Spiral plat avec courbes terminales externe et interne

Influence d'une déformation des courbes terminales

Calculs numériques et approximations de Haag

Caractéristiques du spiral

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

Référence :C:\Résonateur (TA)\Data\Définition Atan.mcd(R)

Dimensions $\quad ép = 0.03\,mm \quad ha = 0.15\,mm \quad S = 4.5\times 10^{-3}\,mm^2 \quad TOL := 10^{-12}$

$d2_{sp} = 4.52\,mm \quad d_V := 1.1\cdot mm \quad d_B := 1.312\cdot d1_{sp} \quad p_{sp} = 0.135\,mm \quad n_{sp} := \dfrac{d2_{sp} - d_B}{2\cdot p_{sp}}$

$L := \pi\cdot\dfrac{n_{sp}}{2}\cdot\left(d2_{sp} + d_B\right) \quad L = 10.674\,cm \quad \psi_0 := 2\cdot\pi\cdot n_{sp} \quad \psi_0 = 4.102\times 10^3\,deg$

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

Forme initiale du spiral

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

$s(\alpha) := \dfrac{1}{2\cdot a}\cdot\left(r_A{}^2 - r_s(\alpha)^2\right) \quad s(\alpha) := r_A\cdot\left(\alpha - \alpha_A\right) - \dfrac{a}{2}\cdot\left(\alpha - \alpha_A\right)^2$

Référence :C:\Résonateur (TA)\Tables\Modules J, I et W des barres élastiques.mcd(R)

$I_{33} := I_{f\_rect}(ép, ha)$

Courbes terminales

Courbe terminale externe

$r_{t1} := 0.8 \quad r_{Ph} := racine\left[\left(2\cdot r_{t1} - 1\right)^4 - 4\cdot\left(1 - r_{t1}\right)^4 - \pi^2\cdot r_{t1}{}^2\cdot\left(1 - r_{t1}\right)^2, r_{t1}\right]\cdot r_A \quad r_{Ph} = 0.832\,r_A$

$r_{t2}\left(r_{t1}\right) := 2\cdot r_{t1} - r_A \quad \beta_0 := arctan\left[\dfrac{\pi\cdot r_{Ph}}{2\cdot\left(r_A - r_{Ph}\right)}\right] \quad \beta_0 = 82.695\,deg \quad l_t\left(r_{t1}\right) := r_{t2}\left(r_{t1}\right)\cdot\beta_0 + \pi\cdot r_{t1}$

$X_{0t1}\left(r_{t1}, \alpha_t\right) := r_A - r_{t1} + r_{t1}\cdot cos\left(\alpha_t\right) \quad Y_{0t1}\left(r_{t1}, \alpha_t\right) := r_{t1}\cdot sin\left(\alpha_t\right)$

$X_{0t2}\left(r_{t1}, \beta_t\right) := -r_{t2}\left(r_{t1}\right)\cdot cos\left(\beta_t\right) \quad Y_{0t2}\left(r_{t1}, \beta_t\right) := -r_{t2}\left(r_{t1}\right)\cdot sin\left(\beta_t\right) \quad \mathbf{OA} := r_A\cdot e^{i\cdot\pi}$

Courbe terminale interne $\quad \alpha_B := mod\left(\psi_0 + \pi, 2\cdot\pi\right) \quad \alpha_B = 322.4\,deg \quad r_B := 0.5\cdot d_B$

$\beta := 121\cdot deg \quad \beta'_0 := racine\left[\beta\cdot\left(\sqrt{2}\cdot sin(\beta) - 1\right) + sin(\beta)\cdot cos(\beta), \beta\right] \quad \beta'_0 = 121.21\,deg$

$r'_{Ph} := \dfrac{r_B}{\sqrt{2}\cdot sin\left(\beta'_0\right)} \quad r'_{Ph} = 0.597\,mm \quad l_{t'}\left(r_{t'}\right) := r_{t'}\cdot 2\cdot\beta'_0 \quad l_{t'}\left(r'_{Ph}\right) = 2.524\,mm$

$X_{0t'}\left(r_{t'}, \alpha_{t'}\right) := r_B - r_{t'} + r_{t'}\cdot cos\left(\alpha_{t'}\right) \quad Y_{0t'}\left(r_{t'}, \alpha_{t'}\right) := r_{t'}\cdot sin\left(\alpha_{t'}\right)$

