ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

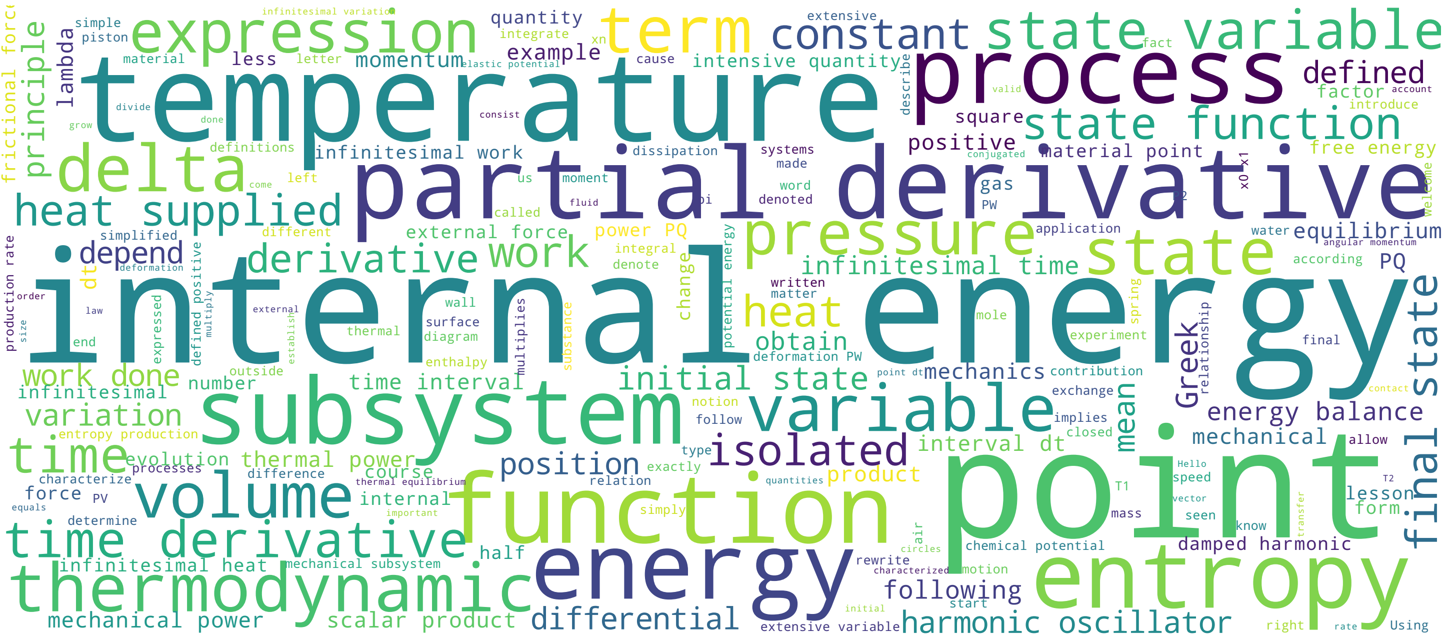
RESCIF Réseau d'excellence des sciences de l'ingénieur de la Francophonie

