot deg$

$x_{0g}(\alpha_g) := R_0\cdot cos(\alpha_g)$ $y_{0g}(\alpha_g) := R_0\cdot sin(\alpha_g)$

$\xi_{0g}(\alpha_g) := \dfrac{R_0}{\alpha_g}\cdot sin(\alpha_g)$ $\eta_{0g}(\alpha_g) := \dfrac{R_0}{\alpha_g}\cdot(1 - cos(\alpha_g))$

$$\beta := arctan\left[\frac{-(x_{0g}(\alpha_g) - \xi_{0g}(\alpha_g))}{y_{0g}(\alpha_g) - \eta_{0g}(\alpha_g)}\right]$$

Jeu entre spiral et goupille au repos $j := \dfrac{\varepsilon\cdot(y_{0g}(\alpha_g) - \eta_{0g}(\alpha_g))}{cos(\beta)}\cdot\theta_1$ $j = 0.011\,mm$

Calcul de la matrice $\boldsymbol{D_g}$

Calcul à partir de la première approximation de la déformée

$$z_{1t}(\theta, \alpha_t) := z_P + \frac{L_t \cdot R_0}{L_t + \theta \cdot R_0} \cdot \left(exp\left(i \cdot \alpha_t \cdot \frac{L_t + \theta \cdot R_0}{L_t} \right) - 1 \right)$$

$$x_1(\theta, \alpha) := Re(z_{1t}(\theta, \alpha)) \qquad y_1(\theta, \alpha) := Im(z_{1t}(\theta, \alpha)) \qquad EI := E \cdot I_s \cdot N^{-1} \cdot m^{-2} \qquad EI = 7.063 \times 10^{-8}$$

$$\xi_{1g}(\alpha_g) := \frac{1}{\alpha_g} \cdot \int_0^{\alpha_g} x_1(\theta_0, \alpha)\, d\alpha \qquad \eta_{1g}(\alpha_g) := \frac{1}{\alpha_g} \cdot \int_0^{\alpha_g} y_1(\theta_0, \alpha)\, d\alpha$$

$$p2_{1g}(\alpha_g) := \frac{1}{\alpha_g} \cdot \int_0^{\alpha_g} x_1(\theta_0, \alpha)^2\, d\alpha \qquad q2_{1g}(\alpha_g) := \frac{1}{\alpha_g} \cdot \int_0^{\alpha_g} y_1(\theta_0, \alpha)^2\, d\alpha$$

$$k_{1g}(\alpha_g) := \frac{1}{\alpha_g} \cdot \int_0^{\alpha_g} x_1(\theta_0, \alpha) \cdot y_1(\theta_0, \alpha)\, d\alpha$$

$$d1_{11}(\alpha_g) := q2_{1g}(\alpha_g) \cdot m^{-2} \qquad d1_{22}(\alpha_g) := p2_{1g}(\alpha_g) \cdot m^{-2} \qquad d1_{33}(\alpha_g) := 1 \qquad \mathrm{R}_0 := R_0 \cdot m^{-1}$$

$$d1_{12}(\alpha_g) := -k_{1g}(\alpha_g) \cdot m^{-2} \qquad d1_{13}(\alpha_g) := \eta_{1g}(\alpha_g) \cdot m^{-1} \qquad d1_{23}(\alpha_g) := -\xi_{1g}(\alpha_g) \cdot m^{-1}$$

$$\boldsymbol{D_{1g}}(\alpha_g) := \frac{\mathrm{R}_0 \cdot \alpha_g}{EI} \cdot \begin{pmatrix} d1_{11}(\alpha_g) & d1_{12}(\alpha_g) & d1_{13}(\alpha_g) \\ d1_{12}(\alpha_g) & d1_{22}(\alpha_g) & d1_{23}(\alpha_g) \\ d1_{13}(\alpha_g) & d1_{23}(\alpha_g) & 1 \end{pmatrix} \qquad \boldsymbol{D_{1g}}(\alpha_g) = \begin{pmatrix} 0.074 & -0.087 & 47.727 \\ -0.087 & 0.17 & -79.645 \\ 47.727 & -79.645 & 3.902 \times 10^4 \end{pmatrix}$$

Approximation à partir de la forme naturelle du spiral

$$p2_{0g}(\alpha_g) := \frac{R_0^2}{2 \cdot \alpha_g} \cdot \left(\alpha_g + \frac{sin(2 \cdot \alpha_g)}{2} \right) \qquad q2_{0g}(\alpha_g) := \frac{R_0^2}{2 \cdot \alpha_g} \cdot \left(\alpha_g - \frac{sin(2 \cdot \alpha_g)}{2} \right) \qquad k_{0g}(\alpha_g) := \frac{R_0^2}{2 \cdot \alpha_g} \cdot sin(\alpha_g)^2$$

$$d_{11}(\alpha_g) := q2_{0g}(\alpha_g) \cdot m^{-2} \qquad d_{22}(\alpha_g) := p2_{0g}(\alpha_g) \cdot m^{-2} \qquad d_{33}(\alpha_g) := 1$$