$\mathbf{OB} := r_B\cdot e^{i\cdot\left(\pi + \psi_0\right)} \quad L_t\left(r_{t1}, r_{t'}\right) := l_t\left(r_{t1}\right) + L + l_{t'}\left(r_{t'}\right)$

Graphes

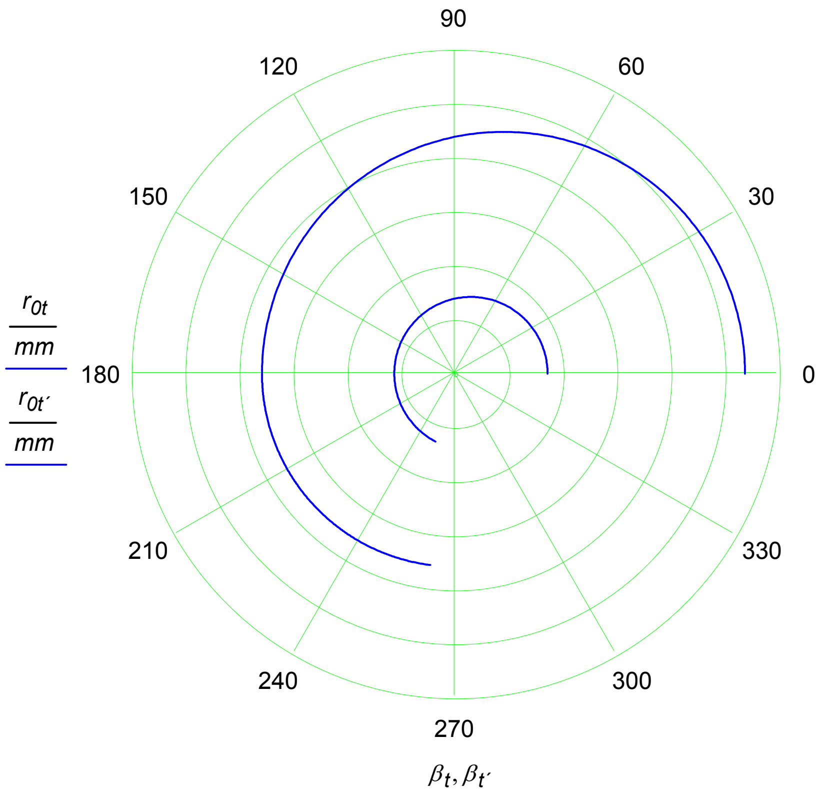
$n_t := 201 \quad j := 0\,..\,n_t - 1 \quad \Delta\alpha_t := \dfrac{\pi}{n_t - 1} \quad \alpha_{t_j} := j\cdot\Delta\alpha_t \quad X_{t_j} := X_{0t1}\left(r_{Ph}, \alpha_{t_j}\right) \quad Y_{t_j} := Y_{0t1}\left(r_{Ph}, \alpha_{t_j}\right)$

$\Delta\beta_t := \dfrac{\beta_0}{n_t - 1} \quad \beta_{t_j} := j\cdot\Delta\beta_t \quad X_{t2_j} := X_{0t2}\left(r_{Ph}, \beta_{t_j}\right) \quad Y_{t2_j} := Y_{0t2}\left(r_{Ph}, \beta_{t_j}\right)$

$X_t := pile(X_t, X_{t2})$ $\quad Y_t := pile(Y_t, Y_{t2})$ $\quad r_{0t} := \overrightarrow{\sqrt{X_t^2 + Y_t^2}}$ $\quad \beta_t := \overrightarrow{Atan(X_t, Y_t)}$

$\Delta\alpha_{t'} := \dfrac{2 \cdot \beta'_0}{n_t - 1}$ $\quad \alpha_{t'_j} := j \cdot \Delta\alpha_{t'}$ $\quad X_{t'_j} := X_{0t'}\left(r'_{Ph}, \alpha_{t'_j}\right)$ $\quad Y_{t'_j} := Y_{0t'}\left(r'_{Ph}, \alpha_{t'_j}\right)$ $\quad r_{0t'} := \overrightarrow{\sqrt{X_{t'}^2 + Y_{t'}^2}}$

