Parametric Resonance

- Consider an oscillator with a changing resonant frequency

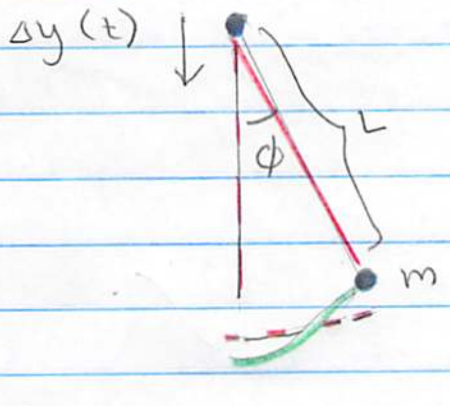
$$\frac{d^2 q}{dt^2} + \omega_0^2 (1 + h \cos \Omega t)\, q = 0$$

$\Omega = 2\omega_0 + \varepsilon$

small

- This model arises in an enormous number of applications
  - Stability of the paul trap for charged ions
  - reheating after inflation
  - Stability of helicopter blades
  - hawking radiation ...

- As a model consider a pendulum with a oscillating support $\Delta y = -y_0 \cos \Omega t$ with $\Omega \simeq 2\omega_0$, so that the support "drops" the mass at the top of the arc ϕ_{max}, and pulls the mass back up at $\phi \simeq 0$



$$\ddot{\phi} + \omega_0^2 \left(1 + \frac{y_0 \Omega^2}{L} \cos \Omega t\right) \phi = 0$$

- First consider the <u>unperturbed</u> oscillator and calculate the tension as a function of time in the rod

- The tension is smaller than mg at ϕ_{max}

$$T_{min} = mg\cos\phi_{max} = mg(1 - \phi_{max}^2/2)$$

$$= mg - \frac{E}{L} \leftarrow \text{energy in oscillator} \propto \phi_{max}^2$$

- But larger than mg at the bottom:

$$T_{max} = mg + \underbrace{\frac{mv^2}{L}}_{\text{"centrifugal force"}} = mg + \underbrace{2E/L}_{E = \frac{1}{2}mv^2}$$

- So if the mass is dropped by Δy at ϕ_{max}, and pulled up by Δy at $\phi \simeq 0$ the external work done in <u>half</u> a period $T_0/2$ is

$$W = (T_{max} - T_{min})\,\Delta y = 3\frac{E}{L}\Delta y$$

Since this is positive, the energy will constantly grow:

$$\dot{E} = \frac{\Delta E}{T_0/2} = 6\,\frac{\Delta y}{L}\,\frac{E}{T_0}$$

leading to exponential growth in the oscillator energy by the external work.

- Now consider what happens if the modulation frequence differs from the resonance condition