Thermodynamique

Travail, chaleur et oscillateur harmonique amorti

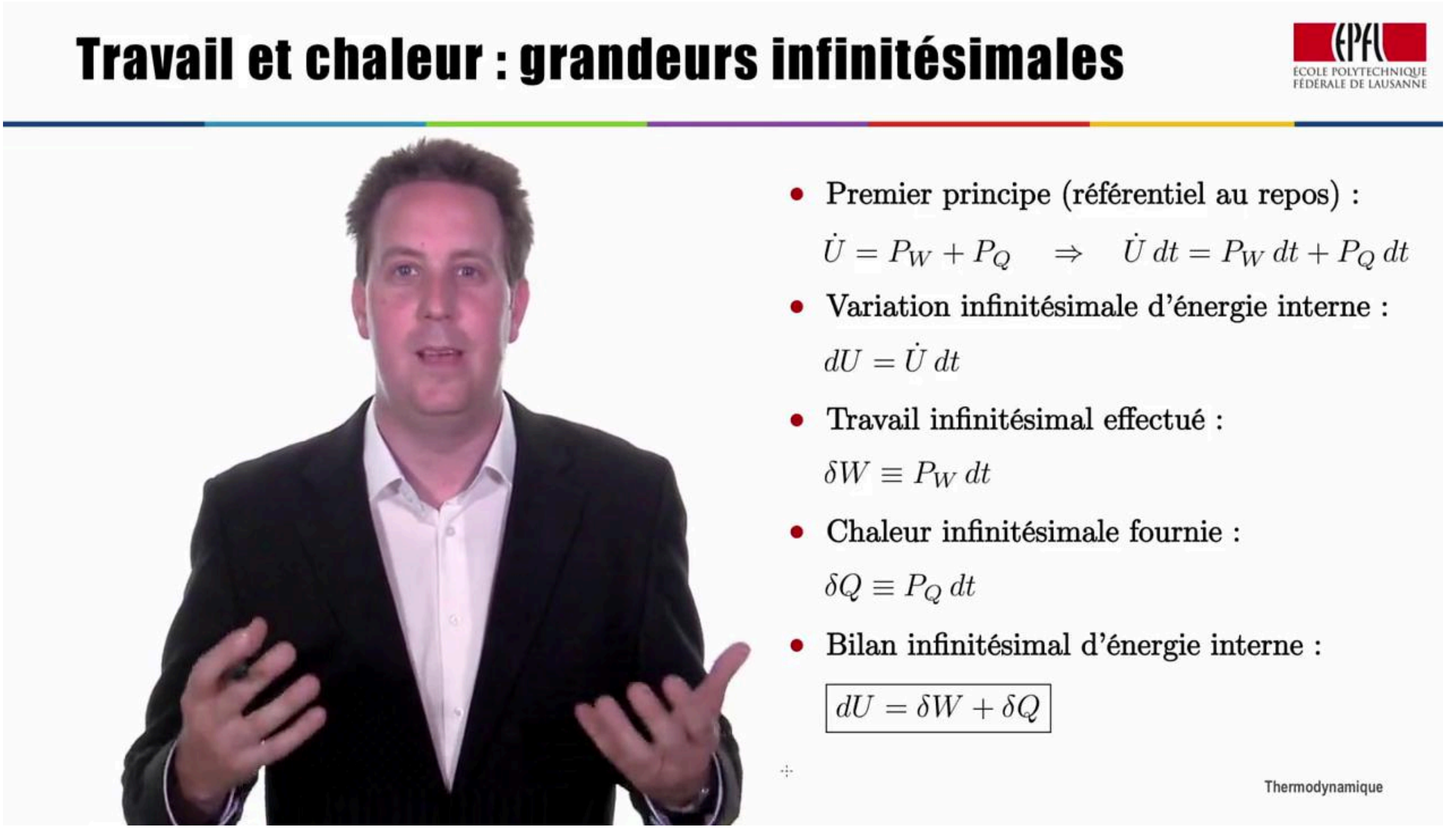
Dr. Sylvain Bréchet

James Prescott Joule, 1818 - 1889



Video

EPFL

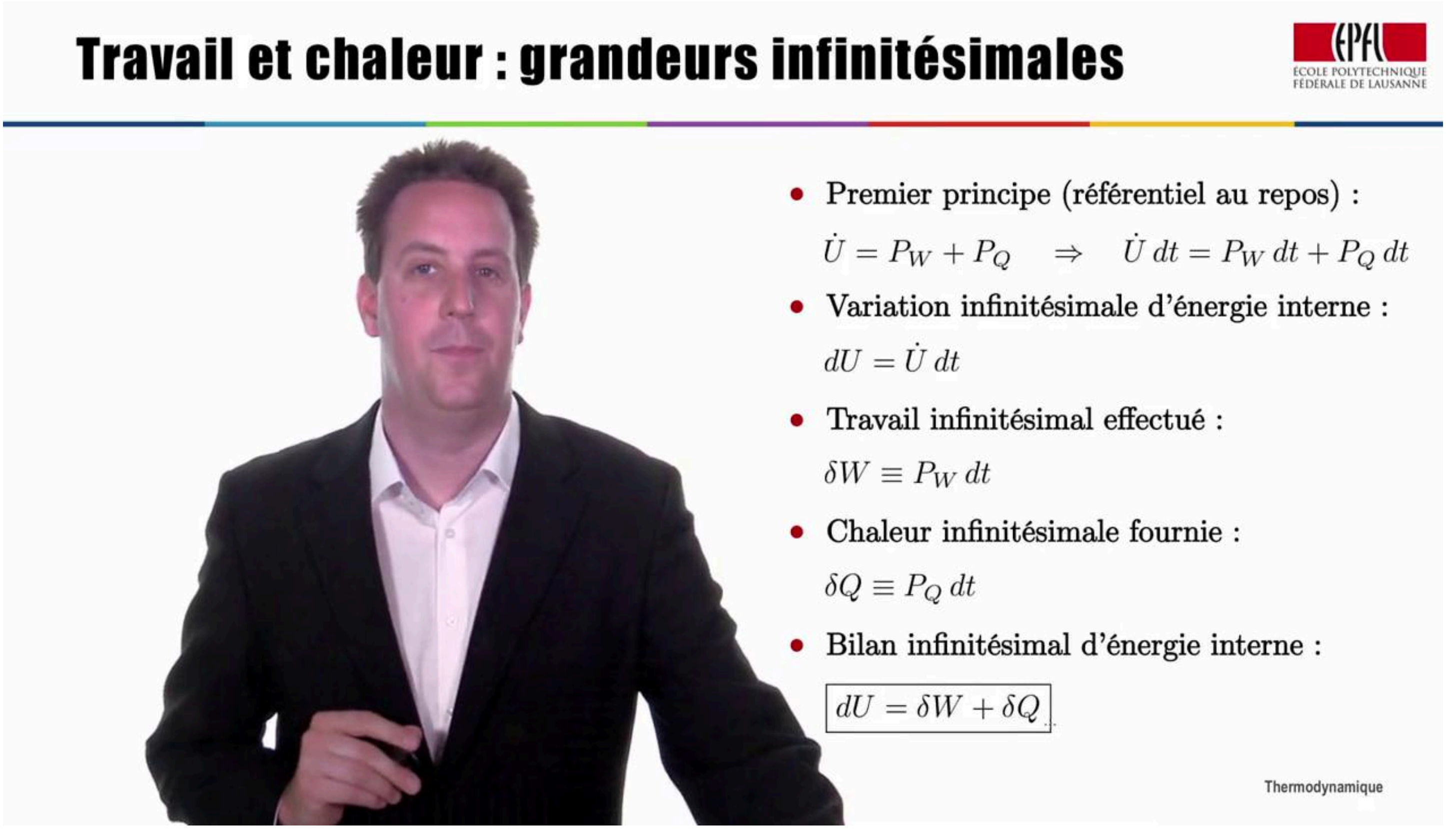


Hello and welcome to this word of thermodynamics. In this lesson, we will define the fundamental concepts in thermodynamics that are work, heat and internal energy. We will see that the internal energy is a state function. We will then establish an internal energy balance. And finally, we will consider an example of the application of everything we have seen so far, which is the damped harmonic oscillator in a fluid. We will consider it in a thermodynamic approach. So let's start with work and heat and we will define the infinitesimal quantities of work and heat. For this, we will base ourselves on the first principle expressed in the reference frame where the system is at rest. In this repository. The first principle tells us the following about the derivative with respect to time of the internal energy of the point is the sum of two powers the mechanical power of deformation PW and the thermal power P. We can now multiply this relation by an infinitesimal time interval dt. There was thus point dt equal pw dt plus pq dt. We can define the infinitesimal variation of internal energy. It is a differential. This is the beginning of hubs. Can also be written as u on dt, x, dt, d, u on dt c eight point.

