WARSAW UNIVERSITY OF THECHNOLOGY
FACULTY OF POWER AND AERONAUTICS

VIBRATIONS AND AEROELASTICITY

Dr inż. Franciszek Dul

Vibrations and aeroelasticity

Short introduction

Vibrations are quite common in life, engineering (especially in aeronautics) and science.

Every student of Faculty of Power and Engineering should have some basic knowledge on these important phenomena.

The aims of the lecture are:

- to give you a basic knowledge on the physics of vibrations,
- to acquaint you with vibrations of various kinds,
- to enrich your knowledge on the unsteady aerodynamics,
- to acquaint you with aeroelastic phenomena in aeronautics,
- to show you what the main concepts of Vibrations and Aeroelasticity are used in practice and…,
- how they are accounted for in the civil and military regulations.
- finally, to give you some basic computational skill in vibrations and aeroelasticity.

Vibrations and aeroelasticity

The basic scope of the lecture is as follows:

- vibrations – 50%, (to the end of November),
- unsteady aerodynamics – 15%, (two weeks of December),
- aeroelasticity – 35% (to the end of the semester).

The basic form of the lecture is the multimedia presentation.

Moreover, there will be also:

- a computer presentation of FEM calculation of the mode shapes of vibrations of wings,
- an experimental presentation of mode shapes of tail rotor blade of the Mi-2 helicopter (a prototype of resonance tests),
- an experimental presentation of various types of flutter of a wing in the wind tunnel,
- a detailed example of solving the homework problem.

Handprints of the lecture - pdf documents will be provided on

Zakład Mechaniki/Dydaktyka/Files for students/Vibrations and Aeroelasticity

Vibrations and aeroelasticity

The administrative order of the lecture - rules of credit

To get a pass one should fulfill two conditions:

1. To have at least 8 (of 15) attendances.

AND

2. To solve the homework problem.

The final grade is the average of attendance and homework.

The attendance list will be checked every lecture - you will be asked to sign the attendance list.

The homework problems:

- will be individual for everyone,
- will be provided at the middle of December,
- should be completed before the end of the semester.

The paper version is required: handwritten, pdf, doc.

INTRODUCTION

SOME EXAMPLES OF VIBRATIONS …

The Tacoma Bridge disaster

The ground resonance of a helicopter

Flutter of a glider

Vibrations and aeroelasticity... what is it?

- This lecture is a union of two subjects that are usually presented separately.
- ***Vibrations*** embraces a wide range of problems:
  - general aspects of vibrations of the physical systems,
  - ... in particular - *vibrations of aerospace structures*,
  - dynamics of machinery,
  - preventing the unwanted vibrations,
  - stability of vibrations and many more...
- ***Aviation aeroelasticity*** concerns analysis of vibrations of flying aircraft and includes:
  - vibrations of aviation structures,
  - fluid mechanics (unsteady aerodynamics),
  - aeroelastic problems of aircraft, helicopters and rockets.
- ***Aeroelasticity*** does not concern the aviation only:
  - aeroelasticity of buildings (civil aeroelasticity),
  - hydroaeroelasticity of turbomachinery.

Vibrations and aeroelasticity... what is it?

- These subjects are being lectured on all respected aeronautical faculties (MIT, Stanford, Berkeley, Princeton, MEiL)
- They cover all the basic domains of mechanics (!):
  - dynamics,
  - strength of materials,
  - fluid mechanics (in addition - unsteady!)
- They are very advanced mathematically employing (among others):
  - ordinary and partial differential equations,
  - theory of stability,
  - theory of complex variable,
  - eigenproblems,
  - the potential theory and singular integral equations,
  - numerical methods...
- They have imprtant practical applications:
  - designing,
  - aviation's regulations..

Vibrations and aeroelasticity...
What should it teach?

First of all - they should give a general clue about vibrations and aeroelastic phenomena, and should prevent students of MEiL:

- to call every vibrations „a resonance”,
- to think that any periodic motion is the vibrations,
- to confuse the circular frequency with the frequency,
- to think, that every vibrations of a wing is always „flutter”.