$$d_{12}(\alpha_g) := -k_{0g}(\alpha_g) \cdot m^{-2} \qquad d_{13}(\alpha_g) := \eta_{0g}(\alpha_g) \cdot m^{-1} \qquad d_{23}(\alpha_g) := -\xi_{0g}(\alpha_g) \cdot m^{-1}$$

$$\boldsymbol{D_g}(\alpha_g) := \frac{\mathrm{R}_0 \cdot \alpha_g}{EI} \cdot \begin{pmatrix} d_{11}(\alpha_g) & d_{12}(\alpha_g) & d_{13}(\alpha_g) \\ d_{12}(\alpha_g) & d_{22}(\alpha_g) & d_{23}(\alpha_g) \\ d_{13}(\alpha_g) & d_{23}(\alpha_g) & 1 \end{pmatrix} \qquad \boldsymbol{D_g}(\alpha_g) = \begin{pmatrix} 0.078 & -0.091 & 48.738 \\ -0.091 & 0.176 & -81.231 \\ 48.738 & -81.231 & 3.902 \times 10^4 \end{pmatrix}$$

Calcul des formes quadratiques

$$Delta(\alpha_g) := sin(\alpha_g) \qquad \gamma(\alpha_g) := cos(\alpha_g) \qquad x_{0g}(\alpha_g) := R_0 \cdot cos(\alpha_g) \qquad y_{0g}(\alpha_g) := R_0 \cdot sin(\alpha_g)$$

$$H(\alpha_g) := \frac{R_0}{\alpha_g} \cdot (1 - cos(\alpha_g)) \qquad J(\alpha_g) := \frac{R_0}{\alpha_g} \cdot (\alpha_g - sin(\alpha_g))$$

$$\boldsymbol{V_1}(\alpha_g) := \left(\gamma(\alpha_g) \quad Delta(\alpha_g) \quad 0 \right)^T \qquad \boldsymbol{V_2}(\alpha_g) := \left(Delta(\alpha_g) \quad -\gamma(\alpha_g) \quad -\mathrm{R}_0 \right)^T$$

$$W1_{g1}(\alpha_g) := \frac{1 \cdot s^2 \cdot kg^{-1}}{2} \cdot \mathbf{V_1}(\alpha_g)^T \cdot \mathbf{D_{1g}}(\alpha_g) \cdot \mathbf{V_1}(\alpha_g) \qquad W1_{g1}(\alpha_g) = 0.038\ kg^{-1} \cdot s^2$$

$$W_{g1}(\alpha_g) := \frac{R_0^{\,3}}{4 \cdot E \cdot I_s} \cdot (\alpha_g - \sin(\alpha_g) \cdot \cos(\alpha_g)) \qquad W_{g1}(\alpha_g) = 0.039\ kg^{-1} \cdot s^2$$

$$W1_{g2}(\alpha_g) := \frac{1 \cdot s^2 \cdot kg^{-1}}{2} \cdot \mathbf{V_2}(\alpha_g)^T \cdot \mathbf{D_{1g}}(\alpha_g) \cdot \mathbf{V_2}(\alpha_g) \qquad W1_{g2}(\alpha_g) = 7.809 \times 10^{-3}\ kg^{-1} \cdot s^2$$

$$W_{g2}(\alpha_g) := \frac{R_0^{\,3}}{4 \cdot E \cdot I_s} \cdot \left[3 \cdot \alpha_g + \sin(\alpha_g) \cdot (\cos(\alpha_g) - 4)\right] \qquad W_{g2}(\alpha_g) = 7.531 \times 10^{-3}\ kg^{-1} \cdot s^2$$

$$W1_{g3}(\alpha_g) := \frac{1 \cdot s^2 \cdot kg^{-1}}{2} \cdot \mathbf{V_1}(\alpha_g)^T \cdot \mathbf{D_{1g}}(\alpha_g) \cdot \mathbf{V_2}(\alpha_g) \qquad W1_{g3}(\alpha_g) = 0.017\ kg^{-1} \cdot s^2$$

$$W_{g3}(\alpha_g) := \frac{R_0^{\,3}}{4 \cdot E \cdot I_s} \cdot (1 - \cos(\alpha_g))^2 \qquad W_{g3}(\alpha_g) = 0.016\ kg^{-1} \cdot s^2$$

$$V_g(\alpha_g) := \begin{pmatrix} R_0 \cdot \sin(\alpha_g) & -R_0 \cdot \cos(\alpha_g) & 1 \end{pmatrix}^T$$

$$W1_{c2}(\alpha_g) := \frac{1 \cdot kg \cdot m^2 \cdot s^{-2}}{2} \cdot \left(\left(V_g(\alpha_g)\right)\right)^T \cdot \mathbf{D_{1g}}(\alpha_g)^{-1} \cdot V_g(\alpha_g) \qquad W1_{c2}(\alpha_g) = 6.41 \times 10^{-5}\ m^2 \cdot kg \cdot s^{-2}$$

$$\Delta_g(\alpha_g) := \frac{R_0^{\,4}}{4 \cdot \alpha_g^{\,3}} \cdot (\alpha_g - \sin(\alpha_g)) \cdot \left[\alpha_g \cdot (\alpha_g + \sin(\alpha_g)) - 4 \cdot (1 - \cos(\alpha_g))\right] \qquad \Delta_g(\alpha_g) = 7.057 \times 10^{-3}\ mm^4$$

