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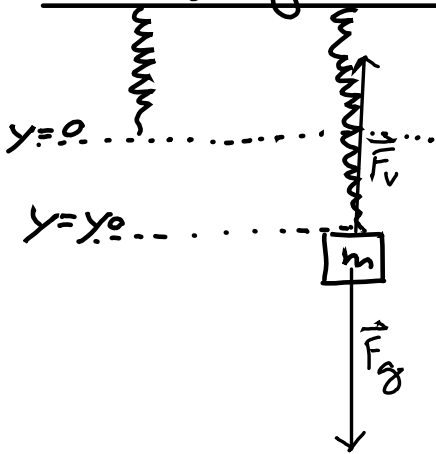
VIII zaključek

I Mehansko nihanje in valovanje

Enostavna nihala

Enačba dušenega nihanja

Utěz na vijachi: vzmeti



$$\vec{F}_g = \begin{bmatrix} 0 \\ -mg_0 \\ 0 \end{bmatrix} \quad \text{smer navzdol}$$

$$g_0 \approx 10 \text{ m/s}^2$$

$$\vec{F}_v = \begin{bmatrix} 0 \\ -ky_0 \\ 0 \end{bmatrix} \quad \begin{array}{l} k \dots \text{koeficient} \\ \text{vzmeti } \text{N/m} \\ y_0 < 0 \end{array}$$

$$-ky_0 > 0 \Rightarrow \text{smer je navzgor}$$

neto sila

$$\vec{a} = 0 \Leftrightarrow \vec{F} = m\vec{a} = 0$$
$$\vec{F}_g + \vec{F}_v = 0$$

$$-mg_0 - ky_0 = 0 \Rightarrow$$

$$mg_0 = -ky_0$$

$$y_0 = \frac{mg_0}{k}$$

$$\vec{F}_g = -mg_0 \hat{e}_y$$

$$\vec{F}_v = -k y \hat{e}_y$$

$$\vec{F}_u \dots \text{sila upora}$$

$$\vec{F}_u = -c \vec{v} \quad (\text{linearne sila upora})$$

$c > 0$ sorazmerna z viskoznostjo tekočina in površino uteži

$$\vec{F}_u = -c \dot{y} \hat{e}_y$$

$$\vec{F} = \vec{F}_g + \vec{F}_v + \vec{F}_u$$

$$\vec{F} = m \cdot \vec{a} \quad ; \quad \vec{a} = \ddot{y} \hat{e}_y$$

$$-c \dot{y} \hat{e}_y - k y \hat{e}_y - m g_0 \hat{e}_y = m \ddot{y} \hat{e}_y$$

$$\underbrace{\left(\ddot{y} + \frac{c}{m} \dot{y} + \frac{k}{m} y + g_0 \right)}_{=0} \hat{e}_y = 0$$

$$\text{Vpeljemo } \beta = \frac{c}{m} \quad [\beta] = s^{-1}$$

$$\omega_0^2 = \frac{k}{m} \quad [\omega_0^2] = s^{-2}$$

$$\ddot{y} + \beta \dot{y} + \omega_0^2 y + g_0 = 0$$

$$y_0 = \frac{m g_0}{k}$$

$$g_0 = \frac{y_0 k}{m} = y_0 \omega_0^2$$

$$\ddot{y} + \beta \dot{y} + \omega_0^2 (y - y_0) = 0$$

$$\ddot{y} + \beta \dot{y} + \omega_0^2 y = \omega_0^2 y_0$$

- diferencialna enačba za y 2. reda
- linearne enačbe
- konstantni koeficienti
- nehomogena (pogojno, ker je lahko z lahkoto prevedemo v homogeno)

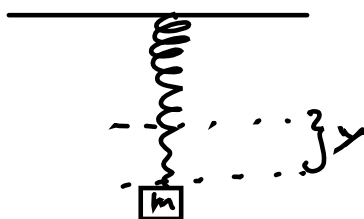
$$y' = y - y_0$$

$$\dot{y}' = (\dot{y} - \dot{y}_0) = \dot{y}$$

$$\ddot{y}' = \ddot{y}$$

$$\text{Dobimo: } \ddot{y}' + \beta \dot{y}' + \omega_0^2 y' = 0$$

je homogeno :



$$\ddot{y}' + \beta \dot{y}' + \omega_0^2 y = 0$$

Nastavek: $y' = A e^{\lambda t}$, A, λ konstante

$$[\lambda] = s^{-1}$$

$$\dot{y}' = \lambda y$$

$$[\lambda] = m$$

$$\ddot{y}' = \lambda^2 y$$

$$(\lambda^2 + \beta \lambda + \omega_0^2) A e^{\lambda t} = 0 \quad \text{za } \lambda \neq 0 \text{ i } A \neq 0$$

$$\lambda^2 + \beta \lambda + \omega_0^2 = 0$$

$$D = \beta^2 - 4\omega_0^2 = -4\omega^2$$

$$(\omega^2 = \omega_0^2 - (\frac{\beta}{2})^2)$$

$$D < 0 \Rightarrow 4\omega^2 > 0 : \text{podkritično dušenje}$$

$$\sqrt{D} = \sqrt{-4\omega^2} = \sqrt{-1} 2\omega ; \omega = +\sqrt{\omega^2}$$

$$\Rightarrow \lambda_{1,2} = \frac{-\beta \pm \sqrt{D}}{2} = -\frac{\beta}{2} \pm i\omega$$

$$y_1' = A_1 e^{\lambda_1 t} = A_1 \exp(-\frac{\beta}{2} + i\omega)t =$$

$$= A_1 \exp(-\frac{\beta}{2}t) \exp(i\omega t)$$

$$y_2' = A_2 \exp(-\frac{\beta}{2}t) \exp(-i\omega t)$$

$$\ddot{y}_1' + \beta \dot{y}_1' + \omega_0^2 y_1' = 0$$

$$\ddot{y}_2' + \beta \dot{y}_2' + \omega_0^2 y_2' = 0 \quad \} t$$

$$(\ddot{y}_1' + \ddot{y}_2') + \beta(\dot{y}_1' + \dot{y}_2') + \omega_0(y_1' - y_2') = 0$$

$$\Rightarrow y' = \exp(-\frac{\beta}{2}t) (A_1 \exp(i\omega t) + A_2 \exp(-i\omega t))$$

Eulerjeva enačba

$$\exp(\pm i\omega t) = \cos(\omega t) \pm i \sin(\omega t)$$

$$\Rightarrow y' = \exp(-\frac{\beta}{2}t) ((A_1 + A_2) \cos(\omega t) + i(A_1 - A_2) \sin \omega t)$$

$$= e^{-\frac{\beta}{2}t} (B_1 \cos(\omega t) + B_2 \sin(\omega t))$$

$$= B e^{-\frac{\beta}{2}t} \sin(\omega t + \delta) \quad \begin{array}{l} \text{Fazni zamik} \\ \sin(\omega t + \delta) = \\ \sin(\omega t) \cos \delta + \sin \delta \cos \omega t \end{array}$$

$$B > 0 ; \delta = \text{fazni zamik}$$

$$B e^{-\frac{\beta}{2}t} (\sin \omega t \sin \delta + \cos \omega t \cos \delta)$$

$$= e^{-\frac{\beta}{2}t} (B \sin \delta \cos(\omega t) + B \cos \omega t \sin \delta)$$

$$B_1 = B \sin \delta$$

$$B_2 = B \cos \delta$$

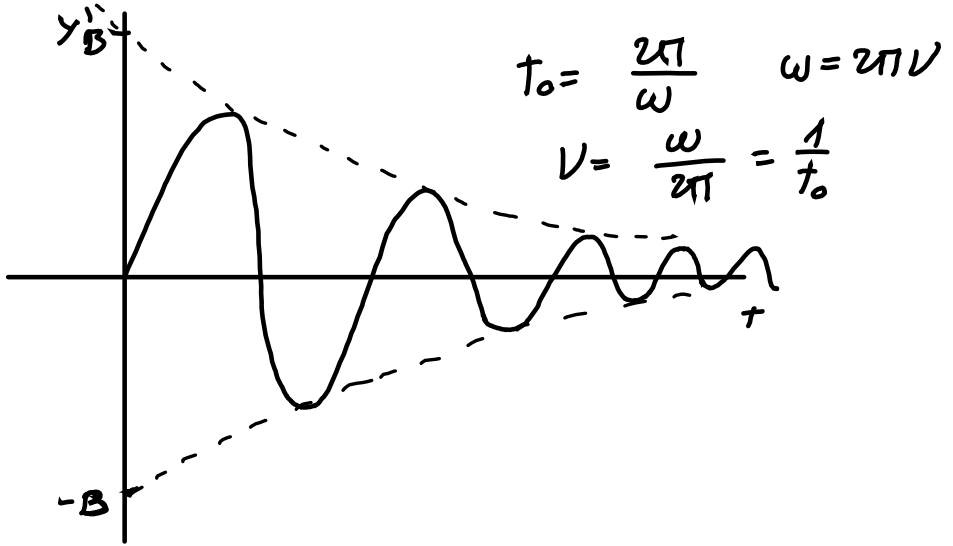
$$\tan \delta = \frac{B_1}{B_2}$$

$$B^2 = B_1^2 + B_2^2$$

$$B = \sqrt{B_1^2 + B_2^2}$$

Primer :

$$\delta = 0 \Rightarrow y = B e^{-\frac{\beta}{2}t} \sin(\omega t)$$



$$\delta = \frac{\pi}{2}$$

$$\begin{aligned} y'(t) &= B e^{-\frac{\beta}{2}t} \sin\left(\omega t + \frac{\pi}{2}\right) = \sin \omega t \cos \frac{\pi}{2} + \cancel{\cos \omega t} \sin \frac{\pi}{2} \\ &= B e^{-\frac{\beta}{2}t} \cos(\omega t) \end{aligned}$$

$$\ddot{y}' + \beta \dot{y}' + \omega_0^2 y' = 0$$

$y' = y - y_0 \rightarrow$ odmik do ravnovesja vzeti v ravnovesni točki
 $\hookrightarrow$ odmik od konca neobremenjene vzeti

$$\omega_0^2 = \frac{k}{m} (> 0)$$

$$\beta \propto c \propto \eta$$

$\nwarrow$ sorazmerne

Nastavek $y' = A e^{\lambda t}$

$$\Rightarrow \lambda^2 + \beta \lambda + \omega_0^2 = 0$$

$$D = \beta^2 - 4\omega_0^2 = -4\omega^2 \quad \omega^2 = \omega_0^2 - \left(\frac{\beta}{2}\right)^2$$

a) $D < 0 \Rightarrow (\omega^2 > 0)$

$$y' = B e^{-\frac{\beta}{2}t} \sin(\omega t + \delta) ; \omega = \sqrt{\omega^2} = \sqrt{\omega_0^2 - \left(\frac{\beta}{2}\right)^2}$$