$\beta_{t'} := \overrightarrow{Atan(X_{t'}, Y_{t'})}$



Perturbation de période en position horizontale

Cas de courbes de Phillips

Paramètres de la courbe terminale externe

$Z_{0t1}(r_{t1}, \alpha) := X_{0t1}(r_{t1}, \alpha) + i \cdot Y_{0t1}(r_{t1}, \alpha)$ $\qquad Z_{0t2}(r_{t1}, \alpha) := X_{0t2}(r_{t1}, \alpha) + i \cdot Y_{0t2}(r_{t1}, \alpha)$

$$Z_1(r_{t1}) := \frac{1}{r_A^2} \cdot \left(\int_0^{\pi} Z_{0t1}(r_{t1}, \alpha) \cdot r_{t1}\, d\alpha + \int_0^{\beta_0} Z_{0t2}(r_{t1}, \beta) \cdot r_{t2}(r_{t1})\, d\beta \right) - i$$

$\rho_{01} := \left|Z_1(r_{Ph})\right|$ $\qquad \varphi_{01} := arg(Z_1(r_{Ph}))$ $\qquad \boxed{\rho_{01} = 0}$ $\qquad \boxed{\varphi_{01} = -90\,deg}$

$$Z_2(r_{t1}) := \frac{1}{r_A^3} \cdot \left[\int_0^{\pi} r_{t1} \cdot \alpha \cdot Z_{0t1}(r_{t1}, \alpha) \cdot r_{t1}\, d\alpha + \int_0^{\beta_0} \left(r_{t1} \cdot \pi + r_{t2}(r_{t1}) \cdot \beta\right) \cdot Z_{0t2}(r_{t1}, \beta) \cdot r_{t2}(r_{t1})\, d\beta \right] + 1$$

$\rho_{02} := \left|Z_2(r_{Ph})\right|$ $\qquad \varphi_{02} := arg(Z_2(r_{Ph}))$ $\qquad \boxed{\rho_{02} = 1.055}$ $\qquad \boxed{\varphi_{02} = 147.579\,deg}$

Paramètres de la courbe terminale interne

$Z_{0t'}(r_{t'},\alpha) := X_{0t'}(r_{t'},\alpha) + i\cdot Y_{0t'}(r_{t'},\alpha)$

$Z'_1(r_{t'}) := \frac{1}{r_B^2}\cdot\int_0^{2\cdot\beta'_0} Z_{0t'}(r_{t'},\alpha)\cdot r_{t'}\,d\alpha - i$ $\qquad \rho'_1 := |Z'_1(r'_{Ph})|$ $\qquad \varphi'_1 := arg(Z'_1(r'_{Ph}))$

$\rho'_1 = 0$ $\qquad \varphi'_1 = -25.264\,deg$

$Z'_2(r_{t'}) := \frac{1}{r_B^3}\cdot\int_0^{2\cdot\beta'_0} r_{t'}\cdot\alpha\cdot Z_{0t'}(r_{t'},\alpha)\cdot r_{t'}\,d\alpha + 1$ $\qquad \rho'_2 := |Z'_2(r'_{Ph})|$ $\qquad \varphi'_2 := arg(Z'_2(r'_{Ph}))$

$\rho'_2 = 1.074$ $\qquad \varphi'_2 = 145.651\,deg$

Modifications de la forme des courbes terminales

Valeurs de test $\qquad x_1 := 1.02 \qquad x_2 := 0.98 \qquad r_{t1} := x_1\cdot r_{Ph} \qquad r_{t'} := x_2\cdot r'_{Ph}$

$\rho_1(r_{t1}) := |Z_1(r_{t1})|$ $\qquad \varphi_1(r_{t1}) := arg(Z_1(r_{t1}))$ $\qquad \rho_2(r_{t1}) := |Z_2(r_{t1})|$ $\qquad \varphi_2(r_{t1}) := arg(Z_2(r_{t1}))$

$\rho_1(r_{t1}) = 0.082$ $\qquad \varphi_1(r_{t1}) = 168.521\,deg$ $\qquad \rho_2(r_{t1}) = 1.274$ $\qquad \varphi_2(r_{t1}) = 156.245\,deg$

$\rho'_1(r_{t'}) := |Z'_1(r_{t'})|$ $\qquad \varphi'_1(r_{t'}) := arg(Z'_1(r_{t'}))$ $\qquad \rho'_2(r_{t'}) := |Z'_2(r_{t'})|$ $\qquad \varphi'_2(r_{t'}) := arg(Z'_2(r_{t'}))$