Moreover, every student should:

- have at least a basic knowledge about physical reasons of vibrations,
- be able to determine basic features of vibrations, e.g., frequency,
- know what are the eigenfrequencies and eigenmodes,
- know what are the resonance tests and why they have to be performed,
- be familiar with the basic aeroelastic phenomena,
- know why they are so dangerous and how to prevent them,
- learn the basic mathematical methods used in vibration and aeroelastic analysis.

Vibrations and aeroelasticity

Timetable

1 Introduction

2 Vibrations

- 2.1 Vibrations of single-degree of freedom systems.
- 2.2 Parametric, self-excited and random vibrations.
- 2.3 Vibrations of multi-degree of freedom systems.
- 2.4 Vibrations of continuous systems (beams, plates, sound).
- 2.5 Vibrations of aerospace structures.

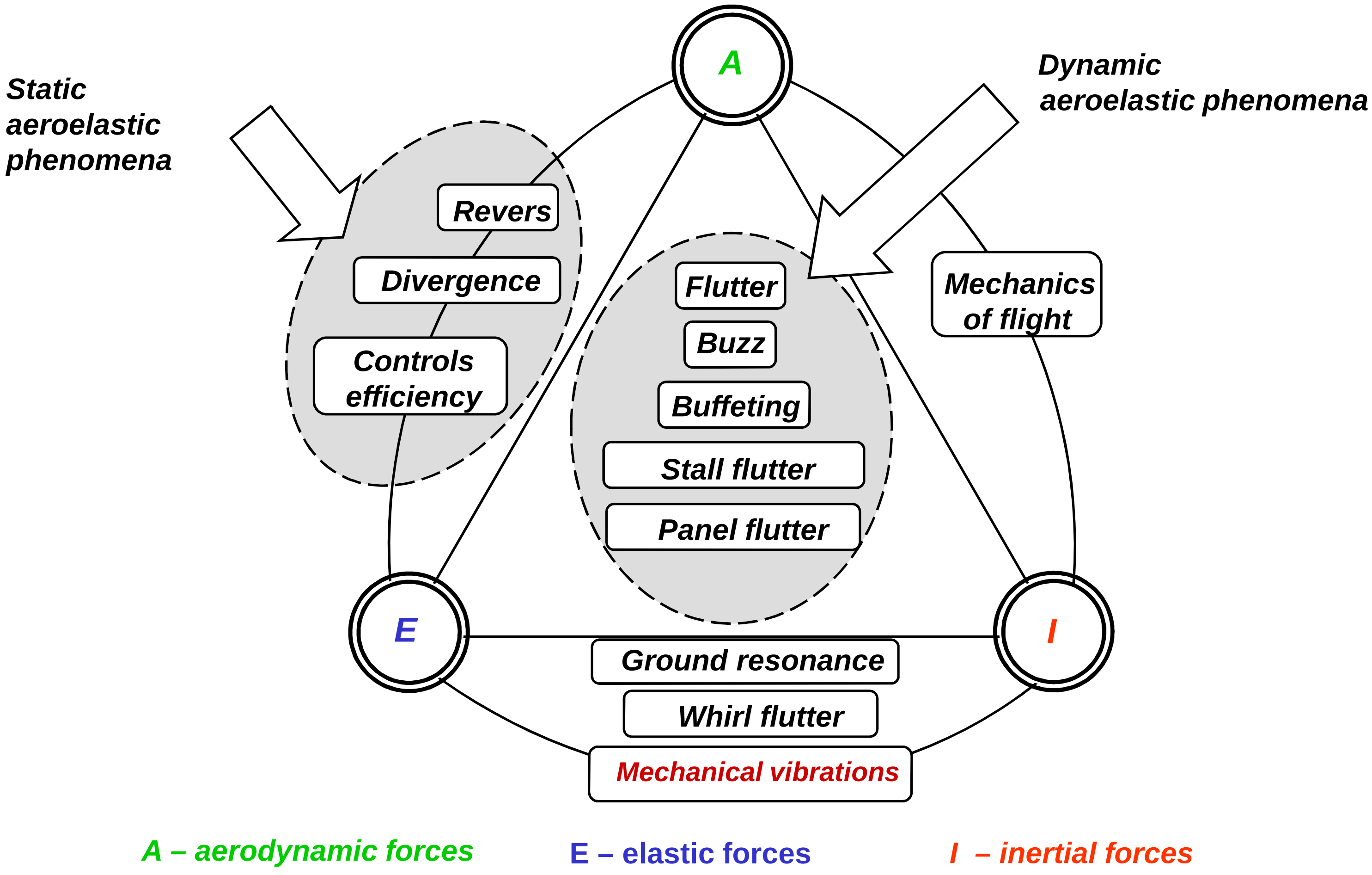
3 Unsteady aerodynamics

- 3.1 Unsteady loadings. Flutter coefficients.
- 3.2 Rapid maneuvers and gust response.
- 3.3 Panel methods.

4 Aeroelasticity

- 4.1 Static aeroelastic phenomena (divergence and revers).
- 4.2 Dynamic aeroelastic phenomena (flutter).
- 4.3 Complex aeroelastic problems
  (buzz, buffeting, whirl flutter, panel flutter).
- 4.3 Aeroelasticity of helicopters.
- 4.4 Aeroelasticity in the aviation's regulations.
- 4.5 Aeroelasticity in the practical engineering.

Vibrations and aeroelastic phenomena



The Collar's triangle

Bibliography

[Hartog] Den Hartog, J.P.; ***Mechanical vibrations***, McGraw-Hill, NY, 1956. (Republished, Dover Publ., 2001)

[Meir] Meirovitch, L.; ***Fundamentals of vibrations***, McGraw-Hill, NY, 1986.