Zelo gibko dušenje $(\frac{3}{2})^2 \ll \omega_0 \Rightarrow$

$$T_0 = \frac{2\pi}{\sqrt{\omega_0^2}} = 2\pi \sqrt{\frac{m}{k}}$$

Primer:

$$m = 500 \text{ g} = 0,5 \text{ kg}$$

$$k y_0 = -m g_0$$

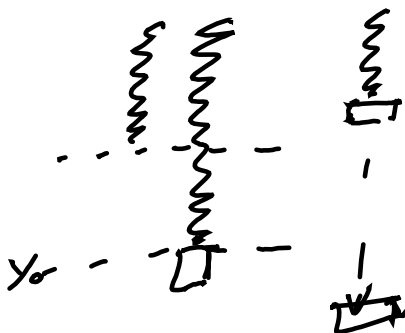
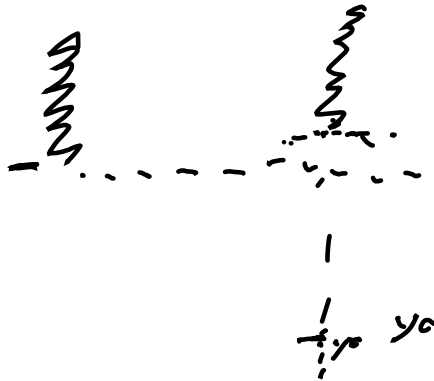
$$k = -\frac{m g_0}{y_0} \Rightarrow \frac{m}{k} = -\frac{y_0}{g_0}$$

$$y_0 = -0,4 \text{ m}$$

$$\frac{m}{k} = \frac{0,4 \text{ m}}{10 \text{ m/s}^2} = 0,04 \text{ s}^2 =$$

$$\sqrt{\frac{m}{k}} = 2 \cdot 10^{-1} = 0,2 \text{ s}$$

$$\Rightarrow T_0 = 2\pi \cdot 0,2 \text{ s} \approx 1,2 \text{ s}$$



B in δ dobimo iz začetnih pogojev

$$y' = B e^{-\frac{\beta}{2}t} \sin(\omega t + \delta)$$

$$\dot{y}' = -\frac{\beta}{2} B e^{-\frac{\beta}{2}t} \sin(\omega t + \delta) + \omega B e^{-\frac{\beta}{2}t} \cos(\omega t + \delta)$$

$$\dot{y}'(0) = -\frac{\beta}{2} B \sin \delta + \omega B \cos \delta =$$

$$y'(0) = B \sin \delta \qquad \qquad \qquad = B(-\frac{\beta}{2} \sin \delta + \omega \cos \delta)$$

$$r = \frac{y'(0)}{\dot{y}'(0)} = \frac{\sin \delta}{\omega \cos \delta - \frac{\beta}{2} \sin \delta} = \frac{\tan \delta}{\omega - \frac{\beta}{2} \tan \delta}$$

$$\Rightarrow \delta = \arctan\left(\frac{r\omega}{1 + \frac{r\beta}{2}}\right)$$

$$\Rightarrow B = \frac{y'(0)}{\sin \delta}$$

$$\dot{y}'(0) = B \omega \sin \delta$$

$$\Rightarrow B = \frac{\dot{y}'(0)}{\pm \omega} = \frac{|\dot{y}'(0)|}{\omega}$$

Energija nihala

$$W_k = \frac{1}{2} m v^2 = \frac{1}{2} m \dot{y}^2$$

$$W_{pr} = \frac{1}{2} k y^2 = \frac{1}{2} k (y + y_0)^2$$

$$W_p = m g_0 (y + y_0)$$

$$\text{Skupna } \boxed{W = W_k + W_p + W_{pr}}$$

a) W za zelo slobko dušenje?

$$\frac{B}{z} + \ll 1$$

$$\left(\frac{B}{z}\right)^2 \ll \omega_0^2 \Rightarrow \omega \approx \omega_0 = \sqrt{\frac{k}{m}}$$

$$y' = B \sin(\omega_0 t + \delta)$$

$$\dot{y}' = \omega_0 B \cos(\omega_0 t + \delta)$$

$$\begin{aligned} W_k &= \frac{1}{2} m \omega_0^2 B^2 \cos^2(\omega_0 t + \delta) = \\ &= \frac{1}{2} m \frac{k}{m} B^2 \cos^2(\omega_0 t + \delta) \end{aligned}$$

$$W_{pr} = \frac{1}{2} k B^2 \sin^2(\omega_0 t + \delta) + \frac{1}{2} k y_0^2 + k y_0 B \sin(\omega_0 t + \delta)$$

$$W_p = m g_0 B \sin(\omega_0 t + \delta) + m g_0 y_0$$

$$\begin{aligned} W &= \frac{1}{2} k B^2 \underbrace{(\sin^2(\omega_0 t + \delta) + \cos^2(\omega_0 t + \delta))}_{1} \\ &\quad + (k y_0 + m g_0) B \sin(\omega_0 t + \delta) + \\ &\quad + \frac{1}{2} k y_0^2 + m g_0 y_0 \\ &= \frac{1}{2} k B^2 + \frac{1}{2} k y_0^2 + m g_0 y_0 = \text{konst.} \end{aligned}$$

b) kritično dušenje

$D=0$ ($\omega=0$) (kritično dušenje)

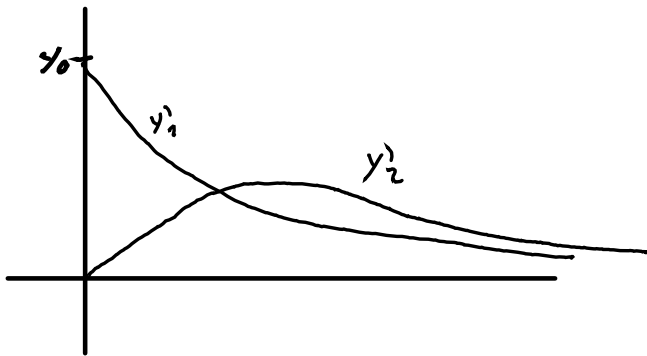
$$D = \beta^2 - 4\omega^2 \Rightarrow \omega_0 = \frac{\beta}{2}$$

$$\lambda_{1,2} = \frac{-\beta \pm \sqrt{D}}{2} = -\frac{\beta}{2}$$

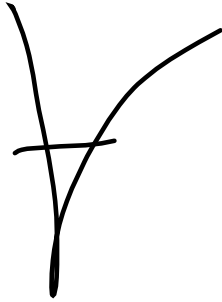
$$\Rightarrow y_1' = B_1 e^{-\frac{\beta}{2}t}$$

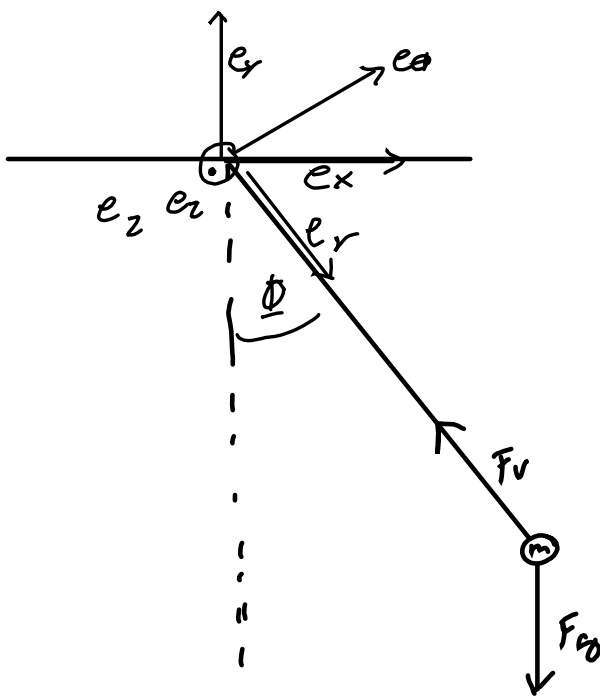
$$y_2' = B_2 t e^{-\frac{\beta}{2}t} \text{ je tudi rešitev (DN) } \star$$

