Systems Physics – A Modeling Approach to Fundamental Concepts

Werner Maurer

Zurich University of Applied Sciences (ZHAW), School of Engineering, Technikumstrasse 9,
8400 Winterthur, Switzerland; *maur@zhaw.ch*

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Abstract. Systems Physics represents a coherent view of physics. Balance equation, constitutive laws and the well defined role of energy form the framework of this newly developed physics course. According to this scheme, all areas of classical physics are taught in the same way: balance equation, constitutive laws and at last the energy as an interconnecting bookkeeper. This unitary structure facilitates the computer-based modeling with a system dynamics tool. Therefore, students at the ZHAW learn physics by forming dynamic models and not primarily by solving exercises.

In this paper, a few examples from different areas are presented (two PET bottles, space jump world record, landing gear drop test, wind shear, cats land on their feet, water rocket simulator, Stirling engine). Most of these models have been developed in the past decade in a bachelor degree course for Aviation.

Introduction

Systems Physics is a novel approach to physics with which beginners are able to grasp the fundamental concepts underlying processes in nature and technology [1]. It is based on everyday concepts known from fluids which are familiar to everybody. The analogy between physical quantities and fluids offers a very intuitive approach to physics [2]. The powerful pictorial modeling by Berkeley Madonna [3] (a system dynamics tool) offered students to understand basic physical processes.

Systems Physics combines the modeling concept of System Dynamics with a unified description for all branches of classical physics known from Bond Graph theory [4].

Our concept of energy carrier is similar to that of the Bond Graph theory. But there is a crucial difference.

In Bond Graph theory, force and torque are potential quantities (effort quantities) and the kinematic variables velocity and angular velocity are seen as flow quantities. In Systems Physics however, this approach is not possible because force and torque are part of the balance equation and velocity and angular velocity are the “driving force” for the appropriate currents. Therefore force and torque are flow quantities and the two velocities are potential variables.

In our model based approach students start by formulating the balance of a fundamental quantity (bathtub-thinking for volume, mass, electrical charge, momentum, angular momentum, entropy or amount of substance). Then they have to specify the currents and the rates of change (feedback-thinking). On a second layer they can add the balance of energy (bookkeeper-thinking).

In the last ten years we have taught these concepts in a course named *Physics and Systems Science for Aviation*. This course is a core subject in the first year of study and carries 16 of the 60 credit points. In this course, consisting of eight lessons per week, the students learn the basic concepts of contemporary physics. At the same time, they apply their newly acquired skills to concrete systems in a modelling laboratory. The insights gained this way then have to be transferred into reports, presentations or posters. This takes place under the supervision of a language lecturer.

In this paper I show based on seven examples how students learn physics. Based on the balance equation the students have to develop the structure of a given dynamic system. For this they have to know the basic laws and they should be able to apply them to new problems. The first system consists of two PET bottles partially filled with water and air. After opening the valve, the pressure between the bottles is equalized.

To solve this problem, the students have to formulate the volume balance at first.

Then they complete the model by means of constitutive laws for pressure and flow. Optionally, the energy balance can still be formulated. The other six problems should be done analogously: balance of a base quantity, capacitive law, resistance law, further constitutive laws and finally the energy balance.

1 Two PET Bottles

Two PET bottles, which are connected together by a long tube, already form a rather complex system. The capacitive behavior of the air-filled bottle is non-linear and the flow may be laminar or turbulent. One or both bottles can be suspended from a force gauge. Thus, the water volume can be measured in function of time.

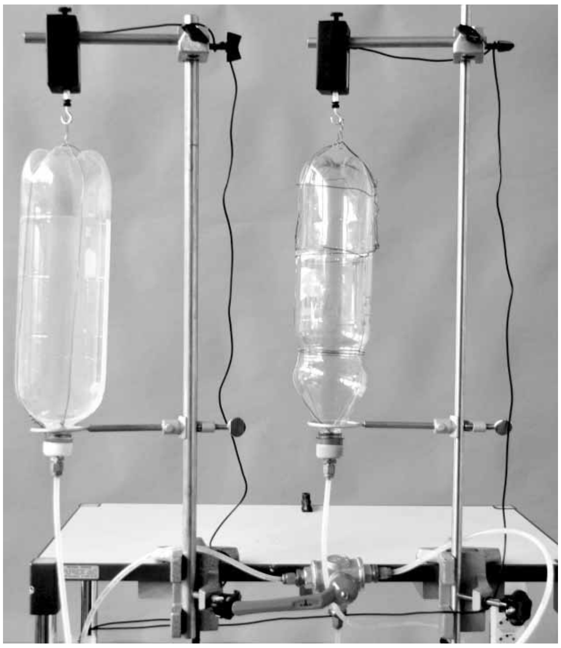

Figure 1: In the first bottle is the air pressurized, the second is under atmospheric pressure.