$$W_{c2}(\alpha_g) := \frac{E \cdot I_s \cdot R_0^{\,3}}{8 \cdot \Delta_g(\alpha_g) \cdot \alpha_g^{\,3}} \cdot \left[3 \cdot \alpha_g^{\,2} - 2 \cdot \alpha_g \cdot \sin(\alpha_g) \cdot (2 + \cos(\alpha_g)) - (1 - \cos(\alpha_g)) \cdot (1 - 7 \cdot \cos(\alpha_g))\right]$$

$$W_{c2}(\alpha_g) = 1.127 \times 10^{-4}\ m^2 \cdot kg \cdot s^{-2}$$

Coefficient de frottement limite

$$F1(\alpha_g) := \frac{H(\alpha_g) \cdot W1_{g3}(\alpha_g) - J(\alpha_g) \cdot W1_{g1}(\alpha_g)}{H(\alpha_g) \cdot W1_{g2}(\alpha_g) - J(\alpha_g) \cdot W1_{g3}(\alpha_g)} \qquad F1(\alpha_g) = 1.645$$

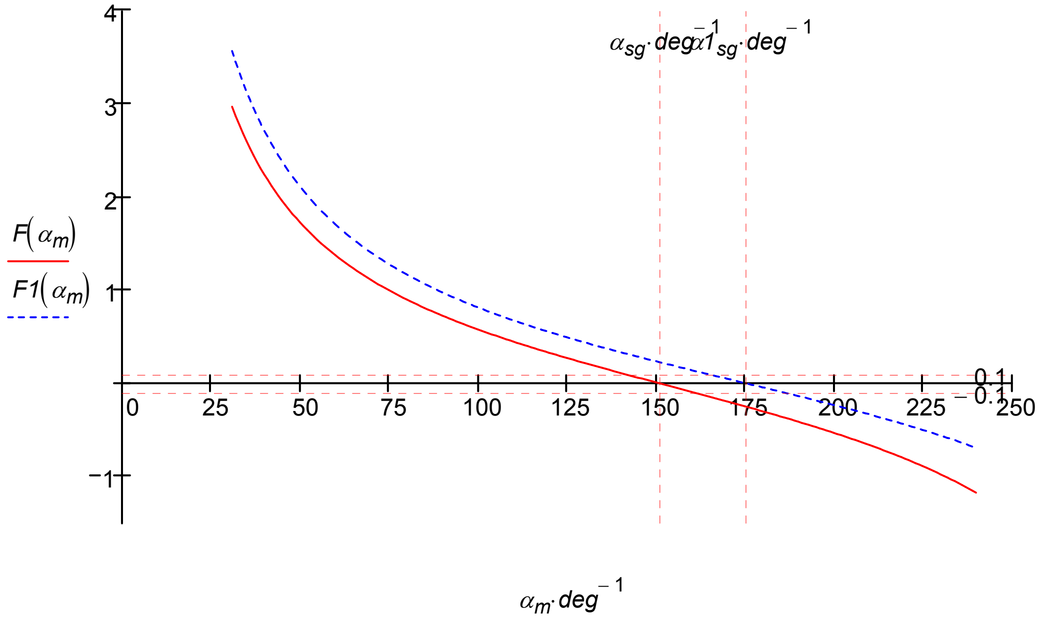
$$F(\alpha_g) := \frac{H(\alpha_g) \cdot W_{g3}(\alpha_g) - J(\alpha_g) \cdot W_{g1}(\alpha_g)}{H(\alpha_g) \cdot W_{g2}(\alpha_g) - J(\alpha_g) \cdot W_{g3}(\alpha_g)} \qquad F(\alpha_g) = 1.322$$

$$F(\alpha_g) := \frac{-\alpha_g^{\,2} + \alpha_g \cdot \sin(\alpha_g) \cdot (1 + \cos(\alpha_g)) + (1 - \cos(\alpha_g)) \cdot (1 - 3 \cdot \cos(\alpha_g))}{(1 - \cos(\alpha_g)) \cdot \left[(2 + \cos(\alpha_g)) \cdot \alpha_g - 3 \cdot \sin(\alpha_g)\right]} \qquad F(\alpha_g) = 1.322$$

$$\alpha_{sg} := 151 \cdot deg \qquad \alpha_{sg} := racine(F(\alpha_{sg}), \alpha_{sg}) \qquad \alpha_{sg} = 151.277\ deg$$

$$\alpha1_{sg} := 175 \cdot deg \qquad \alpha1_{sg} := racine(F1(\alpha1_{sg}), \alpha1_{sg}) \qquad \alpha1_{sg} = 175.718\ deg$$

$$\alpha_m := 31 \cdot deg, 32 \cdot deg \,..\, 240 \cdot deg$$



Réaction normale à la goupille

Coefficient de frottement $f_g := 0.1$ $\mu_g := f_g$

$$F1_{gn}(\theta, \alpha_g) := \frac{\varepsilon \cdot H(\alpha_g) \cdot (\theta - \theta_1)}{2 \cdot \left(W1_{g1}(\alpha_g) - \mu_g \cdot W1_{g3}(\alpha_g)\right)} \qquad F1_{gn}(\theta_0, \alpha_g) = 1.709 \times 10^{-3}\, N$$