$$\Rightarrow y' = y_1' + y_2' = (B_1 + B_2 t) e^{-\frac{\beta}{2}t}$$



20.2





$e_\phi, e_z, e_r \dots$ cylindriche
Koordinate

$$\vec{F} = \vec{F}_g + \vec{F}_v = m\vec{a}$$

$$F_g = -mg_0 \hat{e}_z$$

$$F_v = -F_v \hat{e}_r$$

$$\vec{r} = l \cdot \hat{e}_r$$

$$\vec{r} \times \vec{F} = l \hat{e}_r \times (-mg_0 \hat{e}_z - F_v \hat{e}_r) =$$

$$= -mg_0 l \hat{e}_r \times \hat{e}_z - \underbrace{l F_v \hat{e}_r \times \hat{e}_r}_{=0}$$

$$= -mg_0 l \hat{e}_r \times (\hat{e}_z \cos\phi + \hat{e}_\phi \sin\phi)$$

$$= -mg_0 l \sin\phi \hat{e}_r \times \hat{e}_\phi =$$

$$= -mg_0 l \sin\phi \hat{e}_z$$

$$\vec{r} \times \vec{F} = m \cdot \vec{r} \times \vec{a} = m \cdot l \hat{e}_r \times (a \hat{e}_\phi) =$$

$$\vec{a} = a \cdot \hat{e}_\phi \quad = m a l \hat{e}_z$$

$$a = a_\phi = l \ddot{\phi}$$

$$mg_0 l \sin\phi \hat{e}_z = m l \ddot{\phi} \hat{e}_z$$

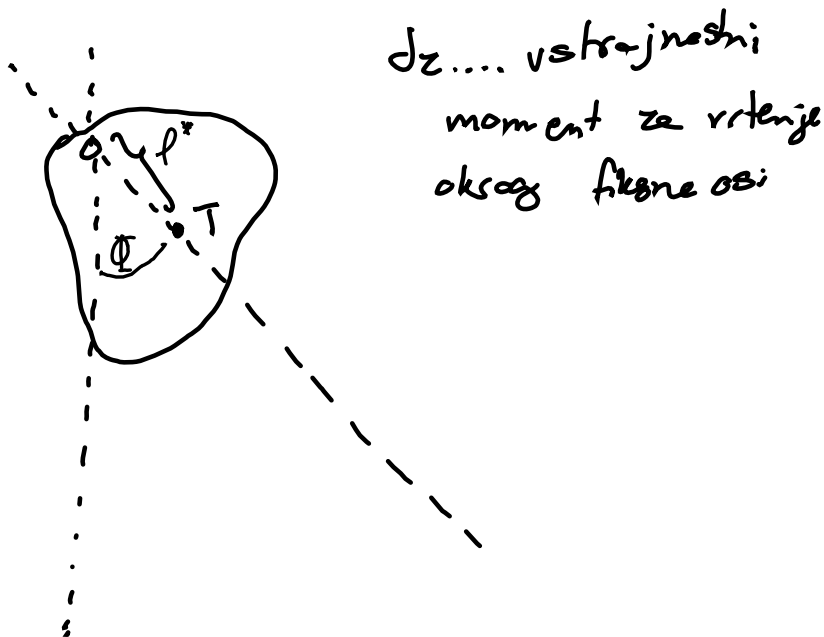
$$m l (l \ddot{\phi} + g_0 \sin\phi) \hat{e}_z \neq \vec{0} = 0$$

$$-l \ddot{\phi} = g_0 \sin\phi$$

$$\ddot{\phi} + \frac{g_0}{l} \sin\phi = 0$$

$$\approx \underbrace{\ddot{\phi}}_{\omega^2} + \frac{g_0}{l} \phi = 0$$

$$\ddot{\phi} + \omega_0^2 \phi = 0$$



J_z vslojnostni

moment za vrtenje

okrog fiksne osi

Primer: palica

$$J_z = \frac{1}{3} m l^2 \quad l^* = \frac{l}{2}$$

$$\sin \Phi \approx \Phi$$

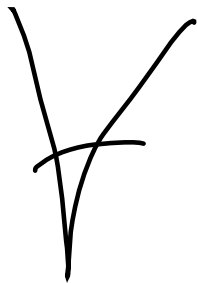
$$\Rightarrow \ddot{\Phi} + \omega_0^2 \Phi = 0$$

$$\omega_0^2 = \frac{m g l^*}{J_z} = \frac{m g \frac{l}{2}}{\frac{1}{3} m l^2} = \frac{3}{2} \frac{g}{l}$$

Ni, ho, u, h, e, l, o:

$$J_z = m l^2 \quad l^* = l$$

$$\omega_0^2 = \frac{m g l}{m l^2} = \frac{g}{l}$$



21.2

Nism Geshkele

$$F = F_0 \sin(\omega_v t) \quad \omega_v = 2\pi N_v$$

$$\ddot{y} + \beta \dot{y} + \omega_0^2 y = \frac{F_0}{m} \sin(\omega_v t)$$

$$\omega_0^2 = \frac{k}{m} \quad \beta = \frac{c}{m} \quad y' = y - y_0 \quad \begin{array}{l} \text{rozcierek} \\ \text{je } k_0 \text{ obtezan} \\ \text{zmet mirna} \end{array}$$

$$y' = y_h' + y_p' \quad \begin{array}{l} \text{homogena} \\ \text{partikularna} \\ \text{rešitev} \end{array}$$

$$y_p' = B \sin(\omega_v t - \delta_p)$$

$$B_p \left\{ (\omega_0^2 - \omega_v^2) [\cos \delta_p \sin(\omega_v t) - \sin \delta_p \cos(\omega_v t)] + \omega_v \beta [\cos \delta_p \cos(\omega_v t) + \sin \delta_p \sin(\omega_v t)] \right\} = \frac{F_0}{m} \sin(\omega_v t) \quad \forall t$$

$$a) t_1 = 0 \Rightarrow \sin \omega_v t = 0, \cos \omega_v t = 1$$

$$B_p \{ -(\omega_0^2 - \omega_v^2) \sin \delta_p + \omega_v \beta \cos \delta_p \} = 0$$

$$\Rightarrow \tan \delta_p = \frac{\omega_v \beta}{\omega_0^2 - \omega_v^2}$$

$$\cos \delta_p = \pm \frac{(\omega_0^2 - \omega_v^2)}{\sqrt{(\omega_0^2 - \omega_v^2)^2 + \omega_v^2 \beta^2}}$$

$$\sin \delta_p = \pm \frac{\omega_v \beta}{\sqrt{(\omega_0^2 - \omega_v^2)^2 + \omega_v^2 \beta^2}}$$

$$\omega_v \rightarrow 0 \Rightarrow \tan \delta_p \rightarrow +0 \Rightarrow \delta_p \rightarrow 0$$

$$\omega_v \rightarrow \uparrow \omega_0 \Rightarrow \tan \delta_p \rightarrow +\infty \Rightarrow \delta_p \rightarrow \uparrow \frac{\pi}{2}$$

$$\omega_v \rightarrow \downarrow \omega_0 \Rightarrow \tan \delta_p \rightarrow -\infty \Rightarrow \delta_p \rightarrow \downarrow \frac{\pi}{2}$$

$$\omega_v \rightarrow \infty \Rightarrow \tan \delta_p \rightarrow -0 \Rightarrow \delta_p \rightarrow \pi$$

$$\omega_v \rightarrow 0 \Rightarrow \delta_p \rightarrow 0 \Rightarrow \cos \delta_p \rightarrow +1$$

$$\cos \delta_p \rightarrow \pm \frac{\omega_0^2}{\sqrt{\omega_0^4}} = \pm 1 \quad \begin{array}{l} \text{ocisti} \\ \text{more Liti +} \end{array}$$

$$b) t_2 = \frac{\pi}{2\omega_v} \Rightarrow \omega_v t_2 = \frac{\pi}{2} \Rightarrow \sin(\omega_v t) = 1, \cos(\omega_v t) = 0$$

$$B_p \{ (\omega_0^2 - \omega_v^2) \cos \delta_p + \omega_v \beta \sin \delta_p \} = \frac{F_0}{m}$$

$$B_p \left\{ \frac{(\omega_0^2 - \omega_v^2)^2 + \omega_v^2 \beta^2}{\sqrt{(\omega_0^2 - \omega_v^2)^2 + \omega_v^2 \beta^2}} \right\} = \frac{F_0}{m}$$

$$\Rightarrow B_p = \frac{F_0}{m} \cdot \frac{1}{\sqrt{(\omega_0^2 - \omega_v^2)^2 + \omega_v^2 \beta^2}}$$

$$\omega_v \rightarrow 0 \Rightarrow B_p \rightarrow \frac{F_0}{m} \cdot \frac{1}{\omega_0^2} = \frac{F_0 \cdot m}{m \cdot k} = \frac{F_0}{k}$$

$$\omega_v \rightarrow \infty \Rightarrow B_p \rightarrow 0$$

$$B_p(\omega_v) = \max$$

Kdaj dosežemo maksimum?