Model. The SD model consists of a balance layer and an energy layer. Using the Ideal Gas Law and the amount of water in the bottle we can calculate the pressure in each bottle. The pressure difference provides the "driving force" for the volume flow. During the pressure equalisaton, the flow turns from turbulent to laminar. The arrows in the flowchart show the dependencies between the variables.

In contrast to the volume of the water that is conserved, the hydraulic energy is not a conserved quantity. The dissipated power results from the difference between the two energy currents. The strength of the energy current is calculated as pressure times strength of volume flow (potential times the flow of the primary quantity). The pot in the middle of the energy layer integrates the power over time.

The formula for calculating the energy current from the volume flow and the pressure is very important for the system physics. In each branch of physics we find an analogous formula.

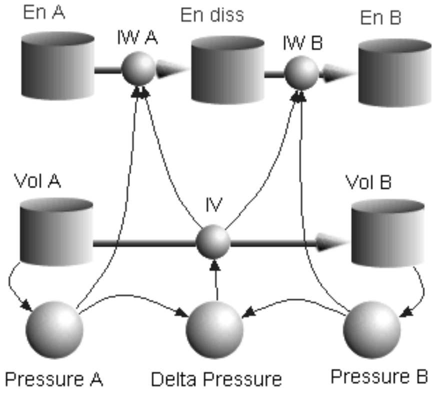

Figure 2: System dynamics model (flowchart) of the two bottles model with volume balance and energy balance layer.

Results. Figure 3 shows the time behavior of the volumes and of the volume flow between the two bottles. The simulation can be adjusted to the measerment (green line) by varying the loss factor. In contrast to the simulation, in reality the turbulent-laminar transition does not happen instantly (buckling in the flow-time function).

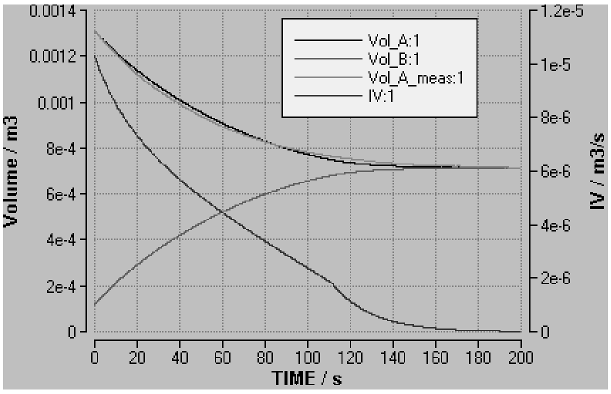

Figure 3: Volume (left axis) and volume flow (right axis) in function of time.

The energy layer is not part of the dynamics system. This is also shown by the causal arrows in Figure 2 which point only from the balance layer to the energy layer. And yet, the energy level contains important additional information related to the system behavior. Compensation processes in which the basic amount is maintained and the associated energy is decreased can also be found in the theory of electricity (charge balance in capacitors) and mechanics (inelastic collision).

Figure 4 shows the energy currents from the first and into the second bottle. The difference between these two currents is known as dissipated power. Figure 4 shows also the dissipated energy which is the inegral of power over time.

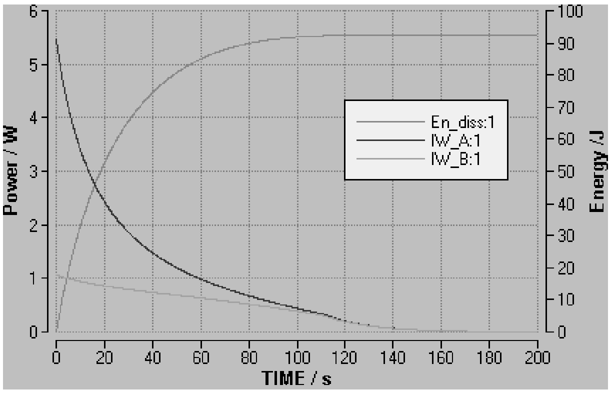

Figure 4: Energy current from the first bottle and into the second bottle (left axis); in the system dissipated energy (right axis).