$$F_{gn}(\theta, \alpha_g) := \varepsilon \cdot (\theta - \theta_1) \cdot \frac{2 \cdot E \cdot I_s}{R_0^{\,2}} \cdot \frac{1 - \cos(\alpha_g)}{\alpha_g \cdot \left[\alpha_g - \sin(\alpha_g) \cdot \cos(\alpha_g) - \mu_g \cdot \left(1 - \cos(\alpha_g)\right)^2\right]}$$

$$F_{gn}(\theta_0, \alpha_g) = 1.675 \times 10^{-3}\, N$$

Calcul du glissement

$$q1(\alpha_g) := \frac{W1_{g1}(\alpha_g)}{W1_{g3}(\alpha_g)} \qquad \Delta s_{1g}(\theta, \theta_1, \alpha_g, f_g) := \varepsilon \cdot (\theta - \theta_1) \cdot \frac{F(\alpha_g) - \mu_g}{q1(\alpha_g) - \mu_g} \cdot \frac{J(\alpha_g) \cdot W1_{g3}(\alpha_g) - H(\alpha_g) \cdot W1_{g2}(\alpha_g)}{W1_{g3}(\alpha_g)}$$

$$\Delta s_g(\theta, \theta_1, \alpha_g, f_g) := -\varepsilon \cdot (\theta - \theta_1) \cdot R_0 \cdot \frac{\left(1 - \cos(\alpha_g)\right) \cdot \left[\left(2 + \cos(\alpha_g)\right) \cdot \alpha_g - 3 \cdot \sin(\alpha_g)\right]}{\alpha_g \cdot \left[\alpha_g - \sin(\alpha_g) \cdot \cos(\alpha_g) - f_g \cdot \left(1 - \cos(\alpha_g)\right)^2\right]} \cdot \left(F(\alpha_g) - f_g\right)$$

$$\Delta s_{1g}(\theta_0, \theta_1, \alpha_g, f_g) = -6.247 \times 10^{-3}\, mm \qquad \Delta s_g(\theta_0, \theta_1, \alpha_g, f_g) = -5.583 \times 10^{-3}\, mm$$

Remarque

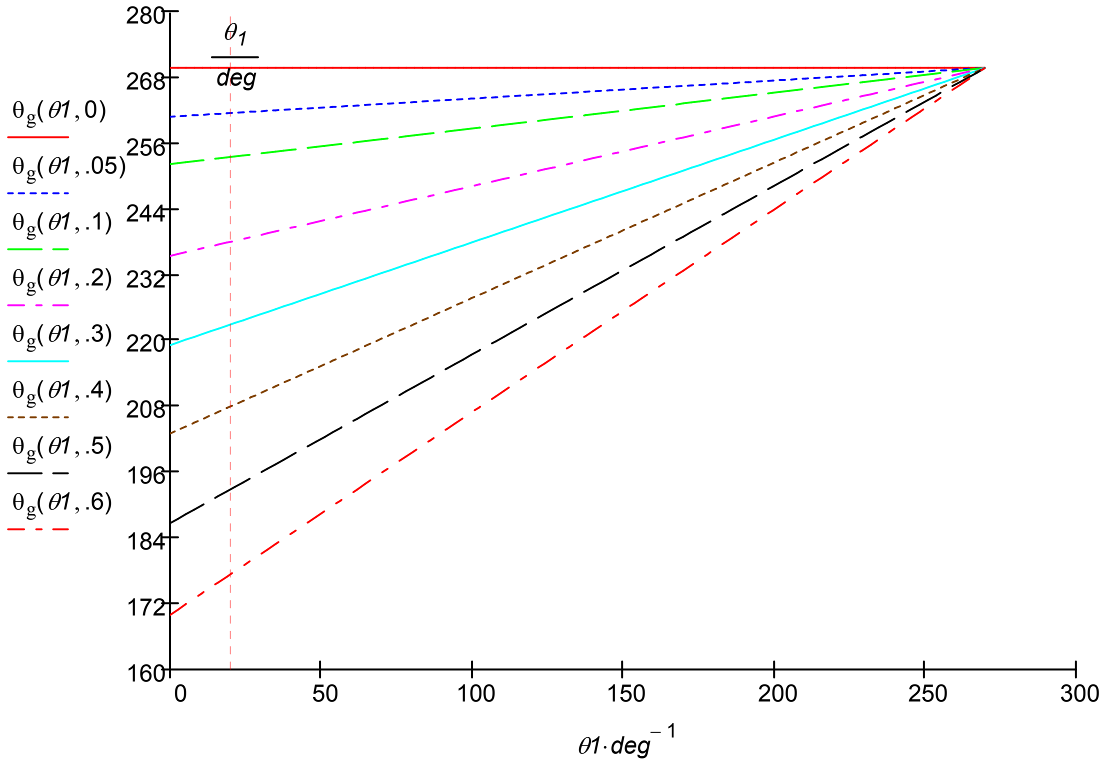
Les erreurs étant relativement faibles pour un angle α_g inférieur à 90°, nous continuerons les calculs en ne considérant que les valeurs obtenues à partir de la forme naturelle du spiral