T.j. kda je v resonanci?

ko je imenoalec najmanjši

$$(\omega_0^2 - \omega_v^2)^2 + \beta^2 \omega_v^2 \text{ je najmanjši}$$

$$\frac{d}{d\omega_v} ((\omega_0^2 - \omega_v^2)^2 + \beta^2 \omega_v^2) = 0$$

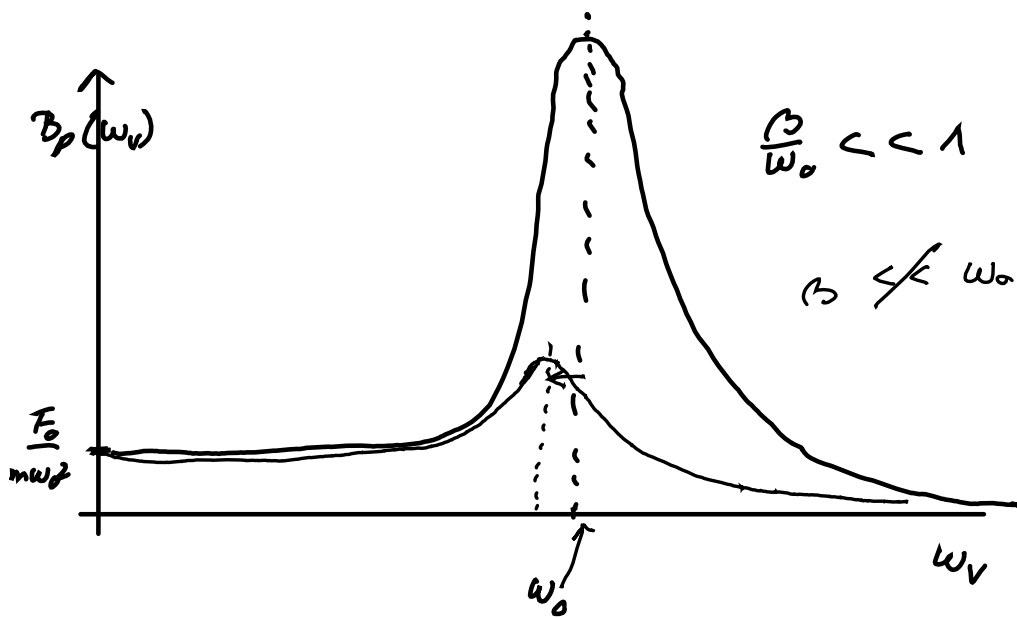
$$2(\omega_0^2 - \omega_v^2)(-2\omega_v) + 2\omega_v\beta^2 = 0$$

$$-2(\omega_0^2 - \omega_v^2) + \beta^2 = 0$$

$$\omega_v^2 = \omega_0^2 - \frac{\beta^2}{2}$$

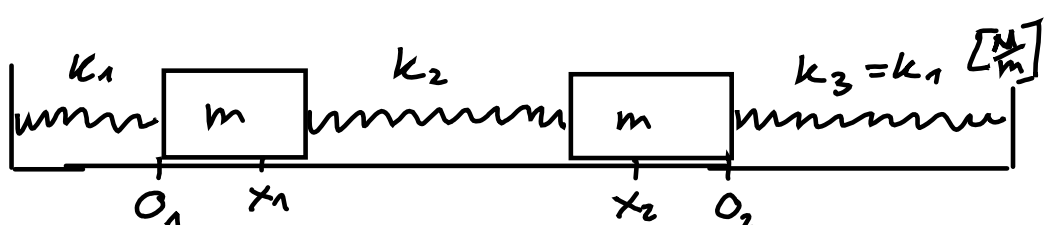
$$\omega_v = +\sqrt{\omega_0^2 - \frac{\beta^2}{2}} = \omega_0 \sqrt{1 - \frac{\beta^2}{2\omega_0^2}}$$

$$\beta \ll \omega_0 \Rightarrow \omega_v = \omega_0$$



Sklopljeno nihanje

- $b \rightarrow 0$ dušenje poskušamo proti 0
- za začetek: simetrični primer



"z druge vzmetje, ki ji bomo rekli: tretja vzmet"

$\vec{F}_{1 \rightarrow 1, r}$... Sile y ue vzmeti napru; vozček ko je v ravnovesni legi

$$\left. \begin{aligned} \vec{F}_{1 \rightarrow 1, r} &= -k_1 \Delta l_{1, r} \hat{e}_x \\ \vec{F}_{2 \rightarrow 1, r} &= +k_2 \Delta l_{2, r} \hat{e}_x \end{aligned} \right\} + = 0$$

v ravnovesju

$$\left. \begin{aligned} \vec{F}_{2 \rightarrow 2, r} &= -k_2 \Delta l_{2, r} \hat{e}_x \\ \vec{F}_{3 \rightarrow 2, r} &= +k_1 \Delta l_{3, r} \hat{e}_x \end{aligned} \right\} + = 0$$

$$\vec{F}_{1 \rightarrow 1} = \vec{F}_{1 \rightarrow 1, r} - k_1 x_1 \hat{e}_x$$

$$\vec{F}_{2 \rightarrow 1} = \vec{F}_{2 \rightarrow 1, r} - k_2 (x_1 - x_2) \hat{e}_x$$

$$\vec{F}_{2 \rightarrow 2} = \vec{F}_{2 \rightarrow 2, r} + k_2 (x_1 - x_2) \hat{e}_x$$

$$\vec{F}_{3 \rightarrow 2} = \vec{F}_{3 \rightarrow 2, r} - k_1 x_2 \hat{e}_x$$

$$\vec{F}_{1 \rightarrow 1} + \vec{F}_{2 \rightarrow 1} = m \ddot{x}_1 \hat{e}_x$$

$$\vec{F}_{1 \rightarrow 1, r} - k_1 x_1 \hat{e}_x + \vec{F}_{2 \rightarrow 1, r} - k_2 (x_1 - x_2) \hat{e}_x = m \ddot{x}_1 \hat{e}_x$$

$$m \ddot{x}_1 + k_1 x_1 + k_2 (x_1 - x_2) = 0$$

$$\ddot{x}_1 + \omega_1^2 x_1 + \omega_2^2 (x_1 - x_2) = 0$$

$$\omega_1^2 = \frac{k_1}{m} \quad \omega_2^2 = \frac{k_2}{m}$$

$$\text{Zelo podobno } \ddot{x}_2 + \omega_1^2 x_2 - \omega_2^2 (x_1 - x_2) = 0$$

$$x_a = x_1 + x_2$$

$$x_b = x_1 - x_2$$

$$\Rightarrow \left. \begin{aligned} x_1 &= \frac{x_a + x_b}{2} \\ x_2 &= \frac{x_a - x_b}{2} \end{aligned} \right\} \begin{aligned} &\ddot{x}_2 + \omega_1^2 x_2 - \omega_2^2 (x_1 - x_2) \\ &\ddot{x}_1 + \omega_1^2 x_1 + \omega_2^2 (x_1 - x_2) \end{aligned}$$

seštejemo ena ob:

$$\ddot{x}_1 + \ddot{x}_2 + \omega_1^2 x_1 + \omega_1^2 x_2 = 0$$

$$(\ddot{x}_1 + \ddot{x}_2) + \omega_1^2 (x_1 + x_2) = 0$$

$$\ddot{x}_a + \omega_a^2 x_a = 0$$

$$\ddot{x}_b + \omega_b^2 x_b = 0$$

$$\omega_a = \omega_1$$

$$\omega_b = \sqrt{\omega_1^2 + 2\omega_2^2}$$

$$x_a = B_a \sin(\omega_a t + \delta_a)$$

$$x_b = B_b \sin(\omega_b t + \delta_b)$$

$$\Rightarrow x_1 = \underbrace{\frac{B_a}{2}}_{B_1} \sin(\omega_a t + \delta_a) + \underbrace{\frac{B_b}{2}}_{B_2} \sin(\omega_b t + \delta_b)$$

$$x_2 = B_1 \sin(\omega_a t + \delta_a) - B_2 \sin(\omega_b t + \delta_b)$$

$$B_1, B_2, \delta_a, \delta_b = ?$$

$$\text{začetni pogoji: } x_1(t=0) \quad \dot{x}_1(t=0)$$

$$x_2(t=0) \quad \dot{x}_2(t=0)$$

iz tega izvedemo

P1,mer

$$x_1(t=0) = x_0 \quad (>0) \quad \dot{x}_1(t=0) = 0$$

$$x_2(t=0) = 0 \quad \dot{x}_2(t=0) = 0$$

$$\dot{x}_1 = B_1 \omega_a \cos(\omega_a t + \delta_a) + B_2 \omega_b \cos(\omega_b t + \delta_b)$$

$$x_2 = B_1 \omega_a \cos(\omega_a t + \delta_a) - B_2 \omega_b \cos(\omega_b t + \delta_b)$$

$$x_0 = B_1 \sin \delta_a + B_2 \sin(\delta_b) \quad \left. \begin{array}{l} \\ 0 = B_1 \sin \delta_a - B_2 \sin \delta_b \end{array} \right\} +, -$$

$$\left. \begin{array}{l} 0 = B_1 \omega_a \cos(\delta_a) + B_2 \omega_b \cos(\delta_b) \\ 0 = B_1 \omega_a \cos(\delta_a) - B_2 \omega_b \cos(\delta_b) \end{array} \right\} +, -$$

$$\rightarrow x_0 = 2B_1 \sin \delta_a = 2B_2 \sin \delta_b$$

$$2B_1 \omega_a \cos \delta_a = 0 \Rightarrow \cos \delta_a = 0$$

$\Rightarrow$

$$B_1 = B_2 = \frac{x_0}{2}$$

$$\delta_a = \pm \frac{\pi}{2}$$

$$\Rightarrow \therefore \delta_b = +\frac{\pi}{2}$$

V

7.3

mentales
adsohne

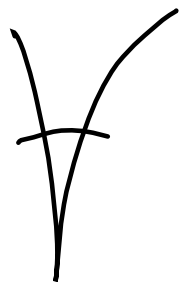
lastna nihanja sestavljenega
sistema

$$\left. \begin{aligned} x_1 &= B_1 \sin(\omega t + \delta_1) + B_2 \sin(\omega t + \delta_2) \\ x_2 &= \dots \end{aligned} \right\}$$