2 Space Jump World Record

‘Red Bull Stratos was a space diving project involving Austrian skydiver Felix Baumgartner. On 14 October 2012, Baumgartner flew approximately 39 kilometres (24 mi) into the stratosphere over New Mexico, United States, in a helium balloon before free falling in a pressure suit and then parachuting to Earth. The total jump, from leaving the capsule to landing on the ground, lasted approximately ten minutes.’ [5]

This jump from the stratosphere is ideal to understand the translation mechacanics and to examine the involved laws. In this branch of physics momentum is the primary quantity and the velocity provides the associated potential.

Model. The SD model consists of a momentum balance layer, a kinematic layer and an energy balance layer.

The momentum balance calculates from the inflowing momentum (gravitational force) and the outflowing momentum (air resistance or drag) the momentum content. Then the velocity is calculated from the momentum by division by the (inertial) mass. On the kinematics layer the velocity is integrated to the actual position.

The air resistance depends on the density of the air and on velocity and shape of the jumper. On the other hand the density of the air is a function of pressure and temperature, which depend on the height above sea level. The drag coefficient depends on the Mach number, because the velocity is temporary higher than the speed of sound.

Students learn the structure of the mechanics by building a model step by step. They also develop a feeling for the size of the different variables and the sensitivity of each parameter. This is much more than the parroting of historical theorems and calculating with prefabricated formulas. They also provide much more often questions as in the classic, formula centered teaching.

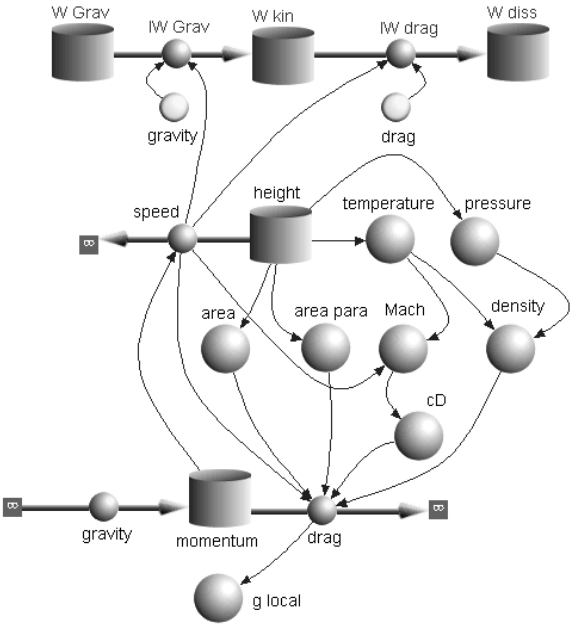

Figure 5: Flowchart of the space jump model with momentum balance, kinematics and energy balance layer.

The energy layer contains three pots for potential, kinetic and dissipated energy. The strength of each of the two energy currents is momentum current time velocity (this formula is also known as power of a force).

As in the hydraulics, the energy layer does not contain any additional information, but promotes an understanding of the orders of magnitude. So you can see out of the simulation that the power of drag rises to more than 500 kW.

Results. Figure 6 shows the velocity-height-diagram with the simulated and the measured data. The measured data are taken from the official website of Red Bull [6]. The two curves could still be better adjusted by adapting the cross section of the jumper in function of altitude. But that is not the aim of such a project. Students should realize how the whole system is set up and how much the individual variables influence the dynamics of such a system.

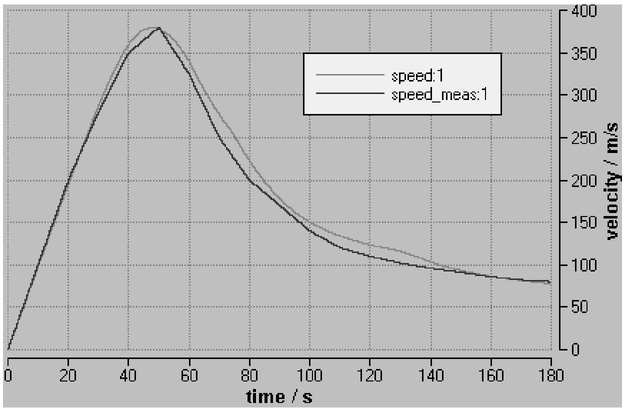

Figure 6: Measured and calculated velocity in function of time.

Skydiving, bungee jumping or base jumping would be other applications of this model. In these examples, the acceleration could be measered by means of a smartphone, and then integrated to speed. So you could compare the measured data with the calculated again.