[ArPieSz] Arczewski, K., Pietrucha, J. Szuster, J.T.; ***Drgania układów fizycznych***, Oficyna Wydawnicza PW, Warszawa, 2008.

[Osiński] Osiński, J.; ***Teoria drgań***, PWN, Warszawa, 1978.

[Awrej] Awrejcewicz, J.; ***Drgania deterministyczne ukłaów dyskretnych***, WNT, Warszawa, 1996.

[Leyko] Leyko, J.; ***Mechanika ogólna***, t.2, PWN, Warszawa, 2004.

[GutSw] Gutowski, R., Świetlicki, W.A.; ***Dynamika i drgania układów mechanicznych***, PWN, Warszawa, 1986.

[Kaliski] Kaliski, S. (red.); ***Drgania i fale***, PWN, Warszawa, 1986.

[CoulJef] Coulson, C.A., Jeffrey, A.; ***Fale. Modele matematyczne***, WNT, Warszawa, 1982.

Bibliography

[BAH] Bisplinghof, R.L., Ashley, H., Halfman, R.L.; ***Aeroelasticity***, Addison-Wesley, Cambridge, Mass. 1955. („Bible of Aeroelasticians”)

[BA] Bisplinghof, R.L., Ashley, H.; ***Principles of Aeroelasticity***, John Wiley, New York, 1962.

[Dowell] Dowell, E.H., Curtiss, H.C., Scanlan, R.H., Sisto, F.; ***A modern course in aeroelasticity***, Sijthof & Noordhoff, Alpen aan den Rijn, 2004.

[Balak] Balakrishnan, A.V.; ***Aeroelasticity***, Springer, New York, 2012.

[WriCo] Wright, J.R., Cooper, J.E.; ***Introduction to aircraft aeroelasticity and loads***, Wiley, 2007

[Hodges] Hodges, D.H., Pierce, G.A.; ***Introduction to structural dynamics and aeroelasticity***, Cambridge, NY, 2012

[ScRo] Scanlan, R.H., Rosenbaum R.; ***Drgania i flatter samolotów***, PWN, Warszawa, 1964.

[Pietrucha] Pietrucha, J.P.; ***Flatter - wstęp do teorii aerosprężystości***, NIT, 1(8), 2005

Bibliography

Some basic Journals

Journal of Sound and Vibrations	(av. in WUT Library)
AIAA Journal	(av. in MEiL Library)
Journal of Aircraft	(av. in MEiL Library)

VIBRATIONS

WHAT ARE VIBRATIONS ?