Notes

Summary

0m 05s



And so d u is written as a point dt. We can now introduce the work infinitesimal carried out on the system which we will denote delta W. The letter W comes from the German work or English work, and the delta symbol means that it is not a differential. The infinitesimal work done on the delta system W is defined as the product of the mechanical power of deformation and w times the infinitesimal time interval dt. In a similar way, we can define the infinitesimal heat supplied to the system. It is denoted delta q. The Q refers to the German Cayley, which means source in French, heat source, and the delta means that the heat infinitesimal is not a differential. We define this infinitesimal heat supplied to the delta Q system as the product of the thermal power PQ for the infinitesimal time interval DT. With these three definitions, we can now rewrite the expression of the first principle multiplied by the infinitesimal time dt. And we obtain the infinitesimal internal energy balance. Who says that the differential of the internal energy of U and the sum of the infinitesimal work done on the delta system W and the infinitesimal heat supplied to the delta system Q.

Notes

Summary

1m 51s

Travail et chaleur

- Bilan infinitésimal d'énergie interne :

  $dU = \delta W + \delta Q$

- Processus : (état initial « i » $\rightarrow$ final « f »)
  - Variation d'énergie interne :

    $$\Delta U_{if} = \int_{U_i}^{U_f} dU = U_f - U_i$$

  - Travail effectué :

    $$W_{if} = \int_i^f \delta W = \int_{t_i}^{t_f} P_W \, dt$$

  - Chaleur fournie :