Evolution du glissement en fonction de l'élongation du balancier

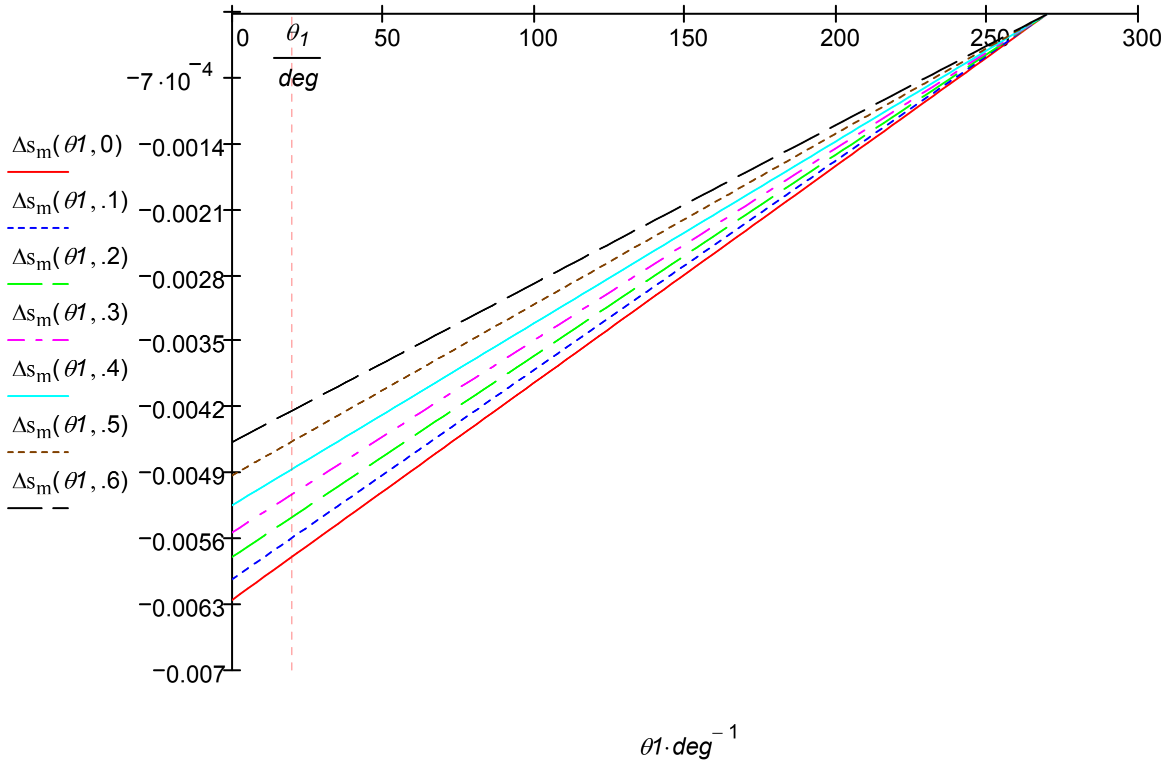
Angle de début de glissement inverse

$$q(\alpha_g) := \frac{\alpha_g - \sin(\alpha_g) \cdot \cos(\alpha_g)}{\left(1 - \cos(\alpha_g)\right)^2} \qquad \theta_g(\theta_0, \theta_1, \alpha_g, f_g) := \frac{q(\alpha_g) + f_g}{F(\alpha_g) + f_g} \cdot \frac{F(\alpha_g) - f_g}{q(\alpha_g) - f_g} \cdot (\theta_0 - \theta_1) + \theta_1$$

$$\theta1 := 0, 0.01 \cdot \theta_0 .. \theta_0 \qquad \Theta_g(\theta_1, f_g) := \theta_g(\theta_0, \theta_1, \alpha_g, f_g) \cdot deg^{-1} \qquad \theta_g(\theta_0, \theta_1, \alpha_g, f_g) = 253.7\, deg$$



Glissement maximum $\Delta s_m(\theta_1, f_g) := \Delta s_g(\theta_0, \theta_1, \alpha_g, f_g)$ $\Delta s_m(\theta_1, f_g) := \Delta s_m(\theta_1, f_g) \cdot mm^{-1}$