$$\rightarrow \begin{cases} x_1 = B_1 \sin(\omega t + \delta_1) \\ x_2 = B_2 \sin(\omega t + \delta_2) \end{cases}$$

$$\ddot{x}_1 + \omega_1^2 x_1 + \omega_2^2 (x_1 - x_2) = 0$$

$$\ddot{x}_2 + \omega_2^2 x_2 - \omega_2^2 (x_1 - x_2) = 0$$



11.3

$$u(x, t) = ?$$

$$\eta := x - ct$$

$$\chi := x + ct$$

$$u(x, t) = f(x - ct) + g(x + ct)$$

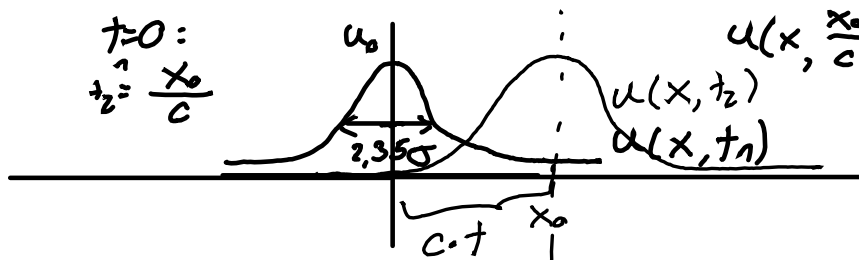
ena zmed moznosti:

$$u(x, t) = f(x - ct)$$

$$\text{npr: } u(x, t) = u_0 e^{-\frac{(x-ct)^2}{2\sigma^2}}$$

$$t=0:$$

$$t_2 = \frac{x_0}{c}$$



$$u(x, 0) = u_0 e^{-\frac{x^2}{2\sigma^2}}$$

$$u(x, \frac{x_0}{c}) = u_0 e^{-\frac{(x-x_0)^2}{2\sigma^2}}$$

↑
samo
premakljena
krivulja

$$\Rightarrow v = \left| \frac{du}{dt} \right| = \left| \frac{\partial u}{\partial t} \right| = \left| \frac{\partial}{\partial t} f(x - ct) \right| = |f'|c$$

$$v \neq c$$

$$u(x, t) = f(x - ct)$$

$$a) \quad \underline{u(x, t) = u(x - ct, 0)}$$

$$x \rightarrow x' = x - ct$$

$$t \rightarrow t' = 0$$

$$u(x', t') = u(x - ct, 0) = f(x', ct) = f(x - ct) = \\ = u(x, t)$$

Če poznamo $u(x', t')$ ob času $t' = 0$ za $\forall x'$
Potem poznam $u(x, t)$ za $\forall x, t$ o $\forall$ času

$$b) \quad u(x, t) = u(0, t - \frac{x}{c})$$

$$x \rightarrow x' = 0$$

$$t \rightarrow t' = t - \frac{x}{c}$$

$$u(x', t') = u(0, t - \frac{x}{c}) =$$

$$f(0 - c(t - \frac{x}{c})) = f(x - ct) = u(x, t)$$

Če poznamo $u(x' = 0, t')$ za $\forall t'$
 $\Rightarrow$ poznam $u(x, t)$ za $\forall x, \forall t$

Podružje sinusno valovanje

$$u(x,t) = f(x-ct)$$

$$u(x=0, t-\frac{x}{c}) = u_0 \sin(-\omega t + \delta); \quad u_0 > 0$$

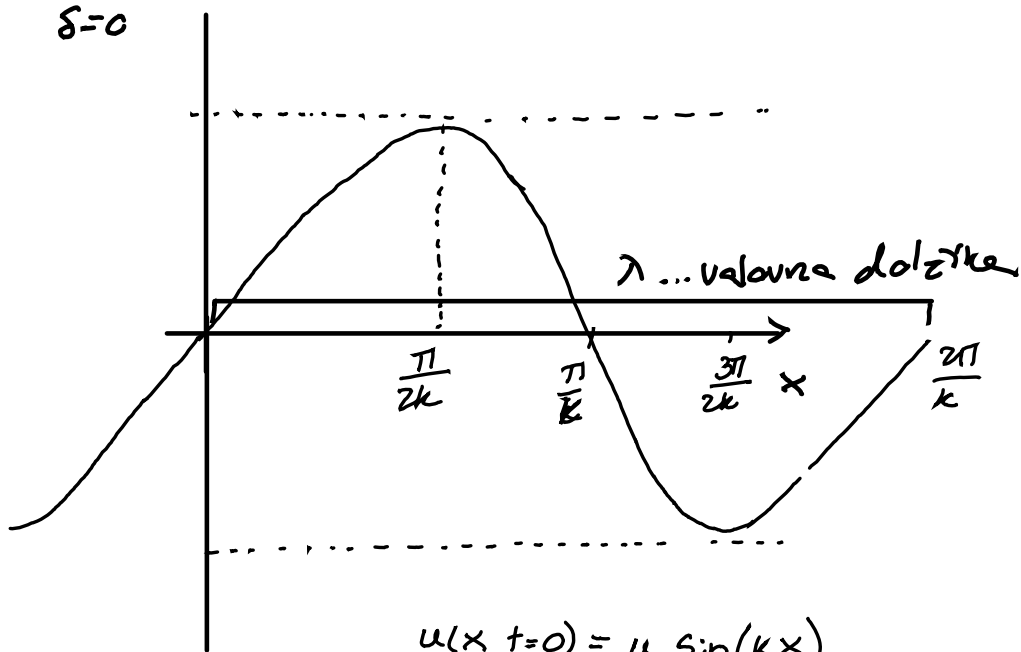
$$u(x,t) = ?$$

$$\begin{aligned} u(x,t) &= u(0, t-\frac{x}{c}) = u_0 \sin(-\omega(t-\frac{x}{c}) + \delta) = \\ &= u_0 \sin(kx - \omega t + \delta); \quad k = \frac{\omega}{c} = \frac{2\pi\nu}{c} \\ [k] &= \frac{1}{m} \end{aligned}$$

$$t=0:$$

$$u(x, t=0)$$

$$\delta=0$$



$$u(x, t=0) = u_0 \sin(kx)$$

$$\lambda = \frac{2\pi}{k} = \frac{2\pi c}{2\pi\nu} = \frac{c}{\nu}$$

$$c = \lambda\nu$$

$$u(x,t) = u_{0,1} \sin(kx - \omega t + \delta_1) + u_{0,2} \sin(kx + \omega t + \delta_2)$$

Valovanje v obe smeri

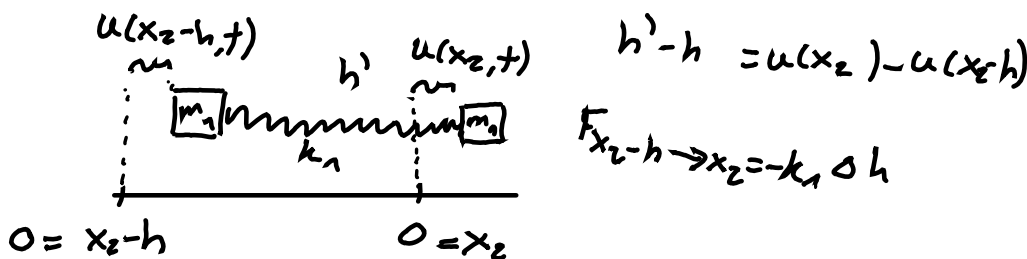
Robni pogoji in stojče sinusno valovanje

a) tog vpeti vzmet

$$u(x_1, t) = u(x_2, t) = 0$$

b) Vzmet (palica) s prostima koncema, x_1, x_2

Model:



$$m_1 \ddot{u}(x_2, t) = -k l \left(\frac{u(x_2, t) - u(x_2 - h, t)}{h} \right) = -\frac{k l}{h} (u(x_2, t) - u(x_2 - h, t))$$

$$m_1 = \frac{m}{l h} \leftarrow \text{st vseh uteži}$$

$$\frac{m}{l h} \frac{\partial^2 u(x_2, t)}{\partial t^2} = -k l \left(\frac{u(x_2' + h, t) - u(x_2', t)}{h} \right)$$

$$x_2 = x_2' + h$$

$$h \rightarrow \infty \Leftrightarrow h \rightarrow 0 \Rightarrow h \ddot{u} \rightarrow 0$$

$$\left. \frac{\partial u(x, t)}{\partial x} \right|_{x_2 - h} \stackrel{h \rightarrow 0}{=} \left. \frac{\partial u(x, t)}{\partial x} \right|_{x_2}$$

$$\left. \frac{\partial u(x, t)}{\partial x} \right|_{x=x_2} = \left. \frac{\partial u(x, t)}{\partial x} \right|_{x=x_1} = 0$$

$$\left. \frac{\partial u}{\partial x} \right|_{x=0} = \left. \frac{\partial u}{\partial x} \right|_{x=L} = 0 \quad \forall t$$