    $$Q_{if} = \int_i^f \delta Q = \int_{t_i}^{t_f} P_Q \, dt$$

- Bilan d'énergie interne : $\boxed{\Delta U_{if} = W_{if} + Q_{if}}$

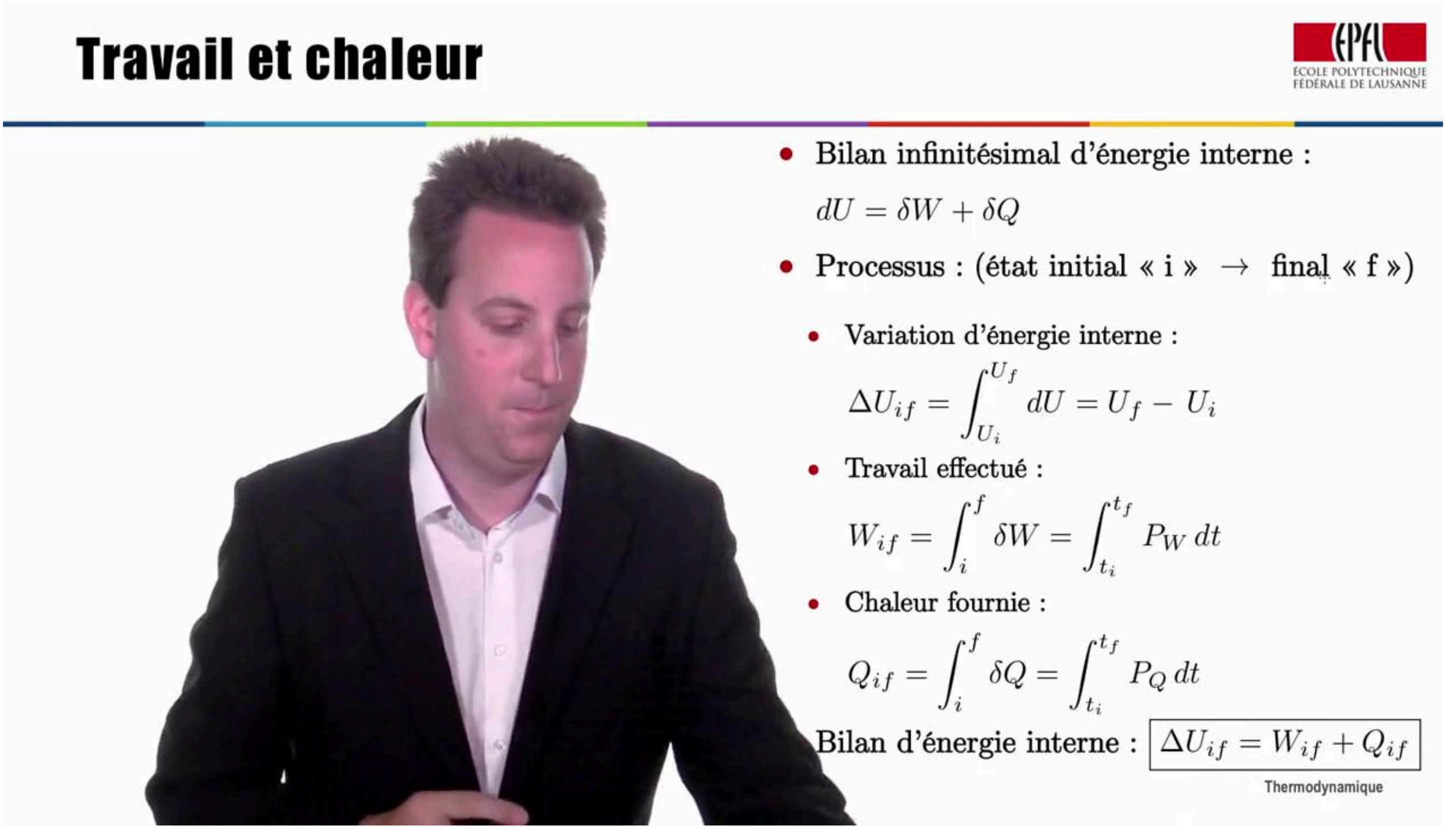
Thermodynamique

We will now determine the work and the heat. For a process that is not necessarily an infinitesimal process, for any process that goes from the initial state Y. In the final state. F. To obtain this work and this heat, we will have to integrate the balance equation infinitesimal internal energy from the initial state I to the final state. F. Let's start with the internal energy variation between these two states. We have Delta U and F grades. It is the integral of the differential of the internal energy d u and therefore it will simply be equal to the final internal energy of F. the initial internal energy U. The work that is done during this process is denoted w. F. It is equal to the integral of the initial state. I in the final state. F of the infinitesimal work done on the Delta W system. This infinitesimal work has been defined previously, it is equal to the product of the mechanical power of deformation PW for the infinitesimal time interval dt. We can now define the heat supplied to the system. During this process, it is denoted. Q y. F. It is the integral from the initial state to the final state. F The infinitesimal heat supplied to the Delta system. Q.

Notes

Summary

3m 41s



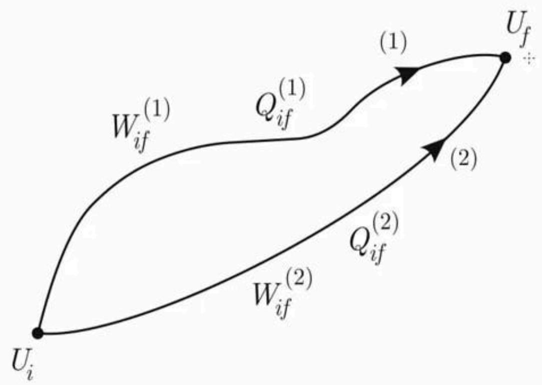
Which has been defined as the product of the thermal power PQ for the infinitesimal time interval DT that we integrate from the initial country time to the final time TF. Using these three definitions. We are now able to announce the internal energy balance during the process from the initial state I to the final state. This internal energy balance was announced as follows the variation of internal energy of the system during this process Delta U and F is equal to the sum of the work done w f and the heat supplied q i f.

Notes

Summary

5m 24s

Energie interne : fonction d'état



- Processus : (état initial « i » $\rightarrow$ final « f »)
  - Variation d'énergie interne : $\Delta U_{if} = U_f - U_i$
  - Travail effectué : $W_{if}^{(1)} \neq W_{if}^{(2)}$
  - Chaleur fournie : $Q_{if}^{(1)} \neq Q_{if}^{(2)}$