$\rho'_1(r_{t'}) = 0.079$ $\qquad \varphi'_1(r_{t'}) = -30.008\,deg$ $\qquad \rho'_2(r_{t'}) = 0.871$ $\qquad \varphi'_2(r_{t'}) = 139.091\,deg$

Calcul numérique de la perturbation de période

$$\mathbf{w_A}(r_{t1},r_{t'},\theta) := \left[i\cdot\left(r_A\cdot\rho_1(r_{t1})\cdot e^{-i\cdot\varphi_1(r_{t1})} + 2\cdot a\right) + \frac{\theta}{L_t(r_{t1},r_{t'})}\cdot r_A^2\cdot\rho_2(r_{t1})\cdot e^{-i\cdot\varphi_2(r_{t1})}\right]\cdot exp\left(\frac{i\cdot\theta\cdot l_t(r_{t1})}{L_t(r_{t1},r_{t'})}\right)\cdot\mathbf{OA}$$

$$\mathbf{w_B}(r_{t1},r_{t'},\theta) := \left[i\cdot\left(r_B\cdot\rho'_1(r_{t'})\cdot e^{i\cdot\varphi'_1(r_{t'})} - 2\cdot a\right) - \frac{\theta}{L_t(r_{t1},r_{t'})}\cdot r_B^2\cdot\rho'_2(r_{t'})\cdot e^{i\cdot\varphi'_2(r_{t'})}\right]\cdot exp\left(i\cdot\theta\cdot\frac{l_t(r_{t1})+L}{L_t(r_{t1},r_{t'})}\right)\cdot\mathbf{OB}$$

$\mathbf{w}(r_{t1},r_{t'},\theta) := \frac{\theta}{L_t(r_{t1},r_{t'})}\cdot\left(\mathbf{w_A}(r_{t1},r_{t'},\theta) + \mathbf{w_B}(r_{t1},r_{t'},\theta)\right)$ $\qquad \mathbf{w}(r_{t1},r_{t'},\theta_0) = 9.093\times 10^{-3} + 0.026i\,mm$

$\sigma2 := \frac{r_A^2 + r_B^2}{2}$ $\qquad \sigma2 = 2.814\,mm^2$ $\qquad X_w(r_{t1},r_{t'},\theta) := \frac{\left(|\mathbf{w}(r_{t1},r_{t'},\theta)|\right)^2}{\sigma2}$ $\qquad \gamma_w(r_{t1},r_{t'},\theta) := \frac{d}{d\theta}X_w(r_{t1},r_{t'},\theta)$

$$\delta_H(r_{t1},r_{t'},\theta_0) := \frac{-1}{2\cdot\pi\cdot\theta_0}\cdot\int_0^{2\cdot\pi}\gamma_w(r_{t1},r_{t'},\theta_0\cdot cos(\varphi))\cdot cos(\varphi)\,d\varphi$$

$\mu_H(x,x',\theta_0) := -86400\cdot\delta_H(x\cdot r_{Ph},x'\cdot r'_{Ph},\theta_0)$ $\qquad \mu_H(x_1,x_2,\theta_0) = 1.321$ $\qquad \mu_H(x_1,x_2,180\cdot deg) = 0.779$

Solution analytique

$$A1(r_{t1},r_{t'}) := \left[r_A^4\cdot\rho_1(r_{t1})^2 + r_B^4\cdot\rho'_1(r_{t'})^2 + 4\cdot a\cdot\left(r_A^3\cdot\rho_1(r_{t1})\cdot cos(\varphi_1(r_{t1})) - r_B^3\cdot\rho'_1(r_{t'})\cdot cos(\varphi'_1(r_{t'}))\right)\right]$$

$$A(r_{t1},r_{t'}) := \frac{1}{L_t(r_{t1},r_{t'})^2}\cdot\left[A1(r_{t1},r_{t'}) + 4\cdot a^2\cdot\left(r_A^2 + r_B^2\right)\right]$$

$$B(r_{t1}, r_{t'}) := \frac{3}{2 \cdot L_t(r_{t1}, r_{t'})^4} \cdot \left(r_A{}^6 \cdot \rho_2(r_{t1})^2 + r_B{}^6 \cdot \rho'_2(r_{t'})^2 \right)$$