3 Landing Gear Drop Test

In many textbooks for introductory physics, only the motion of one single body is treated (inclined plane, motion in a uniform gravitational field, harmonic oscillator). This leads to a very limited understanding of the mechanics with respect to Newton's third law and to momentum conservation. The landing gear drop test is a good example of a more complex two-body problem. In the simplest form of this test, a load on a vertically oriented spring-damper system with underlaying wheel falls from a height of three meters on the floor.

Model. As in the example with the jump from the stratosphere the SD model consists of a momentum balance layer, a kinematic layer and an energy balance layer (Figure 7). Momentum flows from the gravitational field into the load (momentum 1) and from there through the spring-damper system into the wheel (momentum 2).

Thereafter, momentum flows from the wheel over the tire into the ground. The great difficulty lies in modeling of the nonlinear spring-damper system and the dynamic behavior of the tire.

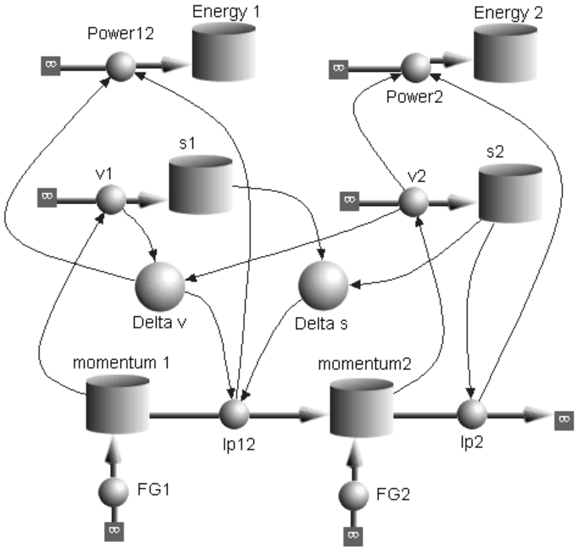

Figure 7: System dynamics model (flowchart) of the landing gear drop test model with momentum balance, kinematics and energy absorption of spring-damper-system and tire.

This model could be validated with the data from an aircraft manufacturer. This data can here not be published because they are confidential.

4 Wind Shear

In the second semester students have to model different phases of the flight of a plane, including wind shear. Wind shear is a difference in wind speed over a relatively short distance in the atmosphere. And wind speed is a very significant factor in landing a plane. First, the students model the flight of a football with drag and Magnus force. Then they have to transform the ball model into a model of a plane. This simple model of an airplane differs from a football by the angle dependence of lift and drag.

Depending on the type of aircraft an engine is also to be modeled. In this simplified model the pilot can influence the thrust and the pitch (angle of the aircraft relative to the horizontal).

Momentum is – unlike mass or electrical charge – a vector quantity. But how can we think about storage and transportation of a vector quantity? To do this, we introduce a global coordinate system which separates momentum in three components.

This fragmentation allows us to treat each component as a single quantity. Then we formulate for each of the three components the balance equation. Therefore, a moving body is able to store a surplus or a deficit of three different components.

The football model is created in the classroom under the guidance of a teacher, and with the help of a video [7]. Then the students are combined into groups with three members. Each group has to model the proper aircraft independently. They must also simulate different self selected scenarios. The results of their studies have to be presented by each group in a speech. The results obtained in this group work are excellent. In addition, students are highly motivated.

Model. To simulate a two-dimensional motion, we need two momentum balances, one for the horizontal and one for the vertical momentum component. The kinematics layer also includes two integrators (reservoir with one flow).

Lift and drag as a function of angle of attack, which is described with the drag polar, characterizes the dynamics of the aircraft. Once the wind begins, both the velociy of the flow and the angle of attack change, but for the first moment the aircraft remains in its state of motion.

This counterintuitive relationship between oncoming flow and aircraft velocity is central to the understanding of the mechanics. In addition to this basic model, students can model further aspects like pitch and thrust control, fuel consumption or load reduction.

Figure 8 shows the flowchart of a student work. This project involved the question, at which wind speed the pilot brings the plane over the hill.

In the last ten years, students have modeled dozens of different problems, from glider winch launch over a parabolic flight path to landing with windsher. It is needless to mention that this project motivated the students of aviation in the highest degree.