$$\Omega = 2\omega_0 + \varepsilon$$

modulation frequency

detuning parameter
if detuned the external work will not always be positive

- If the modulation amplitude is large enough it can overcome the detuning

$$\omega_0^2(1 + h\cos\Omega t)$$

modulation amplitude

Causing exponential growth. We will see: (1) that the condition is

$$\boxed{|\varepsilon| < \frac{1}{2} h\omega_0}$$

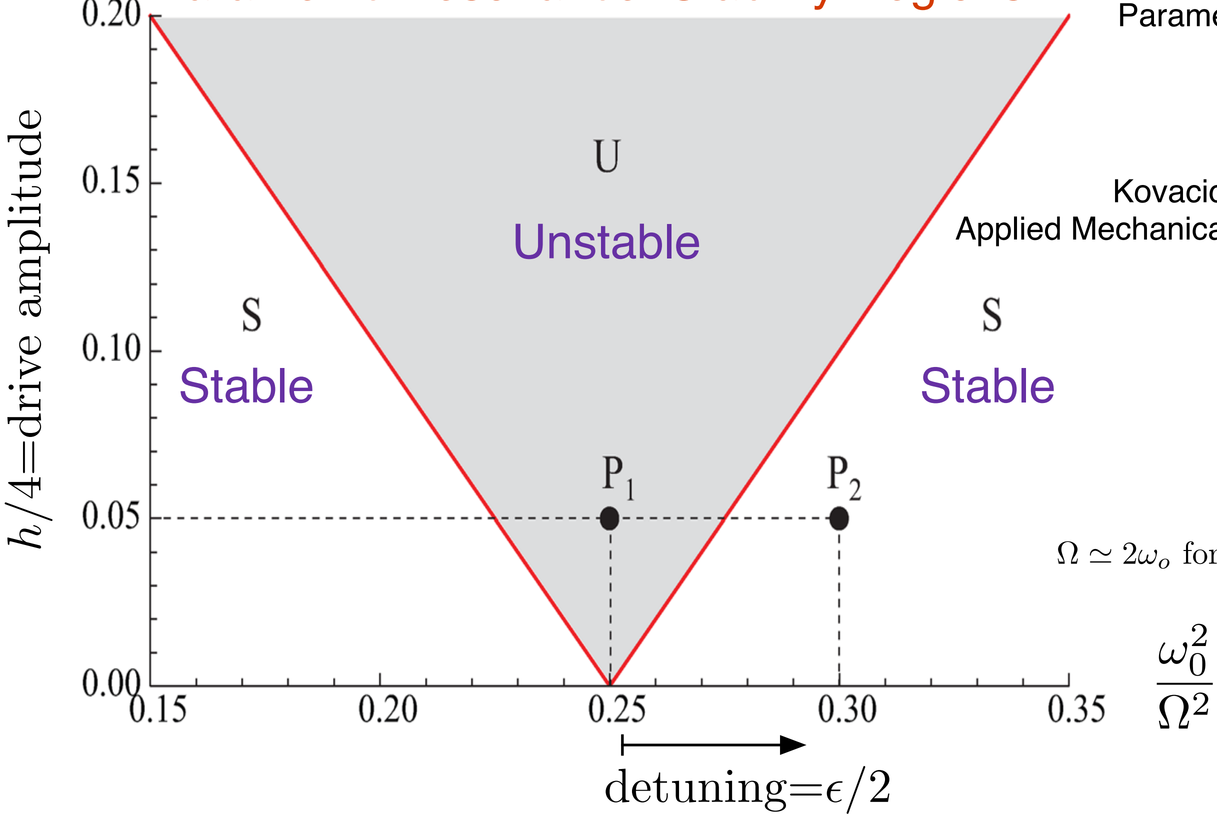
The stability regions are shown on the next slide (click me)