$$C1(r_{t1}, r_{t'}) := 2 \cdot a \cdot r_A \cdot r_B \cdot \left(r_B \cdot \rho'_1(r_{t'}) \cdot cos(\psi_0 + \varphi'_1(r_{t'})) - r_A \cdot \rho_1(r_{t1}) \cdot cos(\psi_0 + \varphi_1(r_{t1})) - 2 \cdot a \cdot cos(\psi_0) \right)$$

$$C(r_{t1}, r_{t'}) := \frac{2}{L_t(r_{t1}, r_{t'})^2} \cdot \left(C1(r_{t1}, r_{t'}) + r_A{}^2 \cdot r_B{}^2 \cdot \rho_1(r_{t1}) \cdot \rho'_1(r_{t'}) \cdot cos(\psi_0 + \varphi_1(r_{t1}) + \varphi'_1(r_{t'})) \right)$$

$$D1(r_{t1}, r_{t'}) := r_A \cdot r_B{}^2 \cdot \rho_1(r_{t1}) \cdot \rho'_2(r_{t'}) \cdot cos(\psi_0 + \varphi_1(r_{t1}) + \varphi'_2(r_{t'}))$$

$$D2(r_{t1}, r_{t'}) := D1(r_{t1}, r_{t'}) + r_A{}^2 \cdot r_B \cdot \rho'_1(r_{t'}) \cdot \rho_2(r_{t1}) \cdot cos(\psi_0 + \varphi'_1(r_{t'}) + \varphi_2(r_{t1}))$$

$$D(r_{t1}, r_{t'}) := \frac{2 \cdot r_A \cdot r_B}{L_t(r_{t1}, r_{t'})^3} \cdot \left[D2(r_{t1}, r_{t'}) + 2 \cdot a \cdot \left(r_B{}^2 \cdot \rho'_2(r_{t'}) \cdot cos(\psi_0 + \varphi'_2(r_{t'})) - r_A{}^2 \cdot \rho_2(r_{t1}) \cdot cos(\psi_0 + \varphi_2(r_{t1})) \right) \right]$$

$$K(r_{t1}, r_{t'}) := \frac{2}{L_t(r_{t1}, r_{t'})^4} \cdot r_A{}^3 \cdot r_B{}^3 \cdot \rho_2(r_{t1}) \cdot \rho'_2(r_{t'}) \cdot cos(\psi_0 + \varphi_2(r_{t1}) + \varphi'_2(r_{t'}))$$

$F(x) := J0(x) - x \cdot J1(x)$ $\quad H(x) := x \cdot (1 + x^2) \cdot J1(x) - 2 \cdot x^2 \cdot J0(x)$ $\quad G(x) := -x \cdot (J1(x) + x \cdot J0(x))$

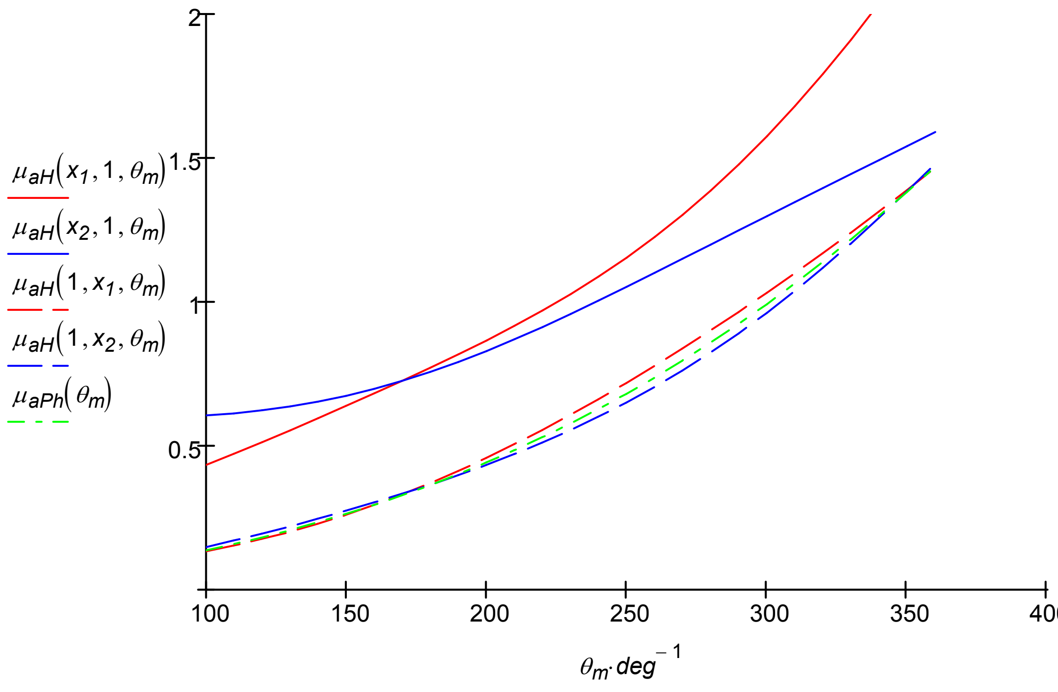
$$\delta_{aH}(r_{t1}, r_{t'}, \theta_0) := \frac{-1}{\sigma 2} \cdot \left(A(r_{t1}, r_{t'}) + B(r_{t1}, r_{t'}) \cdot \theta_0{}^2 + C(r_{t1}, r_{t'}) \cdot F(\theta_0) + D(r_{t1}, r_{t'}) \cdot G(\theta_0) + K(r_{t1}, r_{t'}) \cdot H(\theta_0) \right)$$

