

## OSCILLATIONS OF A HANGING CHAIN

SPRING SEMESTER 2017

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**Equation of motion:** Consider a uniform flexible chain (or heavy rope) of length  $L$ , fixed at the upper end and free at the lower end (see Fig. 1). We let the  $x$  axis be vertical, measured up from the equilibrium position of the free end of the chain.  $Y(x, t)$  is the horizontal displacement of the chain at the point with the vertical coordinate  $x$  at time  $t$ .

We assume that  $Y(x, t)$  is small compared to  $L$ . Therefore we do not need to consider the difference between distances measured along the chain and distances measured along the  $x$  axis, i.e. we can neglect the terms  $\sqrt{x^2 + Y^2} - x \sim \frac{Y^2}{x}$ . For the same reason we can neglect the vertical displacement due to oscillations. We also assume that the angle  $\alpha(x)$  between the local direction of the chain and  $X$  axis is small, thus

$$\sin \alpha \approx \tan \alpha = \frac{\partial Y}{\partial x}. \quad (1)$$

The horizontal component of the net force acting on a segment of the chain of length  $\Delta x$  due to the internal tension  $T(x)$  is (see Fig. 2):

$$T(x + \Delta x) \frac{\partial Y(x + \Delta x)}{\partial x} - T(x) \frac{\partial Y(x)}{\partial x} \approx \frac{\partial}{\partial x} \left( T(x) \frac{\partial Y}{\partial x} \right) \Delta x \quad (2)$$

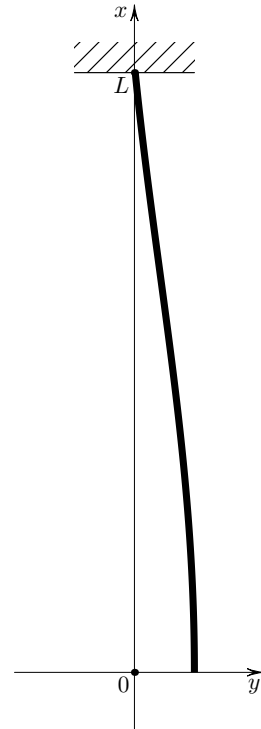


Figure 1: Hanging chain (sketched in bold) and the coordinate axis.

Newton's second law gives the following equation of motion:

$$\frac{\partial}{\partial x} \left( T(x) \frac{\partial Y}{\partial x} \right) \Delta x = \rho \Delta x \frac{\partial^2 Y}{\partial t^2}, \quad (3)$$

where  $\rho$  is the chain's linear density (mass per unit length),  $\rho \Delta x$  is the mass of the segment, and  $\frac{\partial^2 Y}{\partial t^2}$  is its acceleration. Cancelling common factor  $\Delta x$  in both sides of Eq. (3), we obtain:

$$\frac{\partial}{\partial x} \left( T(x) \frac{\partial Y}{\partial x} \right) = \rho \frac{\partial^2 Y}{\partial t^2}. \quad (4)$$

For small oscillations of the chain, when we can neglect the vertical displacement due to oscillations, the tension  $T(x)$  is the same as for the chain at rest, i.e. the tension at the point with the vertical coordinate  $x$  equals to the weight of the part of the chain below  $x$ . Therefore,

$$T = \rho g x, \quad (5)$$

where  $g$  is the acceleration of gravity.

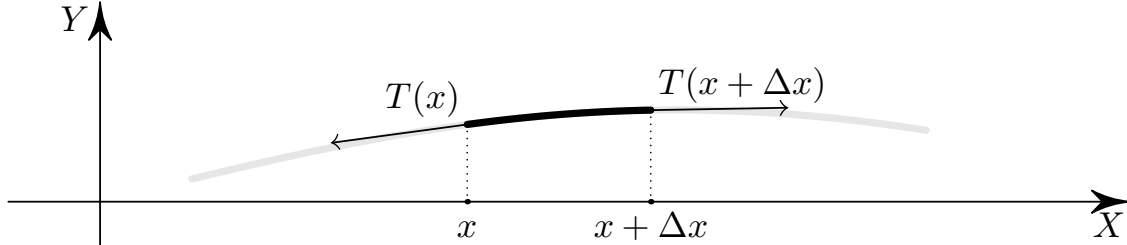


Figure 2: Forces acting on the element of the chain.

The chain is fixed at the top, therefore

$$Y(0, t) = 0. \quad (6)$$

The displacement of the bottom of the chain remain finite at all times, thus

$$|Y(L, t)| < \infty. \quad (7)$$

**Separation of variables:** We solve the partial differential equation Eq. (3) with the boundary conditions Eqs. (6),(7) separating variables, i.e. assuming that

$$Y(x, t) = y(x) u(t). \quad (8)$$

Substituting Eq. (8) into Eq. (4), we obtain:

$$u(t) \frac{d}{dx} \left( T(x) \frac{dy}{dx} \right) = \rho y(x) \frac{d^2 u}{dt^2}, \quad (9)$$

or,

$$\frac{1}{y(x)} \frac{d}{dx} \left( T(x) \frac{dy}{dx} \right) = \rho \frac{1}{u(t)} \frac{d^2 u}{dt^2}. \quad (10)$$

The right hand side of Eq. (10) is a function of time  $t$ . The left hand side is a function of  $x$ . The two sides can be equal at all times and coordinates only if they both are equal to the same constant.

As we see shortly, this constant must be real and negative. Indeed, the mechanical system described by Eq. (3) is conservative. Therefore,  $u(t)$  cannot grow without a limit or decay to zero. The permissible solutions are only possible for real negative separation constants.

Denoting the constant by  $-\omega^2$ , we get the following equations:

$$\frac{1}{u(t)} \frac{d^2 u}{dt^2} = -\omega^2, \quad (11)$$

$$\frac{1}{y(x)} \frac{d}{dx} \left( T(x) \frac{dy}{dx} \right) = -\rho \omega^2. \quad (12)$$

Equation Eq. (11) can be easily solved:

$$\frac{d^2 u}{dt^2} + \omega^2 u(t) = 0, \quad (13)$$

and

$$u(t) = \text{Re} \left( C_0 e^{i\omega t} \right) = A \cos(\omega t) + B \sin(\omega t), \quad (14)$$

where  $A$  and  $B$  are real, and  $C$  is a complex integration constants. We see that  $\omega$  is the frequency of the chain's oscillations.

The equation for the amplitude of the oscillations,  $y(x)$ , is:

$$\frac{d}{dx} \left( T(x) \frac{dy}{dx} \right) + \rho \omega^2 y(x) = 0. \quad (15)$$

Using the expression for the chain tension, Eq. (5), we obtain:

$$xy'' + y' + \frac{\omega^2}{g} y = 0. \quad (16)$$

The boundary conditions for Eq. (16) are

$$y(0) = 0, \quad |y(L)| < \infty. \quad (17)$$

**Assignment:**

1. Write Eq. (16) in dimensionless form.
2. Solve it using the Laplace method for ODEs.
3. Use the method of stationary phase to find the zeroes of the solution.
4. Find the analytical expression for the chain frequencies.
5. Compare your result for the lowest frequency with the actual frequency of the sample chain. It is a part of the assignment to measure the characteristics of the chain that you need.