↑
dolžna ptioc

$$u(x, t) = u_1(x, t) + u_2(x, t)$$

$$\left. \begin{aligned} u_1 &= u_0 \sin(kx - \omega t + \delta_1) \\ u_2 &= u_0 \sin(kx + \omega t + \delta_2) \end{aligned} \right\} +$$

$$= 2u_0 \sin\left(kx + \frac{\delta_1 + \delta_2}{2}\right) \cos\left(-\omega t + \frac{\delta_1 - \delta_2}{2}\right)$$

$$\Rightarrow \frac{\partial u}{\partial x} = \frac{\partial u_1}{\partial x} + \frac{\partial u_2}{\partial x} = ku_0 \cos(kx - \omega t + \delta_1) + ku_0 \cos(kx + \omega t + \delta_2)$$

$$= 2ku_0 \cos\left(kx + \frac{\delta_1 + \delta_2}{2}\right) \cos\left(-\omega t + \frac{\delta_1 - \delta_2}{2}\right)$$

$$\left. \frac{\partial u}{\partial x} \right|_{x=0} = 2ku_0 \cos\left(\frac{\delta_1 + \delta_2}{2}\right) \cos\left(-\omega t + \frac{\delta_1 - \delta_2}{2}\right) \stackrel{\forall t}{=} 0$$

$$\Rightarrow \frac{\delta_1 + \delta_2}{2} = \frac{\pi}{2}$$

$$\cos\left(kx + \frac{\pi}{2}\right) = -\sin(kx)$$

$$\sin\left(kx + \frac{\pi}{2}\right) = \cos(kx)$$

$$u(x, t) = 2u_0 \cos(kx) \cos\left(-\omega t + \frac{\delta_1 - \delta_2}{2}\right)$$

$$\frac{\partial u}{\partial x} = -2ku_0 \sin(kx) \cos\left(-\omega t + \frac{\delta_1 - \delta_2}{2}\right)$$

$$\left. \frac{\partial u}{\partial x} \right|_{x=L} = 0 \Rightarrow$$

$$-2ku_0 \sin(kL) \cos\left(-\omega t + \frac{\delta_1 - \delta_2}{2}\right) = 0 \quad \forall t$$

$$kL = 0 + \pi n, \quad n \in \mathbb{Z}$$

$$k = \frac{n\pi}{L} = \frac{\omega}{c} = \frac{2\pi\nu_n}{c}$$

$$\nu_n = \frac{nc}{2L} \quad n \in \mathbb{N}$$

$$u(x, t) = 2u_0 \cos\left(\frac{n\pi}{L} x\right) \cos\left(-2\pi\nu_n t + \frac{\delta_1 - \delta_2}{2}\right)$$

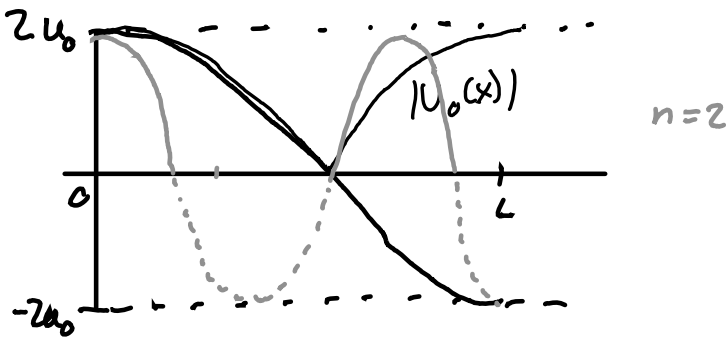
Dobimo stojee valovanje. nima več tner:

$$u(x, t) = 2u_0 \cos\left(\frac{n\pi}{L} x\right) \cos\left(-2\pi\nu_n t + \frac{\delta_1 - \delta_2}{2}\right)$$

$$n=0 \Rightarrow \underset{V=0}{u(x, t)} = 2u_0 \cos\left(\frac{\delta_1 - \delta_2}{2}\right)$$

$$n=1 \rightarrow V_1 = \frac{c}{2L}$$

$$u(x, t) = \underbrace{2u_0 \cos\left(\frac{\pi}{L} x\right)}_{|u_0(x)|} \cos\left(\frac{\pi c}{L} t + \frac{\delta_1 - \delta_2}{2}\right)$$



$$V_1 = \frac{c}{2L} = \frac{1}{2L} \sqrt{\frac{E}{\rho}} \rightarrow E$$

$$\rho = \frac{m}{V} = \frac{m}{LS}$$

10. Energija valovanja

- potovanje matrike $\rightarrow$ potovanje energije
- valovanje po vijaci; vzmeti

x ; x in $x+h$

$$W_k = \frac{1}{2} m_1 v^2 = \frac{1}{2} m_1 \left| \frac{\partial u(x,t)}{\partial t} \right|^2 = \frac{1}{2} \frac{m h}{l} \left| \frac{\partial u(x,t)}{\partial t} \right|^2$$

$$\Rightarrow \frac{W_k}{h} = \frac{1}{2} \frac{m}{l} \left| \frac{\partial u(x,t)}{\partial t} \right|^2$$

$$\begin{aligned} W_{pr} &= \frac{1}{2} k_1 [u(x+h,t) - u(x,t)]^2 \\ &= \frac{1}{2} \frac{k l}{h} [u(x+h,t) - u(x,t)]^2 \\ &= \frac{1}{2} k l \left(\frac{u(x+h,t) - u(x,t)}{h} \right)^2 \end{aligned}$$

$$\frac{W_{pr}}{h} = \frac{1}{2} k l \left[\frac{u(x+h,t) - u(x,t)}{h} \right]^2$$

$\downarrow h \rightarrow 0$

$$\lim_{h \rightarrow 0} \frac{W_{pr}}{h} = \frac{1}{2} k l \left| \frac{\partial u(x,t)}{\partial x} \right|^2 =$$

$$= \frac{1}{2} k l \cdot \frac{l}{m} \cdot \frac{m}{l} \left| \frac{\partial u(x,t)}{\partial x} \right|^2 =$$

$$= \frac{1}{2} c^2 \frac{m}{l} \left| \frac{\partial u(x,t)}{\partial x} \right|^2$$

$$c^2 = \frac{k l^2}{m}$$

Problema polica

$$m = \rho V = \rho S \cdot l \quad \left. \vphantom{m = \rho V = \rho S \cdot l} \right\} \Rightarrow \frac{W_k}{h}(x, t) =$$
$$k = \frac{ES}{l}$$

$$\frac{1}{2} \rho S \left| \frac{\partial u}{\partial t} \right|^2$$

$$\boxed{W_k = \frac{W_k}{\Delta V} = \frac{W_k}{Sl} = \frac{1}{2} \rho \left| \frac{\partial u}{\partial t} \right|^2}$$

↑
gata kinetic energy

$$\frac{W_p}{h} = \frac{1}{2} c^2 \frac{m}{l} \left| \frac{\partial u}{\partial x} \right|^2$$

$$\bar{w} = \frac{1}{2} \rho \omega^2 u_0^2 \dots \text{povprečna gostota energije}$$

$$\omega = 2\pi\nu$$

$$\bar{W} = \bar{w} \, dV \quad dV = S \, c \, t \quad ; \quad S \perp c \\ = \bar{w} S c t$$

energija, ki v času t prepotuje skozi S

$$P := \frac{\bar{W}}{t} = \frac{\bar{w} \cdot S c t}{t} = \bar{w} S c$$

$$[P] = \frac{\text{J}}{\text{m}^3} \frac{\text{m}^2 \cdot \text{m}}{\text{s}} = \frac{\text{J}}{\text{s}} = \text{W} \dots \text{wat}$$

$$j_w := \frac{P}{S} \dots \text{jakost energijskega toka}$$

$$j_w = \frac{P}{S} = \bar{w} c \quad [j_w] = \frac{\text{W}}{\text{m}^2}$$

Primer:

zrak v zraku

$$c^2 = \frac{1}{\chi \rho}$$

$\uparrow$ stisljivost $\nwarrow$ gostota

$$pV = \frac{m}{M} RT$$

$$M = 29 \text{ kg}$$

$$R = 8300 \text{ J/K}$$

$$[T] = K$$

$$\chi := -\frac{1}{V} \frac{\partial V}{\partial p} \quad \chi > 0$$

$$\frac{pV}{T} = \frac{p_0 V_0}{T_0}$$

$\rightarrow T = T_0 = \text{konst}$ (izotermna)

$$pV = p_0 V_0 = K$$

$$\Rightarrow V = \frac{K}{p} \Rightarrow \frac{1}{V} = \frac{p}{K}$$

$$\boxed{\chi = \left(-\frac{1}{V}\right) \left(-\frac{K}{p^2}\right) = \frac{1}{p}}$$

$$\chi = \frac{1}{p} \rightarrow \frac{1}{K_p}$$

$\nwarrow$ K_p

$$c^2 = \frac{K_p R T}{\rho M} = \frac{K R T}{M}$$

$\star$

$K = 1,4$ za vse dvoatomne molekule

$$\Rightarrow c = \sqrt{\frac{K R T}{M}} = \sqrt{\frac{1,4 \cdot 8300 \text{ J} \cdot 300 \text{ K}}{29 \text{ kg}}} \approx 340 \frac{\text{m}}{\text{s}}$$

$V_{\text{max}} \approx 1 \text{ kHz}$... neše uho je najbolj občutljiva za to

$j_0 = 10^{-12} \frac{\text{W}}{\text{m}^2}$... tolikšno jakost je potrebno da slišimo V_{max}

$$U_0 = ?$$

$$j_0 = \frac{1}{2} \rho \omega^2 U_0^2 \cdot c \quad \rho \approx 1,2 \frac{\text{kg}}{\text{m}^3}$$

$$\Rightarrow U_0^2 = \frac{2 j_0}{\rho (2\pi V_{\text{max}})^2 c}$$

Doplerjev pojav

ν : frekvenca oddajnika ($t_0 = \frac{1}{\nu}$)