Glissement inverse

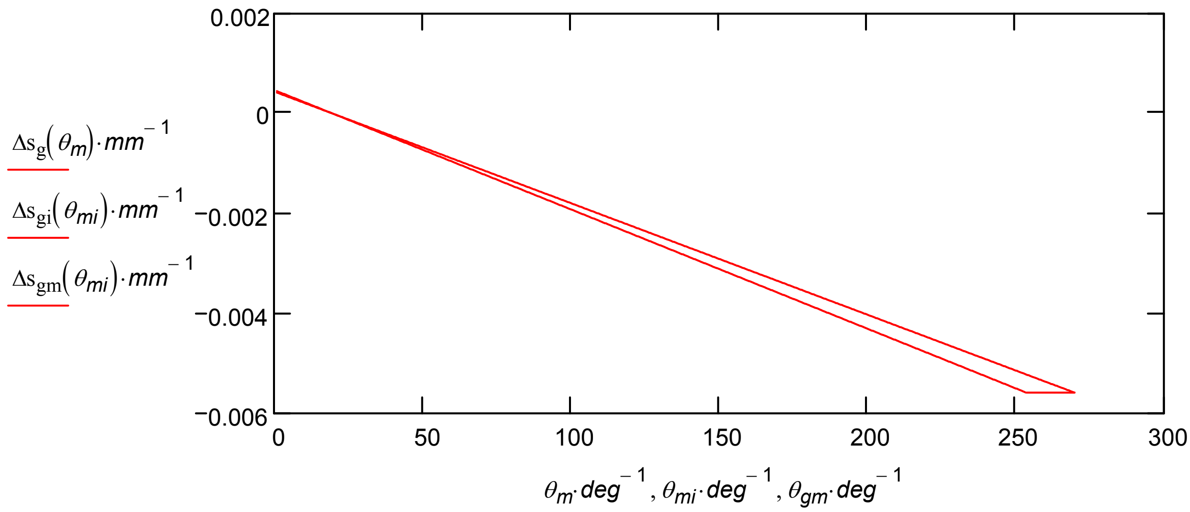
$$\Delta s_{gi}(\theta, \theta_1, \alpha_g, f_g) := -\varepsilon \cdot (\theta - \theta_1) \cdot R_0 \cdot \frac{(1 - \cos(\alpha_g)) \cdot [(2 + \cos(\alpha_g)) \cdot \alpha_g - 3 \cdot \sin(\alpha_g)]}{\alpha_g \cdot \left[\alpha_g - \sin(\alpha_g) \cdot \cos(\alpha_g) + f_g \cdot (1 - \cos(\alpha_g))^2\right]} \cdot (F(\alpha_g) + f_g)$$

Graphe de l'évolution du glissement en fonction de l'élongation du balancier

$\Delta s_g(\theta) := \Delta s_g(\theta, \theta_1, \alpha_g, f_g)$ $\qquad \theta_m := 1 \cdot deg, 1.5 \cdot deg .. \theta_0$

$\Delta s_{gi}(\theta) := \Delta s_{gi}(\theta, \theta_1, \alpha_g, f_g)$ $\qquad \theta_{mi} := 1 \cdot deg, 1.5 \cdot deg .. \theta_g(\theta_0, \theta_1, \alpha_g, f_g)$

$\Delta s_{gm}(\theta) := \Delta s_g(\theta_0, \theta_1, \alpha_g, f_g)$ $\qquad \theta_{gm} := \theta_g(\theta_0, \theta_1, \alpha_g, f_g), \theta_g(\theta_0, \theta_1, \alpha_g, f_g) + 0.2 \cdot deg .. \theta_0$



Accroissement de l'angle polaire de la tangente au spiral au point de contact

$N(\alpha_g) := \dfrac{E \cdot I_s}{2 \cdot R_0 \cdot \alpha_g \cdot W_{c2}(\alpha_g)}$ $\qquad N(\alpha_g) = 0.114$

$M_g(\alpha_g) := \mathbf{D_g}(\alpha_g)^{-1} \cdot \begin{pmatrix} y_{0g}(\alpha_g) \cdot m^{-1} \\ -x_{0g}(\alpha_g) \cdot m^{-1} \\ 1 \end{pmatrix}$ $\qquad m_g(\alpha_g) := M_g(\alpha_g)_0 \cdot N$ $\qquad n_g(\alpha_g) := M_g(\alpha_g)_1 \cdot N$

$$\varphi_{sg}(\theta, \theta_1, \alpha_g, f_g) := \varepsilon \cdot (\theta - \theta_1) \cdot (N(\alpha_g) - 1) - \frac{\Delta s_g(\theta, \theta_1, \alpha_g, f_g)}{2 \cdot W_{c2}(\alpha_g)} \cdot (n_g(\alpha_g) \cdot \gamma(\alpha_g) - m_g(\alpha_g) \cdot Delta(\alpha_g))$$

$\varphi_{sg}(\theta_0, \theta_1, \alpha_g, f_g) = -4.502\, deg$ $\qquad \Delta\varphi_g := \varphi_{sg}(\theta_0, \theta_1, \alpha_g, f_g) + \varepsilon \cdot (\theta_0 - \theta_1)$

Sans goupille $\qquad \Delta\varphi := \theta_0 \cdot \dfrac{R_0 \cdot \alpha_g}{L_t}$ $\qquad \Delta\varphi = 6.21\, deg$ $\qquad \Delta\varphi_g = 1.248\, deg$

Perturbation de marche dans le cas de deux goupilles

$$\phi_1(\theta_1, \theta_0) := arcsin\left(\frac{\theta_1}{\theta_0}\right) \cdot (-\theta_0 \le \theta_1 \le \theta_0) + \frac{\pi}{2} \cdot (\theta_1 > \theta_0) - \frac{\pi}{2} \cdot (\theta_1 < -\theta_0)$$

$$\phi_2(\theta_2, \theta_0) := -arcsin\left(\frac{\theta_2}{\theta_0}\right) \cdot (-\theta_0 \le \theta_2 \le \theta_0) + \frac{\pi}{2} \cdot (\theta_2 < -\theta_0) - \frac{\pi}{2} \cdot (\theta_2 > \theta_0)$$

$$\delta_1(\theta_1, \theta_0) := \frac{-\varepsilon}{4 \cdot \pi} \cdot (\pi - 2 \cdot \phi_1(\theta_1, \theta_0) - sin(2 \cdot \phi_1(\theta_1, \theta_0)))$$

$$\delta_2(\theta_2, \theta_0) := \frac{-\varepsilon}{4 \cdot \pi} \cdot (\pi - 2 \cdot \phi_2(\theta_2, \theta_0) - sin(2 \cdot \phi_2(\theta_2, \theta_0)))$$