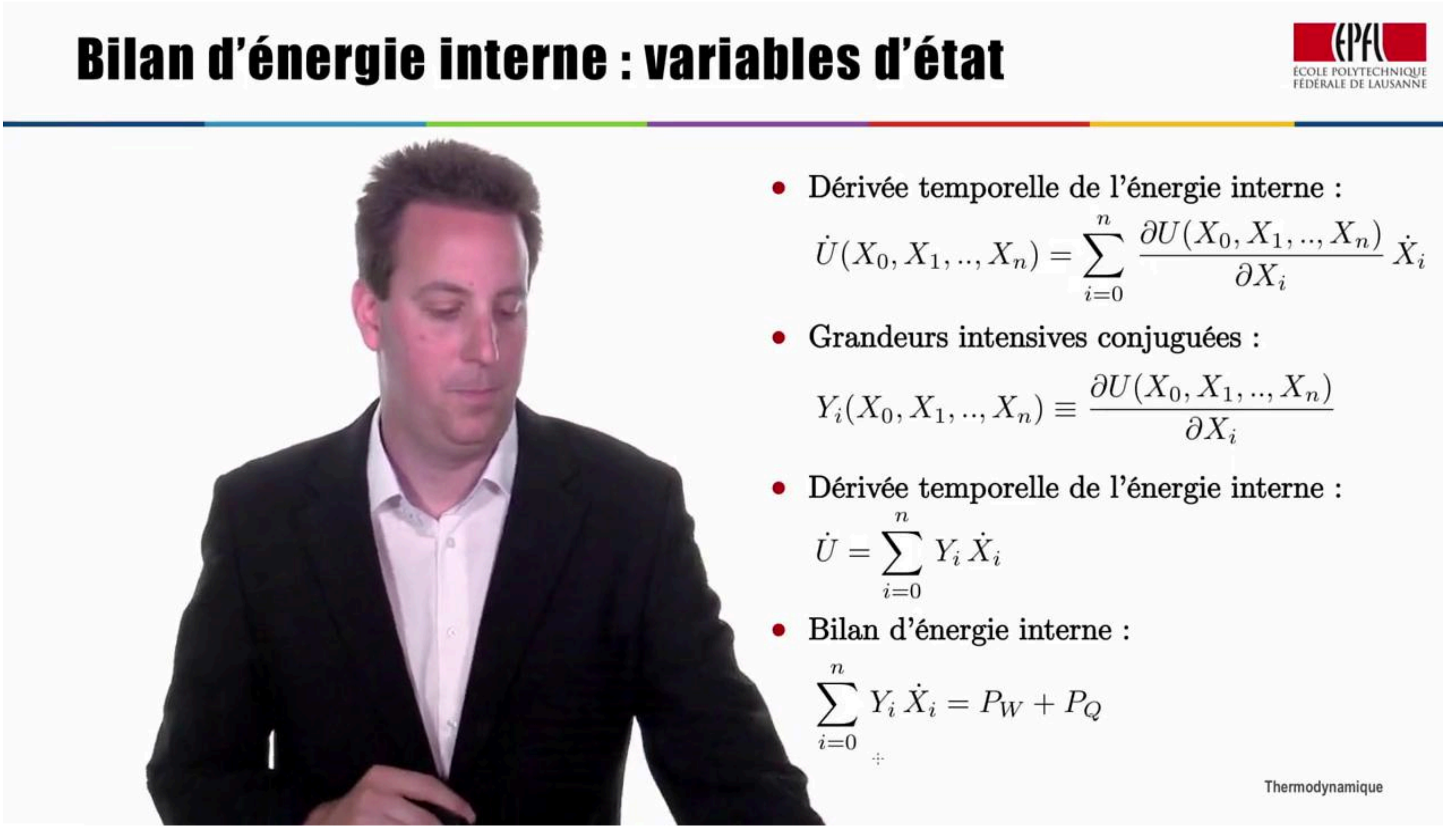
Thermodynamique

Internal energy is a state function, unlike work and heat. To understand it, we will consider two processes that go from an initial state i to a final state f. The variation of internal energy during these processes. Delta I F depends only on the final state f and the initial state. Seven. the internal energy of the final state. the internal energy of the initial state. Therefore, this variation in energy is independent of the chosen process. Let's take the process. One. Or the process. Two We will have exactly the same variation of internal energy. But it depends only on the state and not on the process. the internal energy is a state function. This is not the case for the work done and the heat supplied. The work done in the first process wj f1. Is usually not the same as the work done during the second process. W. FSI. Two. We have exactly the same observation for the heat supplied by the heat supplied during the first process. QF1 is generally not the same as the heat supplied during the second process. Q IF two. So the work and the heat depend on the process and not only on the state. Therefore, these sizes are not state functions. This is an important result.

Notes

Summary

6m 14s



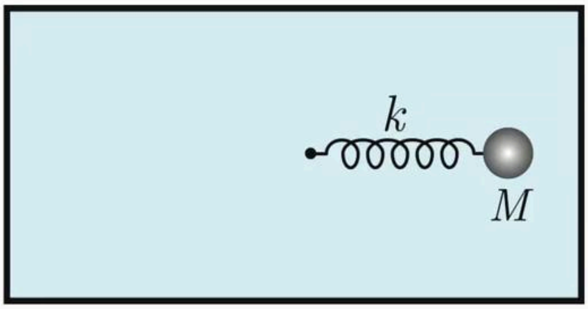
Now we want to determine the internal energy balance. Using the system state variables. So we will explicitly calculate the time derivative of the energy in terms of internal energy, which is a function of the internal variables x0 x1 up to XN. The time derivative of the internal energy is written as the partial derivative of with respect to the variable x x times x y point. Then the sum over all internal variables, i.e. we will sum the undecided from zero to n. We can then introduce intensive quantities that are conjugated to the variable extensive variable delta, the variable y i and the conjugate variable to the variable x y and the functions of all variables of state, i.e. the functions from x0 x1 to xn. It is defined as the partial derivative of u with respect to xj. Using this definition, we can rewrite the time derivative of the internal energy of the point as the sum from zero to n of i there are six points. This allows us to obtain a balance sheet internal energy which is expressed as a function of the state variables of the system. It is the sum from zero to n of i y x y point which is equal to BW plus PQ.

Notes

Summary

8m 06s

Oscillateur harmonique amorti : système isolé



- Variables d'état : $\{\,\boldsymbol{P},\,\boldsymbol{r},\,X_0\,\}$
- Energie (cinétique + interne) :

$$E(\boldsymbol{P},\boldsymbol{r},X_0) = \frac{\boldsymbol{P}^2}{2M} + U(\boldsymbol{r},X_0)$$

- Energie interne (pot. élastique + autre) :

$$U(\boldsymbol{r},X_0) = \Phi\,(\boldsymbol{r}) + U(\boldsymbol{0},X_0)$$

$$\Phi\,(\boldsymbol{r}) = \frac{1}{2}\,k\,\boldsymbol{r}^2$$

Thermodynamique

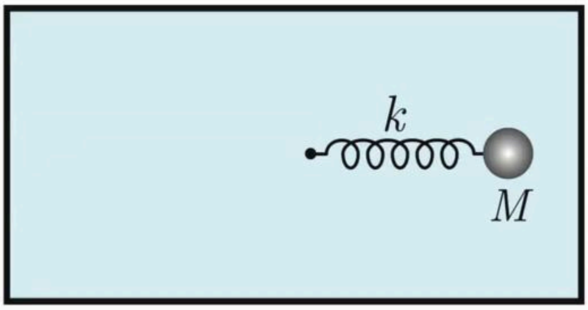
We will now consider an example taken from mechanics and that we will approach in a thermodynamic framework. This is the damped harmonic oscillator. This damped harmonic oscillator consists of a material point of mass M which is attached to a spring of zero empty length and elastic constants K. This harmonic oscillator is located in a viscous fluid. And the whole system is isolated. To describe this system, we must first choose the appropriate state variables. In mechanics, to describe the dynamics of a damped harmonic oscillator, we need two variables. The quantity of motion P and the position R. In mechanics. For a damped harmonic oscillator, the mechanical energy decreases with time. What there is dissipation. Here, the system is isolated, which means that the energy is constant. By application of the first principle. Therefore, there must be another form of energy that will grow in the course of time to compensate for the loss of mechanical energy. This other form of energy will depend on of a variable which is not a variable associated with the motion of the material point. This other extensive variable, whose nature is unknown for the moment and that we will try to identify at the end of this example.