(2) The growth rate in amplitude is

$$\boxed{\lambda = \sqrt{\left(\frac{h\omega_0}{2}\right)^2 - \varepsilon^2}}$$

Parametric Resonance: Stability Regions

Parametric Resonance: 4



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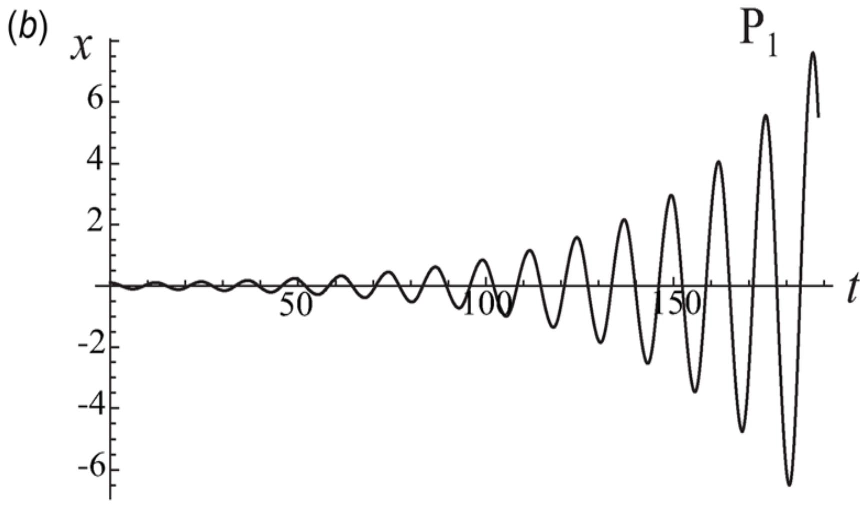
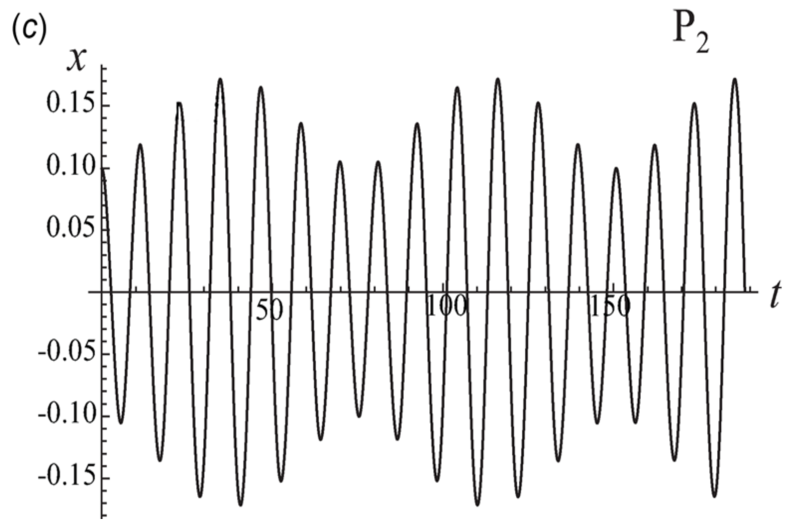
$\Omega \simeq 2\omega_o$ for exponential growth



Unstable oscillations at P1



Stable oscillations at P2

Mathematical Analysis of Parametric Resonance

- We study:

$$\ddot{q} + \omega_0^2 (1 + h\cos\Omega t)\, q = 0$$

with $\Omega = 2\omega_0 + \varepsilon \equiv 2\omega$. As always we work with a rotating wave / slow roll / secular perturbation theory / WKB approximation (all these are basically the same!)

$$q(t) = q^{(0)}(t) + q^{(1)}(t)$$

with

$$q^{(0)} = \mathrm{Re}\left[A(t)\, e^{-i\omega t} \right]$$

$$= \underbrace{a(t)\cos\omega t + b(t)\sin\omega t}_{\text{slow functions of time}}$$

- Then note:

(1) $$\ddot{q}^{(0)} = -\omega^2 q^{(0)} + \left[-2\omega\sin\omega t\, \dot{a} + 2\omega\cos\omega t\, \dot{b} \right] + (\text{small})^2$$

(2) $$(\cos 2\omega t)(\cos\omega t) = \frac{1}{2}\left(e^{i2\omega t} + e^{-2i\omega t}\right)\frac{1}{2}\left(e^{i\omega t} + e^{-i\omega t}\right)$$

$$= \frac{1}{2}\cos 3\omega t + \frac{1}{2}\cos\omega t$$

(3) $\cos 2\omega t \sin\omega t = \frac{1}{2}\sin 3\omega t - \frac{1}{2}\sin\omega t$

(4) $(\omega_0^2 - \omega^2)\, q^{(0)} \simeq -\,\omega \varepsilon\, q^{(0)}$

- Substituting into ☆

this can be set to ω_0 at first order

$$\ddot{q}^{(1)} + \omega_0^2 q^{(1)} + \underline{(2\dot{b} - a\varepsilon + \tfrac{1}{2} h\omega\, a)}\,\omega\cos\omega t$$

$$\underline{(-2\dot{a} - b\varepsilon - \tfrac{1}{2} h\omega\, b)}\,\omega\sin\omega t$$

$$+ \; 3\omega t \text{ terms } = 0$$

- As is usual the $q^{(1)}$ will solve the 3ω terms. The underlined (secular) terms must be set to zero to avoid secular divergences

$$\frac{d}{dt}\begin{pmatrix} a \\ b \end{pmatrix} = \begin{pmatrix} 0 & \varepsilon + h\omega_0/2 \\ -\varepsilon + \frac{h\omega_0}{2} & 0 \end{pmatrix}\begin{pmatrix} a \\ b \end{pmatrix}$$