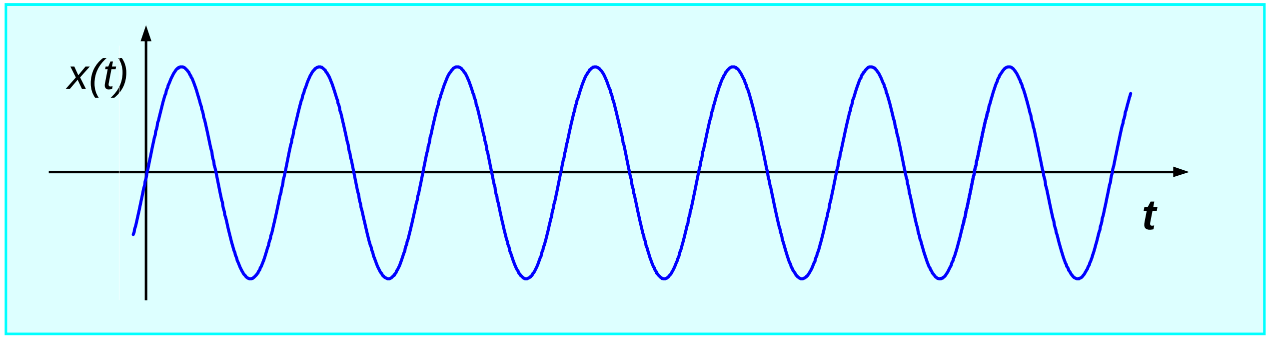
What are vibrations?

There is no unique definition of vibrations.

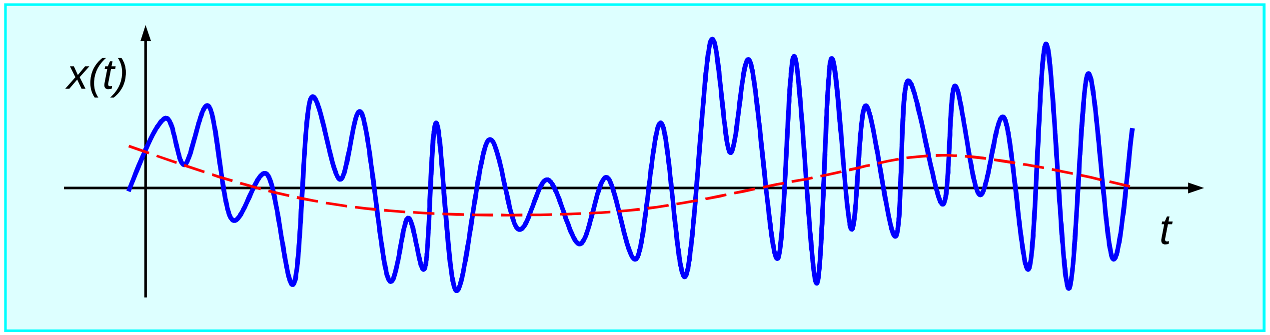
„Vibrations, as they are, everyone can see...”

A descriptive definition (according to *J. Osiński „Teoria drgań”*)

Vibrations are the oscillations of certain physical quantity around some mean value (that may vary in time)



Regular vibrations (periodic, harmonic)



Irregular vibrations (nonperiodic, chaotic)

What are vibrations?

Examples of vibrations:

- motion of a pendulum,
- vibrations of wings, rotor blades, windmills,
- motions of some machines or their elements,
- waving of buildings,
- tidal waves,
- sound (vibrations of the air),
- current and voltage in a resonant circuit,
- electromagnetic waves,
- thermal vibrations of atoms in crystals,
- pulsations of some types of stars,
- ... and many other.

What are vibrations?

But ... caution!

Not every oscillations are the vibrations!

Examples of oscillations that are not physical vibrations:

- periodic relaxations of some systems,
- motion of the piston in the engine,
- motion of the tennis ball,
- motion of bus between the extreme bus-stops,
- annual changes of temperature of the air,
- oscillations of the stock's exchanges...