Notes

Summary

9m 48s

Oscillateur harmonique amorti : système isolé



- Variables d'état : $\{\, \boldsymbol{P},\, \boldsymbol{r},\, X_0 \,\}$
- Energie (cinétique + interne) :

$$E(\boldsymbol{P},\boldsymbol{r},X_0) = \frac{\boldsymbol{P}^2}{2M} + U(\boldsymbol{r},X_0)$$

- Energie interne (pot. élastique + autre) :

$$U(\boldsymbol{r},X_0) = \Phi\,(\boldsymbol{r}) + U(\boldsymbol{0},X_0)$$

$$\Phi\,(\boldsymbol{r}) = \frac{1}{2}\,k\,\boldsymbol{r}^2$$

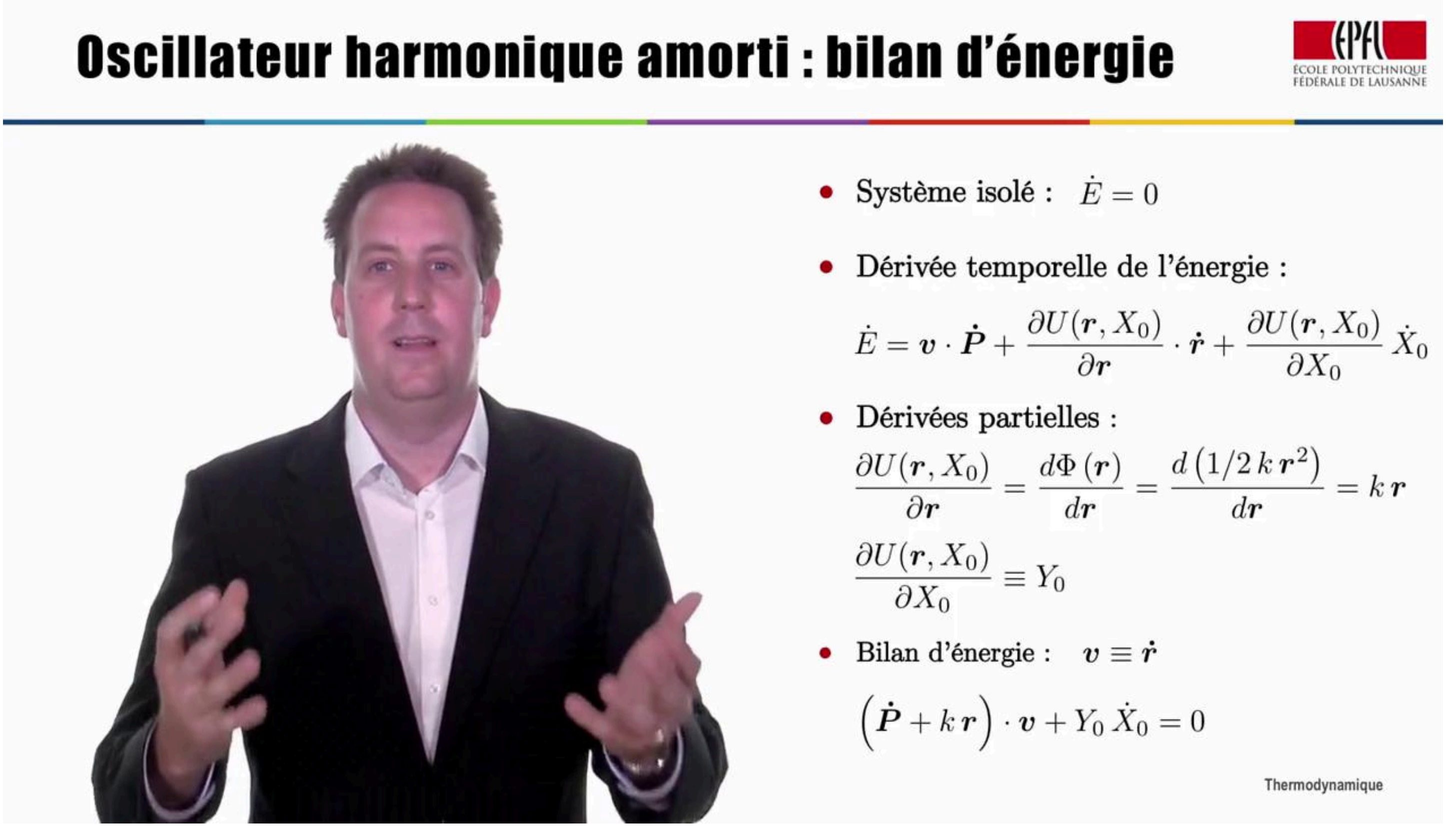
Thermodynamique

It is the variable x zero, we denote it x zero. the Energy of this harmonic oscillator. A state function. Function of the state variables p, r and x0. It consists of two contributions. The first is p squared on two m, it is the kinetic energy. The second is ud RX0, the internal energy. This internal energy is itself composed of two contributions. First, we have a potential energy elastic fi of r which is equal to half of k r square. This is a well known result of mechanics and then we have another contribution that is zero zero. So this contribution depends essentially on this other variable. X zero.