$\mu_{aH}(x, x', \theta_0) := -86400 \cdot \delta_{aH}(x \cdot r_{Ph}, x' \cdot r'_{Ph}, \theta_0)$ $\quad \boxed{\mu_{aH}(x_1, x_2, \theta_0) = 1.308}$ $\quad \boxed{\mu_{aH}(x_1, x_2, 180 \cdot deg) = 0.763}$

Courbes Phillips

$\mu_{aPh}(\theta_0) := -86400 \cdot \delta_{aH}(r_{Ph}, r'_{Ph}, \theta_0)$ $\quad \boxed{\mu_{aPh}(\theta_0) = 0.796}$ $\quad \boxed{\mu_{aPh}(180 \cdot deg) = 0.363}$

$\theta_m := 100 \cdot deg, 110 \cdot deg .. 360 \cdot deg$ $\qquad x_1 := 1.02 \quad x_2 := 0.98$



Déplacement du centre de gravité

Modifications de la forme des courbes terminales

$\kappa := 0.372$

$$f_g(r_{t1}, r_{t'}, \theta, s) := \left[1 + i\cdot\theta\cdot\left(\frac{s}{L_t(r_{t1}, r_{t'})} - \kappa\right)\right]\cdot e^{i\cdot\theta\cdot\frac{s}{L_t(r_{t1}, r_{t'})}} \qquad f_{g1}(r_{t1}, r_{t'}, \theta, s) := \frac{d}{ds} f_g(r_{t1}, r_{t'}, \theta, s)$$

$$f_{gA}(r_{t1}, r_{t'}, \theta) := f_g(r_{t1}, r_{t'}, \theta, l_t(r_{t1})) \qquad f_{gB}(r_{t1}, r_{t'}, \theta) := f_g(r_{t1}, r_{t'}, \theta, l_t(r_{t1}) + L)$$

$$f_{g1A}(r_{t1}, r_{t'}, \theta) := f_{g1}(r_{t1}, r_{t'}, \theta, l_t(r_{t1})) \qquad f_{g1B}(r_{t1}, r_{t'}, \theta) := f_{g1}(r_{t1}, r_{t'}, \theta, l_t(r_{t1}) + L)$$

$$\zeta_{at}(r_{t1}, r_{t'}, \theta) := \left[\left(r_A\cdot\rho_1(r_{t1})\cdot e^{-i\cdot\varphi_1(r_{t1})} + 2\cdot a\right)\cdot f_{gA}(r_{t1}, r_{t'}, \theta) - r_A^{\,2}\cdot\rho_2(r_{t1})\cdot e^{-i\cdot\varphi_2(r_{t1})}\cdot f_{g1A}(r_{t1}, r_{t'}, \theta)\right]\cdot \mathbf{OA}$$

$$\zeta_{at'}(r_{t1}, r_{t'}, \theta) := \left[\left(r_B\cdot\rho'_1(r_{t'})\cdot e^{i\cdot\varphi'_1(r_{t'})} - 2\cdot a\right)\cdot f_{gB}(r_{t1}, r_{t'}, \theta) + r_B^{\,2}\cdot\rho'_2(r_{t'})\cdot e^{i\cdot\varphi'_2(r_{t'})}\cdot f_{g1B}(r_{t1}, r_{t'}, \theta)\right]\cdot \mathbf{OB}$$

$$\zeta_a(x, x', \theta) := \frac{1}{L_t(x\cdot r_{Ph}, x'\cdot r'_{Ph})}\cdot\left(\zeta_{at}(x\cdot r_{Ph}, x'\cdot r'_{Ph}, \theta) + \zeta_{at'}(x\cdot r_{Ph}, x'\cdot r'_{Ph}, \theta)\right)$$