- This system of equations is solved by finding the eigenvectors and evalues

$$\boxed{\lambda_{\pm} = \pm\sqrt{-\varepsilon^2 + \left(\frac{h\omega_0}{2}\right)^2}}$$ and corresponding vectors

E_+ and E_-

The Solution is

$$\begin{pmatrix} a \\ b \end{pmatrix} = c_+ e^{\lambda_+ t} \begin{pmatrix} E_+ \\ \end{pmatrix} + c_- e^{\lambda_- t} \begin{pmatrix} E_- \\ \end{pmatrix}$$

(1) If the drive amplitude is large enough:

$$\boxed{|\varepsilon| < \frac{h\omega}{2}},$$

- It overwhelms the detuning, and the eigen values are real with $\lambda_+ > 0$. The oscillation explodes exponentially. This is the point P_1 on the next slide (click me)

(2) If the drive frequency Ω is not too close to $2\omega_0$. Then the e-values are imaginary:

$$\lambda_\pm = \pm i \sqrt{\varepsilon^2 - \left(\frac{h\omega}{2}\right)^2} \qquad \text{for} \quad \frac{h\omega_0}{2} < |\varepsilon|$$

- The oscillations are stable. The slowly oscillating $a(t)$ and $b(t)$ will envelope the more rapid $\cos \Omega t$ oscillations. This is the point P_2 on the next slide. Click me