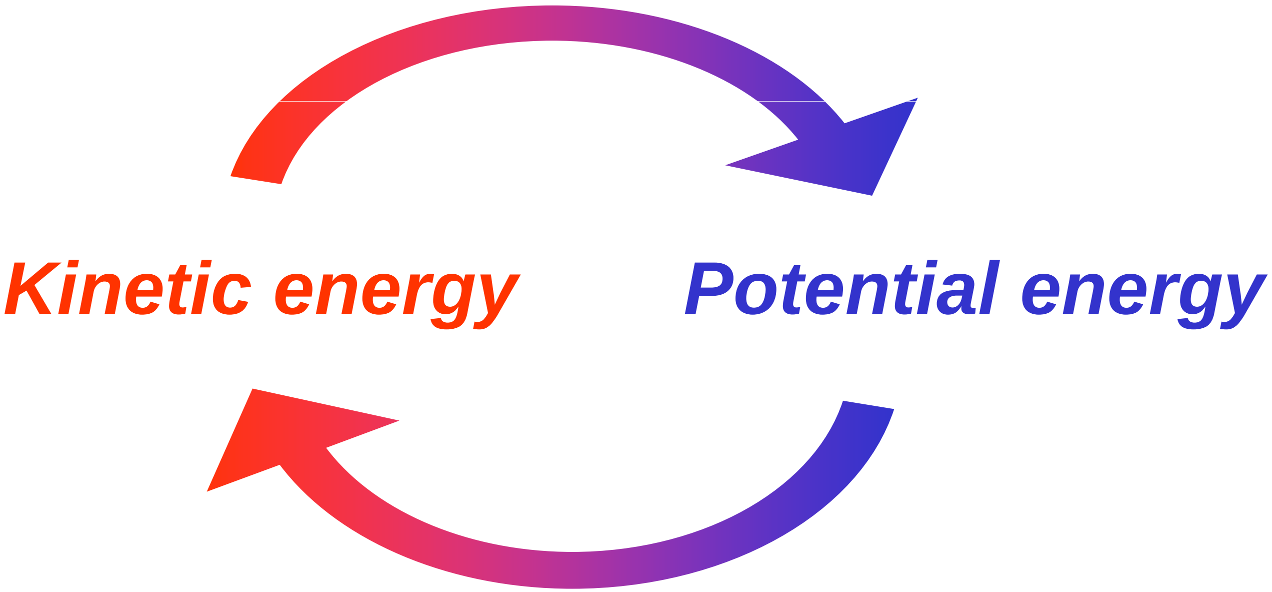
When oscillations are really the physical vibrations?

What are vibrations?

The physical mechanism of vibrations -
periodic exchange of the two forms of the energy of the system