Spiral à égales distances des goupilles en position d'équilibre: $\theta_2 := -\theta_1$

Théorie élémentaire

$\delta_1(\theta_1, \theta_0) = -5.208 \times 10^{-3}$ $\delta_2(\theta_2, \theta_0) = -5.208 \times 10^{-3}$ $\phi_1(\theta_1, \theta_0) = 0.074$ $\phi_2(\theta_2, \theta_0) = 0.074$

$\mu_{él}(\theta_0) := -86400 \cdot (\delta_1(\theta_1, \theta_0) + \delta_2(\theta_2, \theta_0))$ $\mu_{él}(\theta_0) = 899.975$

Théorie avancée

$$M'(\alpha_g) := \frac{[\alpha_g \cdot (2 + \cos(\alpha_g)) - 3 \cdot \sin(\alpha_g)] \cdot [\alpha_g^2 - \alpha_g \cdot \sin(\alpha_g) \cdot (1 + \cos(\alpha_g)) - (1 - \cos(\alpha_g)) \cdot (1 - 3 \cdot \cos(\alpha_g))]}{\alpha_g \cdot (1 - \cos(\alpha_g)) \cdot [3 \cdot \alpha_g^2 - 2 \cdot \alpha_g \cdot \sin(\alpha_g) \cdot (2 + \cos(\alpha_g)) - (1 - \cos(\alpha_g)) \cdot (1 - 7 \cdot \cos(\alpha_g))]}$$

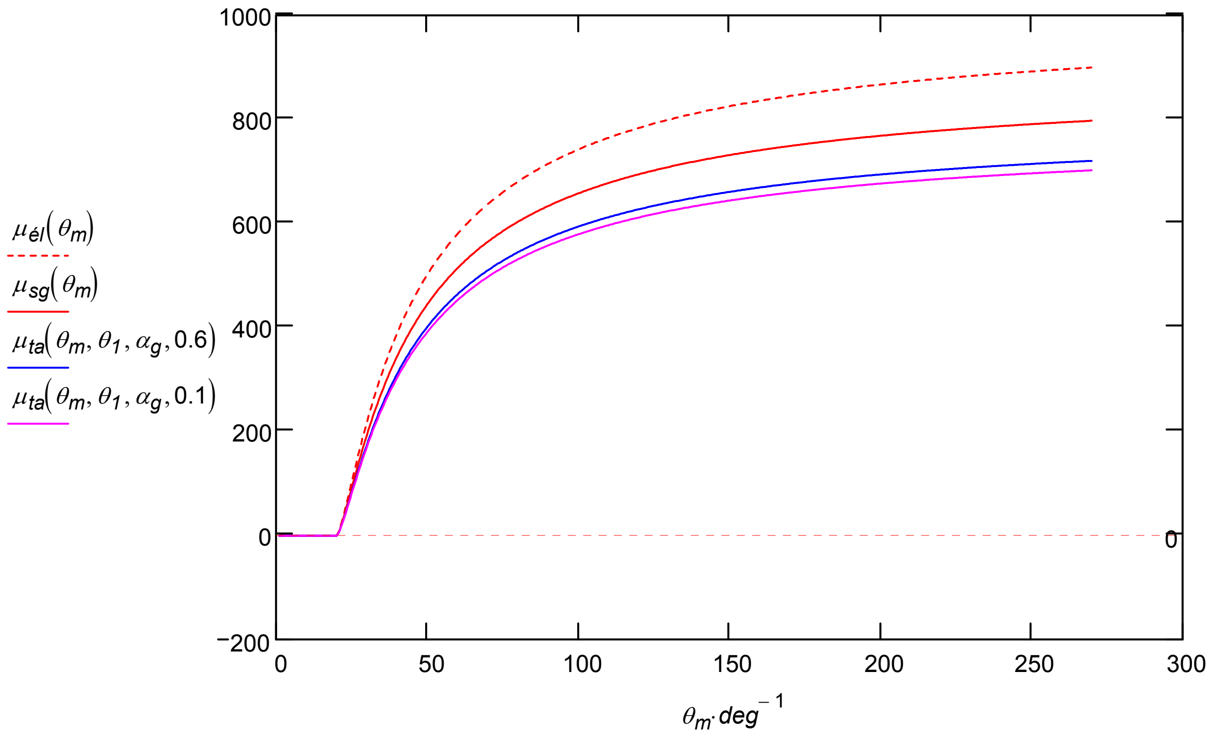
$$\phi_g(\theta_0, \theta_1, \alpha_g, f_g) := \arcsin\left[\sin(\phi_1(\theta_1, \theta_0)) + \frac{F(\alpha_g) - f_g}{q(\alpha_g) - f_g} \cdot \frac{q(\alpha_g) + f_g}{F(\alpha_g) + f_g} \cdot (1 - \sin(\phi_1(\theta_1, \theta_0)))\right]$$

$$\delta_g(\theta_0, \theta_1, \alpha_g, f_g) := \frac{\varepsilon}{4 \cdot \pi} \cdot (\pi - 2 \cdot \phi_g(\theta_0, \theta_1, \alpha_g, f_g) - \sin(2 \cdot \phi_g(\theta_0, \theta_1, \alpha_g, f_g)))$$