Parametric Resonance: Stability Regions

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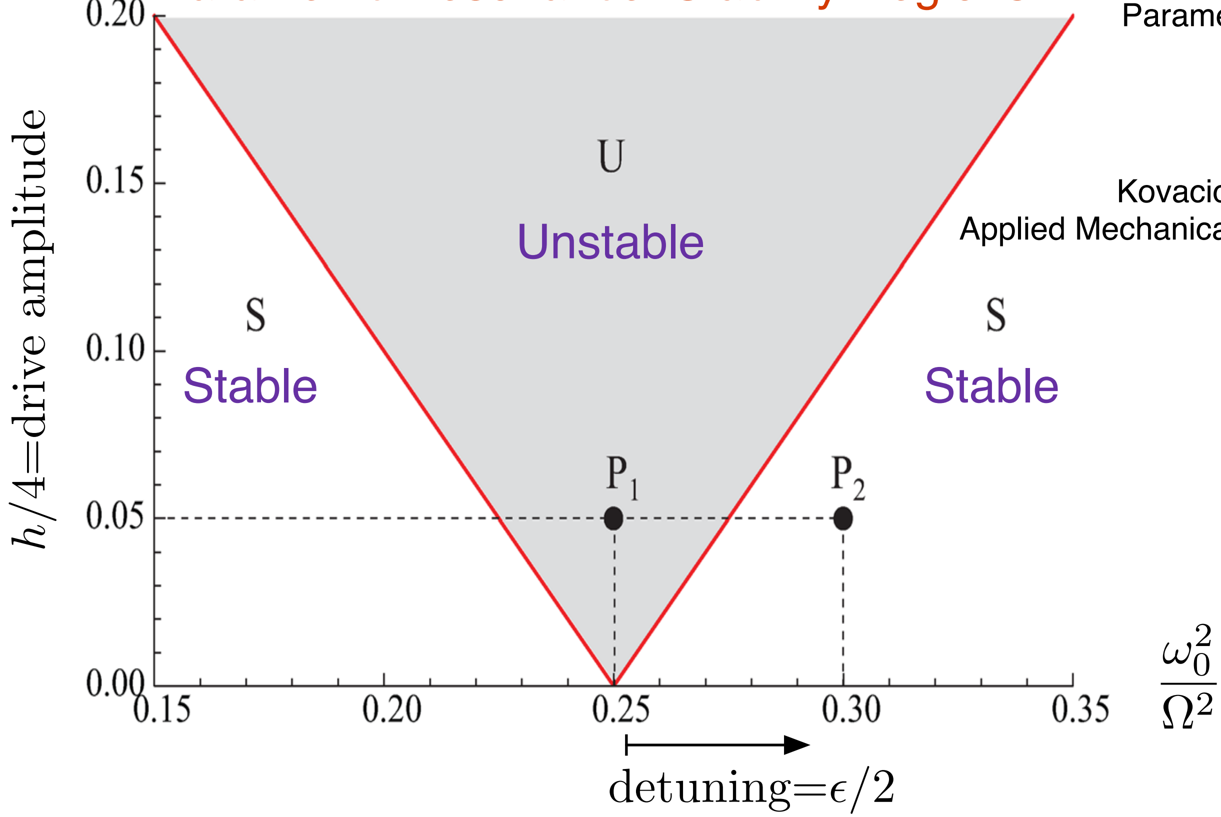
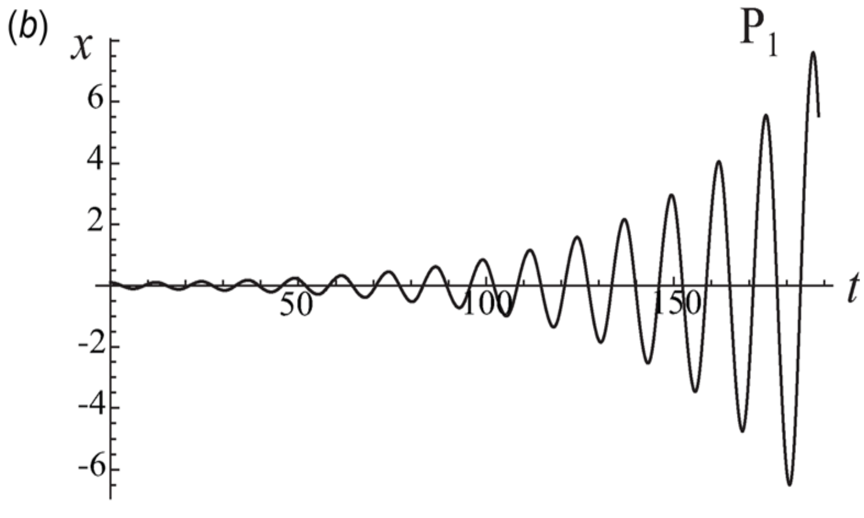
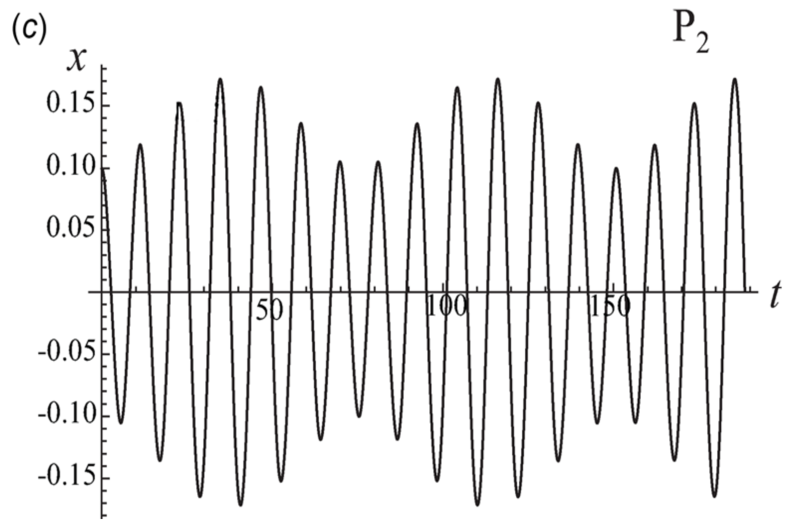




Unstable oscillations at P1



Stable oscillations at P2