Notes

Summary

11m 24s

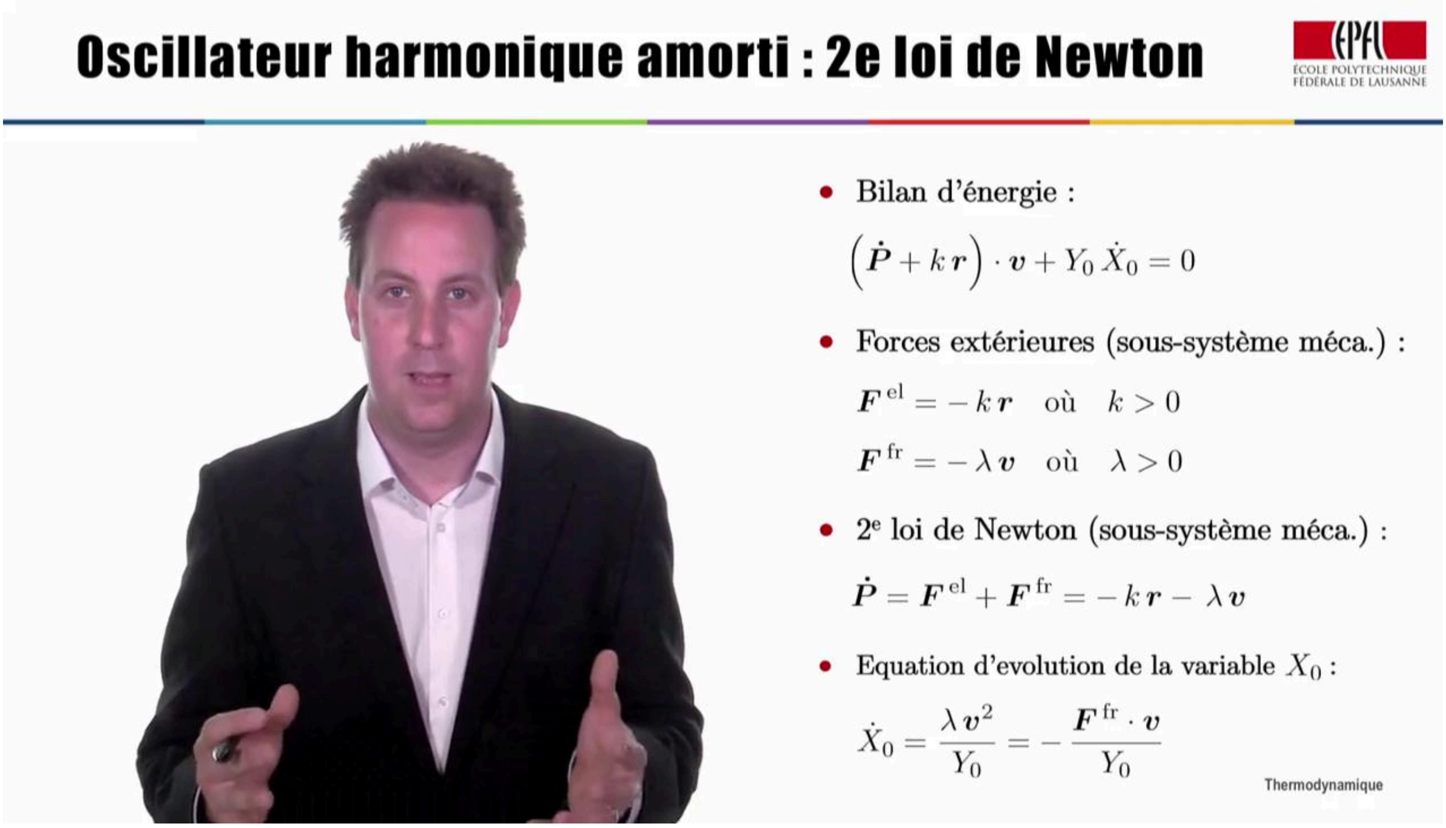


The system being isolated by application of the first principle. Energy is a constant, so the derivative with respect to time of the energy at the point is zero. This time derivative of energy. It can be developed since energy is a state function that depends on of the momentum of the position R and of the variable x0. The point is therefore made up of three terms. The first term is the derivative of the energy with respect to to the momentum, i.e. the velocity scalar product with the derivative with respect to time of the momentum p. The second term. It is the partial derivative of the energy with respect to the position R. Which is equal to the partial derivative of energy internal with respect to the position R scalar product with R. For the third term, it is the partial derivative of the energy with respect to zero which is equal to the partial derivative of internal energy with respect to x0 XX0 point now examined a little more closely. The partial derivatives that appear in this expression of the time derivative of energy. First, the partial derivative of the internal energy with respect to the position is equal to the total derivative. Of the wire elastic potential energy with respect to the position R.

Notes

Summary

12m 19s



Elastic potential energy. It is a half career because you can put the factor one half, the factor K in evidence. We are left with the derivative of R square compared to R which is simply two r the factor one half. The factor two is simplified. It only remains for us to R. And then, according to the writing convention we chose, the intensive quantity I zero and the quantity conjugated to the quantity extensive which is a state variable that is x zero. In addition, by using the fact that the velocity is the temporal derivative of the position. We can rewrite the expression of the time derivative of the energy. Which sucks. Is the system isolated? In the following form. This is p point more scalar. Scalar product with speed plus I0X 0.0. In order to detail this energy balance equation, we must now consider the mechanical subsystem constituted by the material point. This mechanical subsystem is subject to external forces. These external forces are the elastic force k. R or k is positive definite. This is the spring constant of the spring. It is also the viscous frictional force that is of the lambda form. V or lambda is defined positive. We are here in laminar regime.

Notes

Summary

13m 45s

Oscillateur harmonique amorti : 2e loi de Newton

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- Bilan d'énergie :

$$\left(\dot{\boldsymbol{P}} + k\,\boldsymbol{r}\right) \cdot \boldsymbol{v} + Y_0\,\dot{X}_0 = 0$$

- Forces extérieures (sous-système méca.) :

$$\boldsymbol{F}^{\,\mathrm{el}} = -\,k\,\boldsymbol{r} \quad \text{où} \quad k > 0$$

$$\boldsymbol{F}^{\,\mathrm{fr}} = -\,\lambda\,\boldsymbol{v} \quad \text{où} \quad \lambda > 0$$

- 2$^{\mathrm{e}}$ loi de Newton (sous-système méca.) :

$$\dot{\boldsymbol{P}} = \boldsymbol{F}^{\,\mathrm{el}} + \boldsymbol{F}^{\,\mathrm{fr}} = -\,k\,\boldsymbol{r} - \lambda\,\boldsymbol{v}$$