λ : valovna dolžina zvoka v snovi (zraku)

c : hitrost zvoka v snovi (zraku)

ν' : frekvenca, ki jo sliši sprejemnik

a) sprejemnik miruje glede na zrak ($v_2 = 0$), oddajnik se mu približuje s hitrostjo v_1 (glede na zrak)



$t_1 = 0$ odda prvi pisk

$t_2 = t_0$ odda drugi pisk

pri tem se premakne za $t_0 \cdot v_1$ proti sprejemniku
prvo čelo se premakne za $t_0 \cdot c$ proti sprejemniku



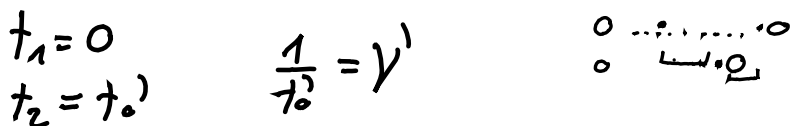
$$\lambda = c t_0 - v_1 t_0 = t_0 (c - v_1)$$

$$\boxed{\nu' = \frac{c}{\lambda} = \frac{c}{(c - v_1) t_0} = \frac{1}{1 - \frac{v_1}{c}} \nu}$$

$-$ za približevanje
 $+$ za oddaljevanje

b) oddajnik miruje ($v_1 = 0$), sprejemnik se približuje z v_2

Po zraku proti sprejemniku potujejo valovi z valovno dolžino λ



$t_1 = 0$

$t_2 = t_0'$

$$\frac{1}{t_0'} = \nu'$$

$$c t_0' + v_2 t_0' = \lambda = \frac{c}{\nu}$$

$$t_0' (c + v_2) = \frac{c}{\nu}$$

$$t_0' = \frac{1}{\nu'}$$

$$\frac{c + v_2}{\nu'} = \frac{c}{\nu}$$

$$\boxed{\nu' = \nu \cdot \frac{c + v_2}{c} = \nu \left(1 + \frac{v_2}{c} \right)}$$

$$\boxed{\nu' = \nu \frac{1 \pm \frac{v_2}{c}}{1 \mp \frac{v_1}{c}}}$$

predpostavke:

T1: vpliv okolice upade z razdaljo

$$\lim_{d_{\min} \rightarrow \infty} \vec{F} = 0$$

skupna sila okolice
↑ najmanjša razdalja okolice do predmeta

T2: definicija inercialnega op. sistema

$$d_{\min} \rightarrow \infty \stackrel{T1}{\Rightarrow} \vec{F} = 0 \text{ skupna sila okolice}$$

$$S: \vec{a} = \vec{0} \Rightarrow S \text{ inercialni}$$

T3: Definicija katikone neto sile $\vec{F}$

T2: S inercial

m... masa v sistemu v katerem
telo miruje

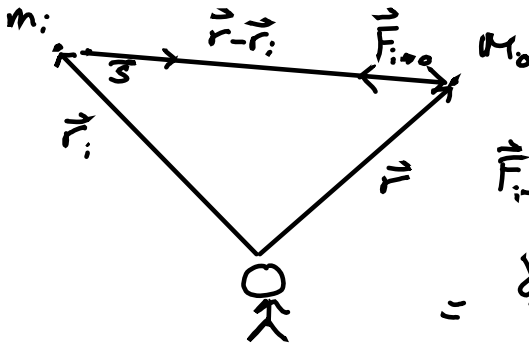
$$\vec{a} \Rightarrow \vec{F} := m\vec{a}$$

↑ v inercialnem sistemu

T4: Princip superpozicije: $\vec{F}_1, \vec{F}_2, \vec{F}_3 \dots$

$$\Rightarrow \vec{F} = \sum_{i=0}^n \vec{F}_i$$

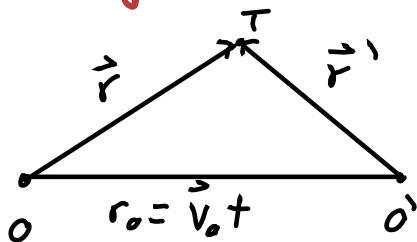
Primer: $\vec{F}_g$



$$\begin{aligned}\vec{F}_{i \rightarrow o} &= -G \frac{m_i M_o}{|\vec{r} - \vec{r}_i|^2} \hat{e}_i = \\ &= \frac{G m_i M_o (\vec{r} - \vec{r}_i)}{|\vec{r} - \vec{r}_i|^3}\end{aligned}$$

$$\vec{F}_{o \rightarrow i} = \frac{G M_o m_i (\vec{r}_i - \vec{r})}{|\vec{r} - \vec{r}_i|^3} = -\vec{F}_{i \rightarrow o}$$

Galilejeve transformacije



$$\vec{r} = \vec{r}_0 + \vec{r}' \Rightarrow \vec{r}' = \vec{r} - \vec{r}_0$$

$$t' = t$$

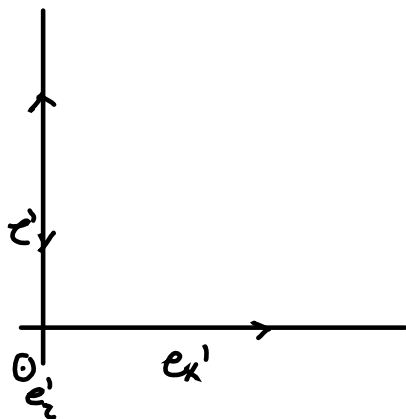
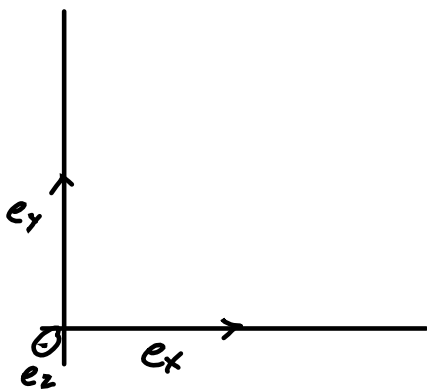
$$S: \vec{v} = \frac{d\vec{r}}{dt}$$

$$S': \vec{v}' = \frac{d\vec{r}'}{dt} = \frac{d\vec{r}'}{dt} = \frac{d}{dt}(\vec{r} - \vec{r}_0) = \frac{d\vec{r}}{dt} - \frac{d(\vec{v}_0 \cdot t)}{dt} =$$

$$S: \vec{a} = \frac{d\vec{v}}{dt} = \vec{v} - \vec{v}_0$$

$$S': \vec{a}' = \frac{d\vec{v}'}{dt'} = \frac{d\vec{v}'}{dt} = \frac{d}{dt}(\vec{v} - \vec{v}_0) = \frac{d\vec{v}}{dt} - \frac{d\vec{v}_0}{dt} =$$
$$= \vec{a} - 0 = \vec{a}$$

$$\vec{F}' = m\vec{a}' = m\vec{a} = \vec{F}$$



$$r_0 = v_0 t e_x = \begin{bmatrix} v_0 t \\ 0 \\ 0 \end{bmatrix}$$

$$\vec{r} = x e_x + y e_y + z e_z = \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

$$\vec{r}' = x' e'_x + y' e'_y + z' e'_z = x' e'_x + y' e'_y + z' e'_z = \begin{bmatrix} x' \\ y' \\ z' \end{bmatrix}$$

$$\vec{r} = \vec{r} - \vec{r}_0 = \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} x \\ y \\ z \end{bmatrix} - \begin{bmatrix} v_0 t \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} x - v_0 t \\ y \\ z \end{bmatrix}$$

$$c_0 t' = c_0 t$$

$$x' = x - \frac{v_0}{c_0} c_0 t = x - \beta_0 c_0 t$$

$$y' = y$$

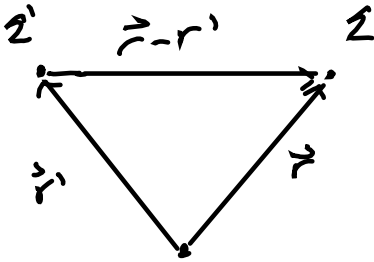
$$z' = z$$

$$X = \begin{bmatrix} c_0 t' \\ x' \\ y' \\ z' \end{bmatrix}$$

$$\Gamma = \begin{bmatrix} 1 & 0 & 0 & 0 \\ \beta_0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