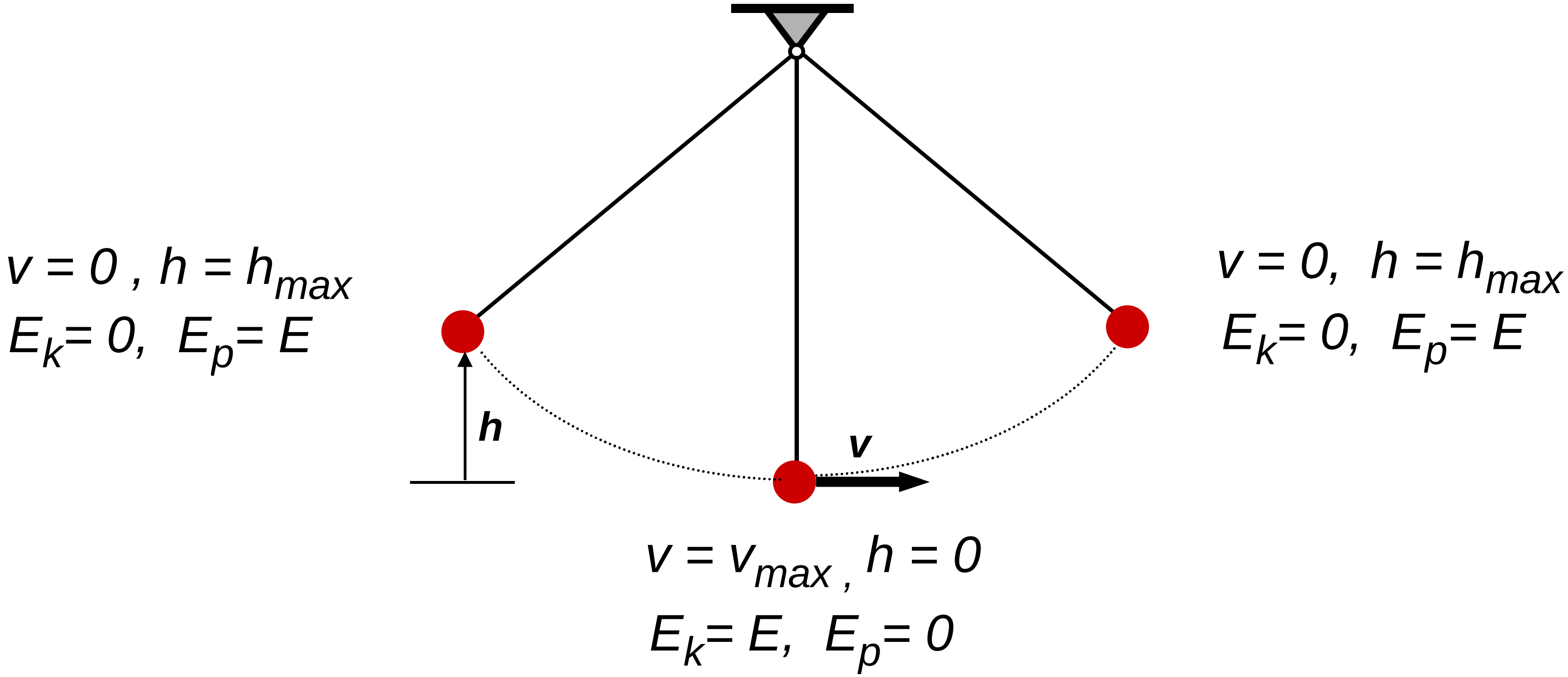
Kinetic energy $E_k = {}^1/_2\, mv^2$

Potential energy $E_p = mgh$



What are vibrations?

The physical mechanism of vibrations - periodic change of the two forms of the energy of the system



What are vibrations?

What physical features determine vibrations?

- **energy storage,**
- **inertia**

Explanation the roles of both features

- Energy storage (e.g., tension of the spring, deflection of the pendulum) is necessary to **start** the motion.
- Inertia is necessary for **keeping** the motion.
- If there wasn't inertia, the elastic force would move object to the neutral position (where the elastic force disappears).
- The inertia causes, however, that the motion of the object does not stop in the neutral position - the object moves further on, despite the absence of the elastic force there.
- As a consequence, the motion lasts until the increasing elastic force will stop the object.
- The state of the system is then the same as it was at the beginning, and the entire cycle repeats.

What are vibrations?

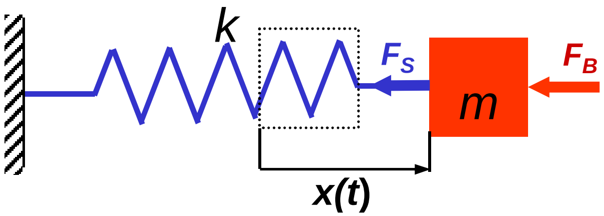
Examples:

Vibrations	*Inertia*	*Energy storage*
Pendulum	pendulum mass	position (gravity)
Mass on a spring	mass	stiffness of a spring
Vibrating beam	mass of a beam	stiffness of a beam
Sound	air density	air compressibility
Tidal waves	water mass	accumulation of water
Resonant circuit	inductance	electric capacity
Vibrations of a crystal	masses of atoms	electrostatic forces

What are vibrations?