- Equation d'evolution de la variable X_0 :

$$\dot{X}_0 = \frac{\lambda\,\boldsymbol{v}^2}{Y_0} = -\,\frac{\boldsymbol{F}^{\,\mathrm{fr}} \cdot \boldsymbol{v}}{Y_0}$$

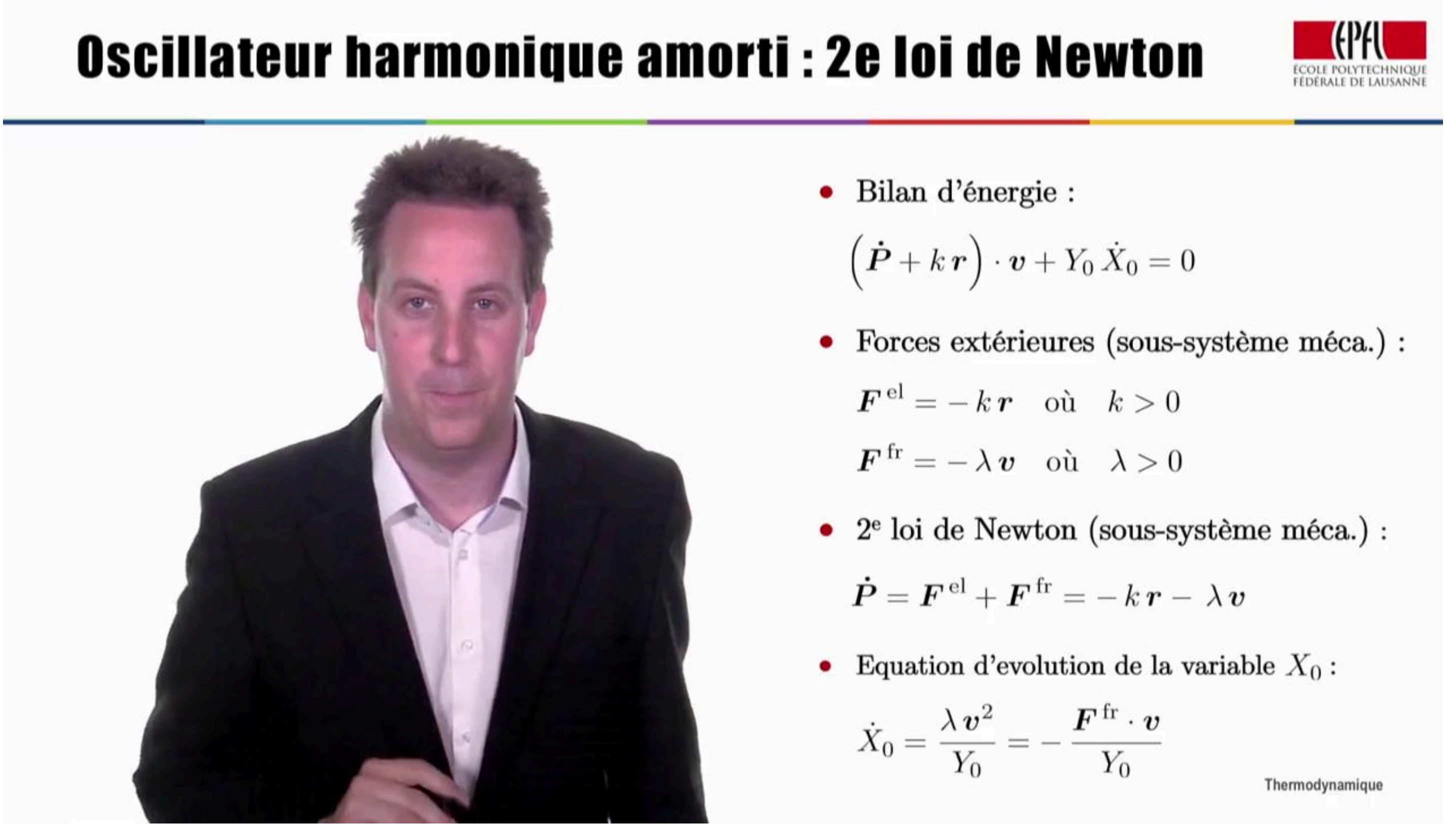
Thermodynamique

It is important to mention that these forces are forces external to the mechanical subsystem, even if they are internal forces of the thermodynamic system. But here, to apply Newton's second law, there is the center of mass theorem applied to a material point. We consider that these forces apply to the mechanical subsystems. They are therefore considered as external forces. Newton's second law says the following. The time derivative of the momentum p points is equal to the sum of the external forces, i.e. the force and the frictional force. We therefore substitute this expression of p point in the expression of the energy balance. The term backwards is simplified with the term in career and it remains us a term in less lamda v. Because this term at least lambda v square, we can pass it in the right member. And then we can divide the equation by i zero and those we get. It is an evolution equation of the variable x zero which is of the form x zero point is equal to lambda v square on i zero. Considering that the frictional force is defined as less high, so we get less the scalar product of the force of friction with the speed divided by i zero of mechanics.

Notes

Summary

15m 26s



We know that the scalar product of the frictional force with the speed, it is the dissipated power, the mechanical power dissipated inside the system. If there is dissipation, it means that there is heating. So the system, intuitively, should depend on the temperature. Temperature is an intensive quantity. We have here in this equation an intensive quantity that we do not know. This intensive quantity is the quantity I zero, we say, we will see in the continuation of this course that zero is precisely the temperature. Zero is the temperature and the extensive variable conjugated to y zero. This is what is called entropy in thermodynamics. As it is true that zero which is the temperature is defined positive, that lambda is positive and v square is positive. This implies that x0 point is positive. In other words, the entropy will grow in this isolated system because of dissipation. And this is at the heart of the second principle of thermodynamics which we will deal with in the next sequel, so in the next episode.

Notes

Summary

16m 58s