② Elektrische side

(Kolumbar zeken)



$$F_{q' \rightarrow q} = \frac{qq'}{4\pi\epsilon_0} \frac{(\vec{r} - \vec{r}')}{|\vec{r} - \vec{r}'|^3}$$

$$F_{m' \rightarrow m} = -g \frac{mm'}{|\vec{r} - \vec{r}'|^3}$$

$$q_0 = 1,6 \cdot 10^{-19} \text{ As}$$

$$q = -q_0 = -1,6 \cdot 10^{-19} \text{ As}$$

$$\epsilon_0 = 8,9 \cdot 10^{-12} \frac{\text{As}}{\text{Vm}}$$

$$q = Nq_0$$

3. Električno polje

$\vec{F}(\vec{r}) \dots$ sila

$\vec{E} \dots$ vektor. el. polja oz jakost. el. polja

$q \dots$ naboj

$$F_{el, q} = q \cdot \vec{E} \quad \vec{E} = \frac{\vec{F}_{el, q}}{q}$$

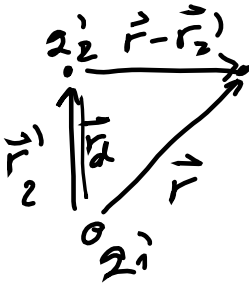
$$\vec{E}_{\vec{r}'(\vec{r}')}(\vec{r}) = \frac{\vec{F}_{\vec{r}' \rightarrow \vec{r}}}{q} = \frac{q' (\vec{r} - \vec{r}')}{4\pi\epsilon_0 |\vec{r} - \vec{r}'|^3}$$

$$[F_{\vec{r}' \rightarrow \vec{r}}] = \frac{As^2 V m m}{As m^3} = \frac{VAS}{m} = N$$

$$[E] = \frac{V}{m}$$

✓ 27.3 odsotke zadnjih
10 minut

Primer:



$$q_1' = q > 0$$

$$q_2' = -q \quad (\infty)$$

$$r_2' = -r_2$$

$$\vec{E}(\vec{r}) = \vec{E}_1 + \vec{E}_2$$

$$\vec{E}_1 = \frac{q_1' (\vec{r} - \vec{r}_1')}{4\pi\epsilon_0 |\vec{r} - \vec{r}_1'|^3} = \frac{q \vec{r}}{4\pi\epsilon_0 |\vec{r}|^3}$$

$$\vec{E}_2 = \frac{q_2' (\vec{r} - \vec{r}_2')}{4\pi\epsilon_0 |\vec{r} - \vec{r}_2'|^3} = - \frac{q (\vec{r} - \vec{r}_2')}{4\pi\epsilon_0 |\vec{r} - \vec{r}_2'|^3}$$

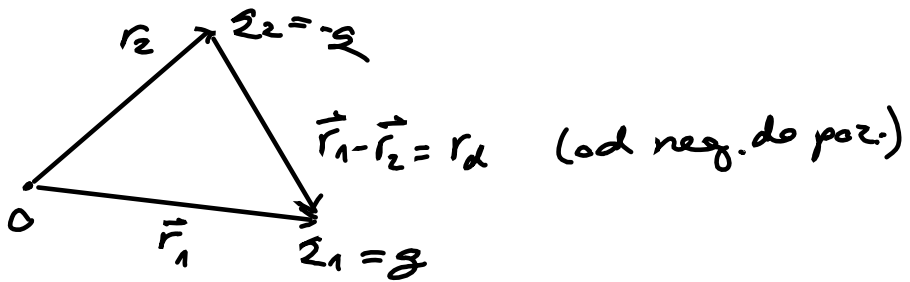
$$\vec{E} \approx \frac{1}{4\pi\epsilon_0 r^3} (3\vec{p}_e \cdot \hat{e}_r) \hat{e}_r - \vec{p}_e$$

$$\hat{e}_r = \frac{\vec{r}}{r} \quad \vec{p}_e := q \vec{r}_2$$

Naboj na $\vec{p}_c$ v homogenom polju $\vec{E}$

$$\vec{z}_1 \rightarrow z_1 : \vec{F}_{el, z_1} = q_1 \vec{E}(\vec{r}_1) = q \vec{E}$$

$$z_2 \rightarrow z_2 : \vec{F}_{el, z_2} = q_2 \vec{E}(\vec{r}_2) = -q \vec{E}$$



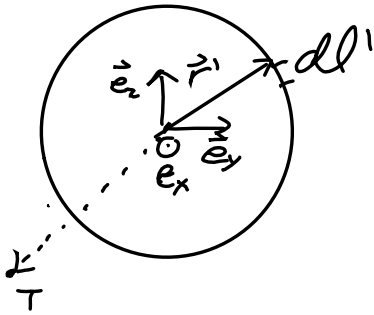
$$\vec{M}_1 = \vec{r}_1 \times \vec{F}_1 = \vec{r}_1 \times q \vec{E} = q \vec{r}_1 \times \vec{E}$$

$$M_2 = \vec{r}_2 \times \vec{F}_2 = \vec{r}_2 \times (-q \vec{E}) = -q \vec{r}_2 \times \vec{E}$$

$$M = M_1 + M_2 = q \vec{r}_1 \times \vec{E} - q \vec{r}_2 \times \vec{E} =$$

$$q (\vec{r}_1 - \vec{r}_2) \times \vec{E} = q \vec{r}_d \times \vec{E} = \vec{p}_{el} \times \vec{E}$$

E na simetrali crakomere nab. zanke



$$\vec{r} = r \hat{e}_x$$

$$\vec{r}' = r' \cos \varphi \hat{e}_y + r' \sin \varphi \hat{e}_z$$

$$\vec{r} - \vec{r}' = r \hat{e}_x - r \cos \varphi \hat{e}_y - r \sin \varphi \hat{e}_z$$

$$|\vec{r} - \vec{r}'|^3 = (r^2 + r'^2)^{\frac{3}{2}}$$

$$g_1 = \frac{z'}{2\pi r'} = \frac{dz'}{dl'} = \frac{z'}{r' d\varphi}$$

$$\Rightarrow dz' = \rho_p r' d\varphi$$

$$dE_p(\vec{r}) = \frac{dz'}{4\pi\epsilon_0} \frac{(\vec{r} - \vec{r}')}{|\vec{r} - \vec{r}'|^3} =$$

$$= \frac{\rho_p r' (r \hat{e}_x - r \cos \varphi \hat{e}_y - r \sin \varphi \hat{e}_z) d\varphi}{4\pi\epsilon_0 (r^2 + r'^2)^{\frac{3}{2}}}$$

$$\Rightarrow \vec{E}(\vec{r}) = \int dE_p = \int \frac{\rho_p r'}{4\pi\epsilon_0} \left[\frac{r \hat{e}_x I_1 - r' \hat{e}_y I_2 - r' \hat{e}_z I_3}{(r^2 + r'^2)^{\frac{3}{2}}} \right] d\varphi$$

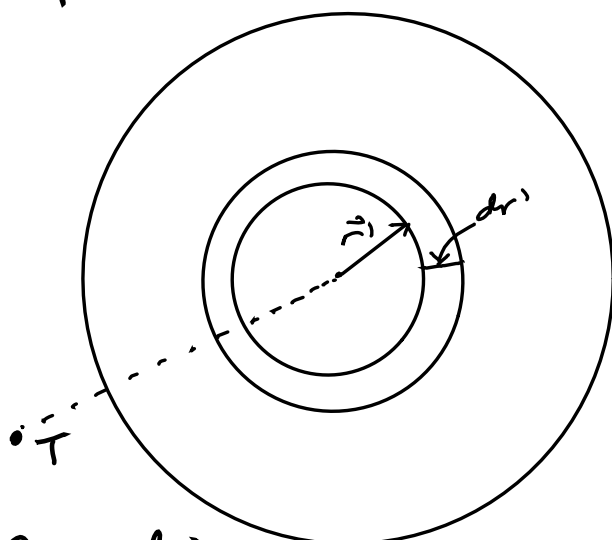
$$I_1 = \int_0^{2\pi} d\varphi = 2\pi$$

$$I_2 = \int_0^{2\pi} \cos \varphi d\varphi = 0$$

$$I_3 = \int_0^{2\pi} \sin \varphi d\varphi = 0$$

$$\vec{E}(\vec{r}) = \frac{\rho_p r (2\pi) \hat{e}_x}{4\pi\epsilon_0 (r^2 + r'^2)^{\frac{3}{2}}} = \frac{z r \hat{e}_x}{4\pi\epsilon_0 (r^2 + r'^2)^{\frac{3}{2}}}$$

Ne vidim na tablo oznake so to
mogoče pravilne



$$S = \pi R^2$$

$$\rho_s = \frac{q'}{S} = \frac{q'}{\pi R^2}$$

$$dS' = 2\pi r' dr' \quad (\text{površina zunke})$$

$$\begin{aligned} \rho_s' &= -\frac{dq'}{ds'} \Rightarrow dq' = \rho_s' ds' = \frac{q'}{\pi R^2} 2\pi r' dr' = \\ &= \frac{q' 2r' dr'}{R^2} \end{aligned}$$

$$dE(r)(\vec{r}) = \frac{dq' r}{4\pi \epsilon_0 (r^2 + r'^2)^{\frac{3}{2}}} \hat{e}_x =$$

$$\frac{\frac{q' r' dr'}{2\pi \epsilon_0 (r^2 + r'^2)^{\frac{3}{2}}} \hat{e}_x}{R^2}$$

$$\Rightarrow \vec{E}(\vec{r}) = \frac{q' r}{2\pi \epsilon_0 R^2} \hat{e}_x I$$

$$I = \int_0^R \frac{r' dr'}{(r^2 + r'^2)^{\frac{3}{2}}} = \frac{1}{r} \left(1 - \frac{1}{\sqrt{1 + \frac{R^2}{r^2}}} \right)$$

$$\vec{E}(\vec{r}) = \frac{q'}{\pi r^2} \frac{1}{3\epsilon_0} \cdot \left(1 - \frac{1}{\sqrt{1 + \frac{R^2}{r^2}}} \right)$$

$$= \frac{\rho_p}{2\epsilon_0} \left(1 - \frac{1}{\sqrt{1 + \frac{R^2}{r^2}}} \right)$$

$$\frac{r}{R} \ll 1 \Rightarrow \sqrt{1 + \frac{R^2}{r^2}} = \sqrt{\frac{R^2}{r^2}} = \frac{R}{r}$$

$$\Downarrow$$

$$\frac{R}{r} \gg 1$$

$$\vec{E}(r) \approx \frac{\rho_p}{2\epsilon_0} \left[1 - \frac{r}{R} \right] \approx \frac{\rho_p}{2\epsilon_0}$$