Examples of inertial and elastic forces

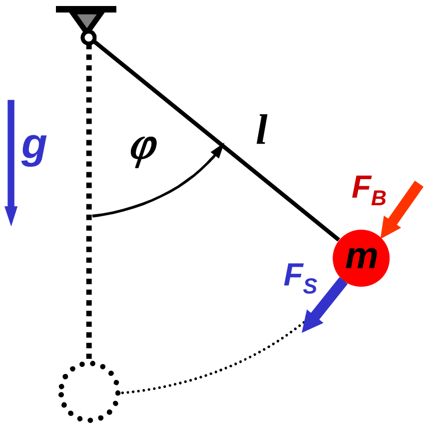
1. Mass on a spring



$$F_S = -kx$$

$$F_B = -m\ddot{x}$$

2. Mathematic pendulum



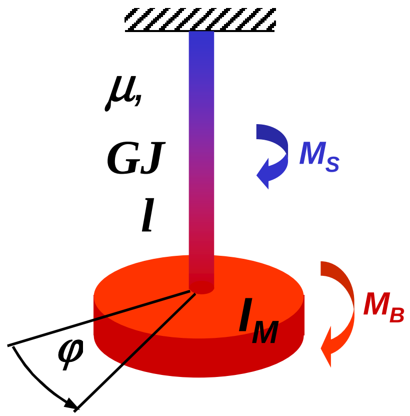
$$F_B = -ml\ddot{\varphi}$$

$$F_S = -mgl\sin\varphi$$

What are vibrations?

Examples of inertial and elastic forces

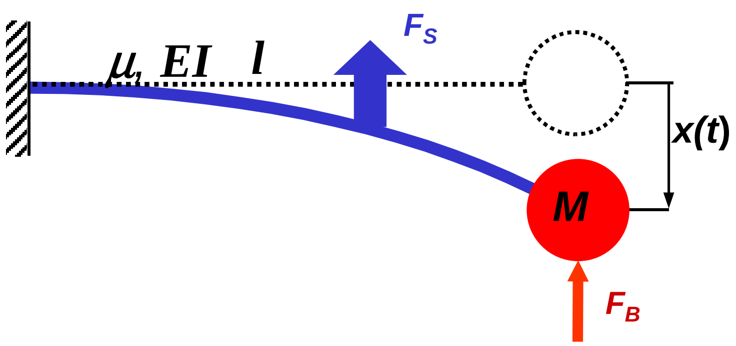
3. Torsional pendulum



$$M_S = -\frac{GJ}{l}\varphi$$

$$M_B = -I_{red}(I_M, \mu, l)\ddot{\varphi}$$

4. Bending beam



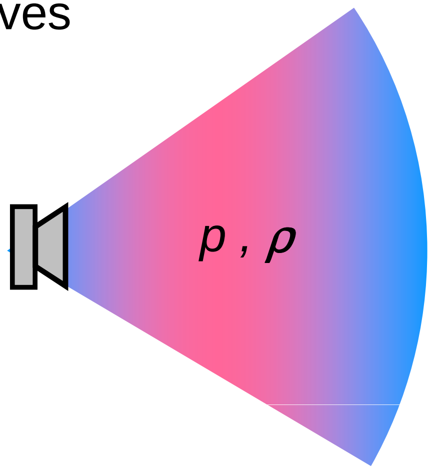
$$F_S = -\frac{3EI}{l^3}x$$

$$F_B = -m_{red}(M, \mu, l)\ddot{x}$$

What are vibrations?

Examples of inertial and elastic forces

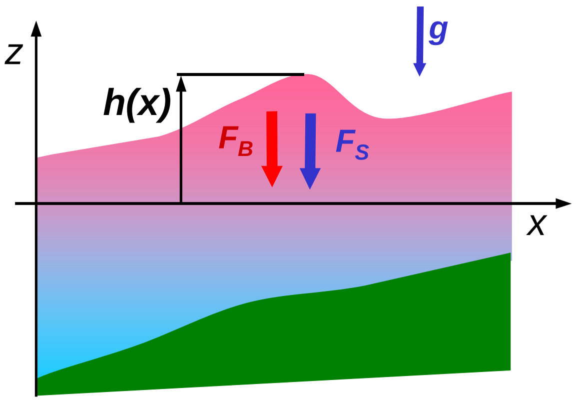
5. Sound waves



$$F_S = -\nabla^2 p$$

$$F_B = -\frac{1}{c^2}\frac{\partial^2 p}{\partial t^2}$$

6. Tidal waves



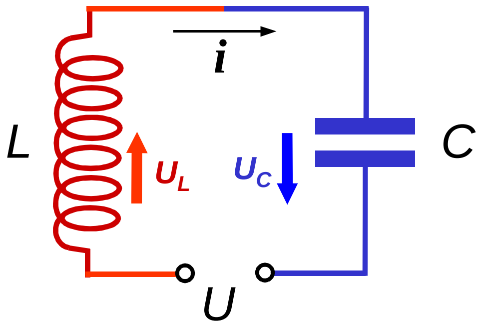
$$F_S = -g\frac{\partial^2 h}{\partial x^2}$$

$$F_B = -\rho\frac{\partial^2 h}{\partial t^2}$$

What are vibrations?