Courbes Phillips

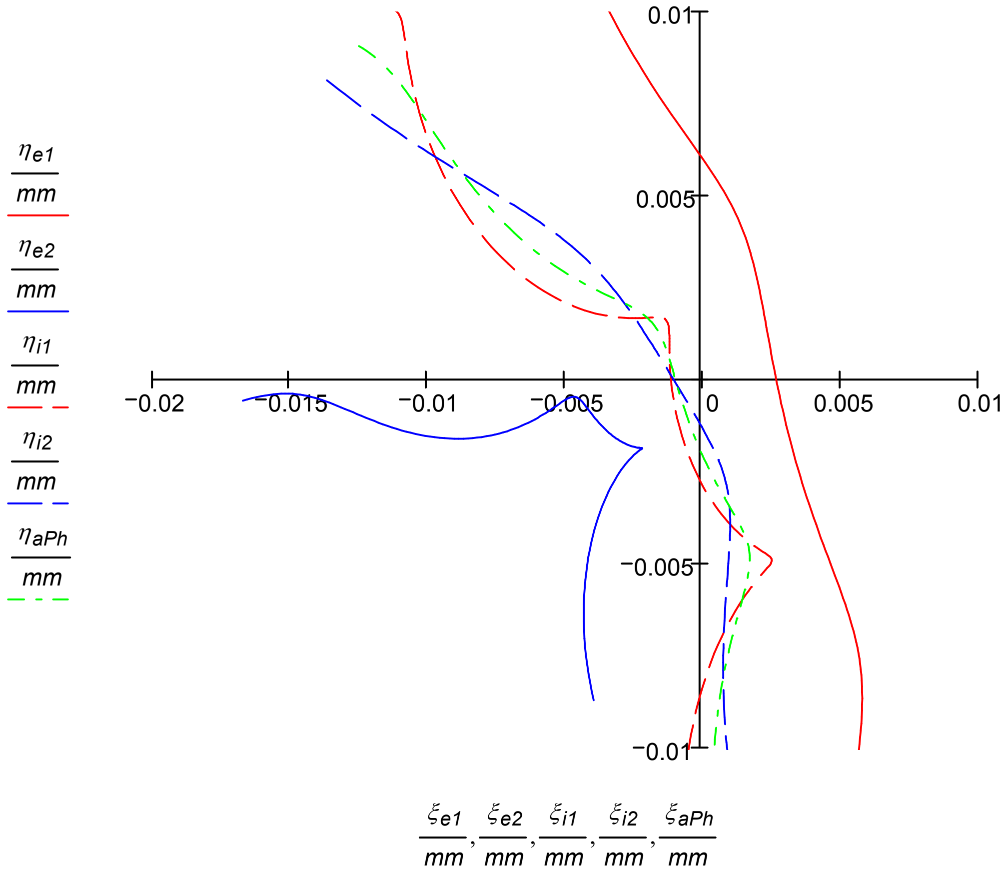
$\zeta_{aPh}(\theta) := \zeta_a(1, 1, \theta)$

Graphes du déplacement du centre de gravité

$n := 201 \qquad i := 0 .. n-1 \qquad \Delta\theta := \frac{4\cdot\pi}{n-1} \qquad \theta_i := -2\cdot\pi + i\cdot\Delta\theta \qquad \xi_{aPh_i} := Re(\zeta_{aPh}(\theta_i)) \qquad \eta_{aPh_i} := Im(\zeta_{aPh}(\theta_i))$

$\xi_{e1_i} := Re(\zeta_a(x_1, 1, \theta_i)) \qquad \eta_{e1_i} := Im(\zeta_a(x_1, 1, \theta_i)) \qquad \xi_{e2_i} := Re(\zeta_a(x_2, 1, \theta_i)) \qquad \eta_{e2_i} := Im(\zeta_a(x_2, 1, \theta_i))$