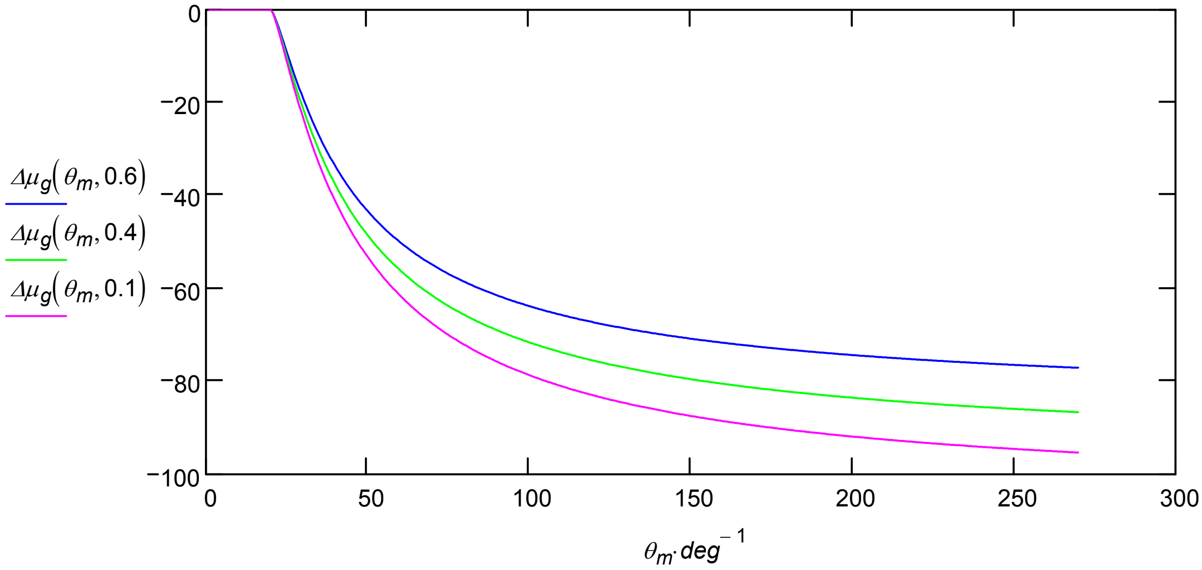
$$K_1(\alpha_g, f_g) := (1 - N(\alpha_g)) + M'(\alpha_g) \cdot \left(\frac{F(\alpha_g) - f_g}{q(\alpha_g) - f_g} + \frac{F(\alpha_g) + f_g}{q(\alpha_g) + f_g}\right) \qquad K_2(\alpha_g, f_g) := M'(\alpha_g) \cdot \frac{F(\alpha_g) + f_g}{q(\alpha_g) + f_g}$$

$$\mu_{ta}(\theta_0, \theta_1, \alpha_g, f_g) := -86400 \cdot 2 \cdot (K_1(\alpha_g, f_g) \cdot \delta_1(\theta_1, \theta_0) + K_2(\alpha_g, f_g) \cdot \delta_g(\theta_0, \theta_1, \alpha_g, f_g))$$

$\mu_{sg}(\theta_0) := \mu_{él}(\theta_0) \cdot (1 - N(\alpha_g))$ marche en cas de glissement impossible



$$\Delta\mu_g(\theta_0, f_g) := \mu_{ta}(\theta_0, \theta_1, \alpha_g, f_g) - \mu_{sg}(\theta_0)$$



Réglage par la raquette

$$\delta_1(\theta_1, \theta_0, \alpha_g) := \frac{-R_0 \cdot \alpha_g}{4 \cdot \pi \cdot L_t} \cdot (\pi - 2 \cdot \phi_1(\theta_1, \theta_0) - \sin(2 \cdot \phi_1(\theta_1, \theta_0)))$$

$$\delta_g(\theta_0, \theta_1, \alpha_g, f_g) := \frac{R_0 \cdot \alpha_g}{4 \cdot \pi \cdot L_t} \cdot (\pi - 2 \cdot \phi_g(\theta_0, \theta_1, \alpha_g, f_g) - \sin(2 \cdot \phi_g(\theta_0, \theta_1, \alpha_g, f_g)))$$

$$\mu_{ta}(\theta_1, \theta_0, \alpha_g, f_g) := -86400 \cdot 2 \cdot (K_1(\alpha_g, f_g) \cdot \delta_1(\theta_1, \theta_0, \alpha_g) + K_2(\alpha_g, f_g) \cdot \delta_g(\theta_0, \theta_1, \alpha_g, f_g))$$

$$\alpha_m := 40 \cdot deg, 42 \cdot deg .. 90 \cdot deg$$