Examples of inertial and elastic forces

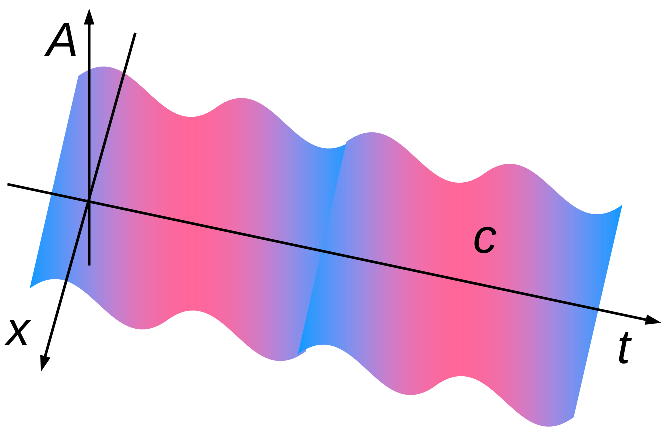
7. Resonant circuit



$$U_L = L\ddot{Q} \qquad (F_B)$$

$$U_C = \frac{1}{C} Q \qquad (F_S)$$

8. Electromagnetic waves



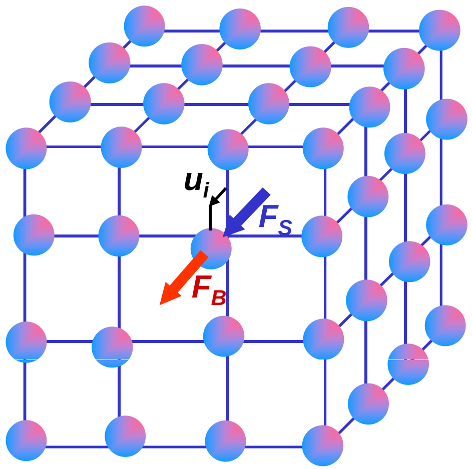
$$F_S \Rightarrow \frac{\partial^2 A}{\partial x^2}$$

$$F_B \Rightarrow \frac{1}{c^2} \frac{\partial^2 A}{\partial t^2}$$

What are vibrations?

Examples of inertial and elastic forces

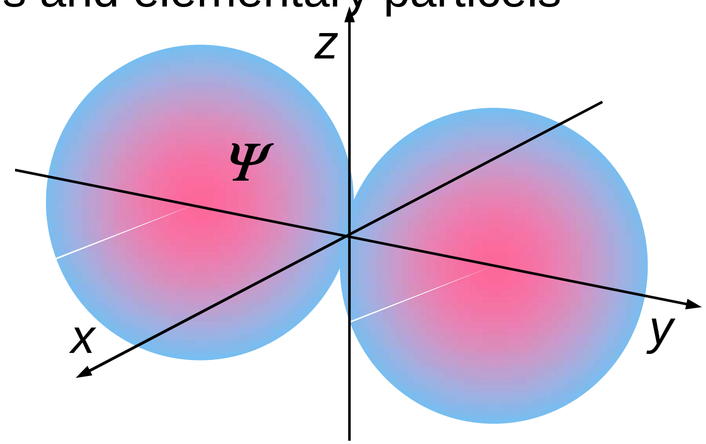
9. Vibrations of atoms in the crystal



$$F_S = -\sum_{j=1}^{j=n} \Phi_{ij}^{AB} u_j^B$$

$$F_B = -m_i \ddot{u}_i^A$$

10. Atoms and elementary particels



$$F_S \Rightarrow \nabla^2 \Psi$$

$$F_B \Rightarrow i\hbar \frac{\partial^2 \Psi}{\partial t^2}$$