$\xi_{i1_i} := Re(\zeta_a(1, x_1, \theta_i)) \qquad \eta_{i1_i} := Im(\zeta_a(1, x_1, \theta_i)) \qquad \xi_{i2_i} := Re(\zeta_a(1, x_2, \theta_i)) \qquad \eta_{i2_i} := Im(\zeta_a(1, x_2, \theta_i))$



Perturbation de période en position verticale

Modifications de la forme des courbes terminales

$$f(r_{t1}, r_{t'}, \theta_0, s) := \frac{s}{L_t(r_{t1}, r_{t'})} \cdot \left[\left(\kappa - \frac{s}{L_t(r_{t1}, r_{t'})} \right) \cdot J0\left(\theta_0 \cdot \frac{s}{L_t(r_{t1}, r_{t'})} \right) - \frac{1}{\theta_0} \cdot J1\left(\theta_0 \cdot \frac{s}{L_t(r_{t1}, r_{t'})} \right) \right]$$

$$f_1(r_{t1}, r_{t'}, \theta_0, s) := \frac{d}{ds} f(r_{t1}, r_{t'}, \theta_0, s)$$

$$f_A(r_{t1}, r_{t'}, \theta_0) := f(r_{t1}, r_{t'}, \theta_0, l_t(r_{t1})) \qquad f_B(r_{t1}, r_{t'}, \theta_0) := f(r_{t1}, r_{t'}, \theta_0, l_t(r_{t1}) + L)$$

$$f_{1A}(r_{t1}, r_{t'}, \theta_0) := f_1(r_{t1}, r_{t'}, \theta_0, l_t(r_{t1})) \qquad f_{1B}(r_{t1}, r_{t'}, \theta) := f_1(r_{t1}, r_{t'}, \theta_0, l_t(r_{t1}) + L)$$

$$Z_{a1}(r_{t1}, r_{t'}, \theta_0) := \left[\left(r_A \cdot \rho_1(r_{t1}) \cdot e^{-i \cdot \varphi_1(r_{t1})} + 2 \cdot a \right) \cdot f_A(r_{t1}, r_{t'}, \theta_0) - r_A^{\,2} \cdot \rho_2(r_{t1}) \cdot e^{-i \cdot \varphi_2(r_{t1})} \cdot f_{1A}(r_{t1}, r_{t'}, \theta_0) \right] \cdot \mathbf{OA}$$

$$Z_{a2}(r_{t1}, r_{t'}, \theta_0) := \left[\left(r_B \cdot \rho'_1(r_{t'}) \cdot e^{i \cdot \varphi'_1(r_{t'})} - 2 \cdot a \right) \cdot f_B(r_{t1}, r_{t'}, \theta_0) + r_B^{\,2} \cdot \rho'_2(r_{t'}) \cdot e^{i \cdot \varphi'_2(r_{t'})} \cdot f_{1B}(r_{t1}, r_{t'}, \theta_0) \right] \cdot \mathbf{OB}$$

$$Z_a(r_{t1}, r_{t'}, \theta_0) := \frac{1}{L_t(r_{t1}, r_{t'})} \cdot \left(Z_{a1}(r_{t1}, r_{t'}, \theta_0) + Z_{a2}(r_{t1}, r_{t'}, \theta_0) \right)$$

$$\delta_{aV}(r_{t1}, r_{t'}, \theta_0) := -g \cdot \frac{m_s \cdot L}{E \cdot I_{33}} \cdot Im(Z_a(r_{t1}, r_{t'}, \theta_0)) \qquad \delta_{aV}(r_{t1}, r_{t'}, \theta_0) = 4.881 \times 10^{-6}$$

$$\mu_{aV}(x, x', \theta_0) := -86400 \cdot \delta_{aV}(x \cdot r_{Ph}, x' \cdot r'_{Ph}, \theta_0)$$

$$\boxed{\mu_{aV}(x_1, x_2, \theta_0) = -0.422} \qquad \boxed{\mu_{aV}(x_1, x_2, 180 \cdot deg) = -0.317}$$

Courbes Phillips $\qquad \mu_{aVPh}(\theta) := \mu_{aV}(1, 1, \theta)$

$$\theta_m := 100 \cdot deg, 105 \cdot deg .. 360 \cdot deg$$