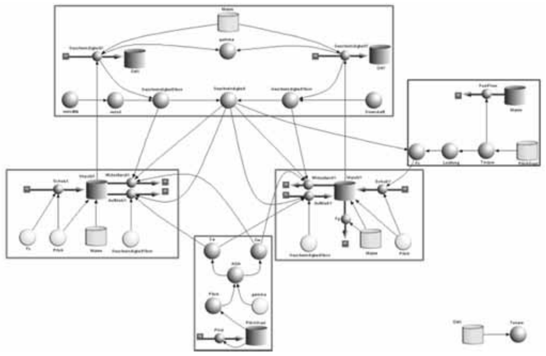

Figure 8: System dynamics model of the two-dimensional motion of a plane with momentum balance (red framed area), kinematics (green framed area), mass balance of the fuel (violet framed area) and pitch control (blue framed area).

The validation of these models is not easy, but the students are very creative. Some use the data of commercial flight simulators. Others rely on the data from an accident report. Because many students have their own pilot's license, a simulated flight is often flown by themselve. To obtain the data they take the acelleration sensor, the GPS-tracker and the video camera from their own smartphone. The most creative examples are modeled by the pilot candidate of the Swiss Army. Parabolic flight with an airliner, looping with a fighter aircraft or take off from an aircraft carrier are only a small selection of what has already been modeled.

5 Fluid Image

In any discussion of angular momentum, the fluid image should be introduced at an early stage, as is the case in any discussion about momentum [8]. In the fluid image of angular momentum, each rotating body is represented as a cylindrical tank standing in an enormous lake. The tank’s crosssection corresponds to the mass moment of inertia J, the fill level indicates the momentary angular velocity ω and the lake simulates the earth with its almost immeasurable capacitance. The fluid itself represents the angular momentum.

Figure 9 shows a simple example to illustrate this: two flywheels of different sizes, which initially rotate in opposite directions, are connected by a sliding clutch. In addition, there is a certain noticeable friction in both bearings. What can therefore be learned from the fluid image? First of all, the law of capacitance: angular momentum content equals base area times fill level. In this equation, a negative angular velocity results in a lack of angular momentum content.

The balance equation, which states that the sum of all angular momentum currents is equal to the change rate of the content, appears directly as a volume balance. If the change rate is divided by the mass moment of inertia, the result is angular acceleration. This leads us to an advantage of the fluid image. In this figure, the angular velocity mutates into a length and the angular acceleration into a velocity. In this way, these two abstract quantities are clearly illustrated.

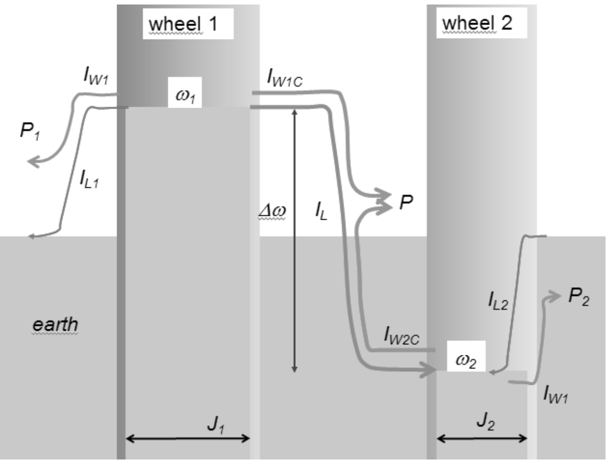

Figure 9: This fluid image of two flywheels which are axially connected by a sliding clutch. Angular momentum flows from the forward rotating wheel into the ground and into the second wheel. The bearing friction supplies the second wheel with additional angular momentum.

The energy becomes intuitively understandable with the fluid image. Every angular momentum current is loaded with an energy flow (I_W). The corresponding angular velocity functions as an energy charge value. If, therefore, an angular momentum current flows at great height i.e. at high energy charge value, it is heavily loaded with energy due to the high angular velocity of the material through which the current flows. As in electrophysics, where energy is often transported against the current, energy flows against the angular momentum as soon as the energy charge value becomes negative. We can easily see this if we look at the second flywheel. Although angular momentum flows from the first flywheel and from the ground into the second flywheel, the second wheel itself releases energy. The process-oriented thinking provides some more clarity: all three angular momentum currents flow from a body with higher angular velocity into a body with lower angular velocity and, at the same time, convert a process power (P) which equals current strength times falling height.

Rotating bodies store angular momentum and energy. Apart from the angular momentum, the momentary value of the rotational energy can also be seen in the fluid image. The rotational energy equals angualar momentum content times the mid height around which angular momentum has been pumped out of the earth and into the body (forward rotation), or out of the body and into the earth (backward rotation).

This relationship, which can be directly inferred from the fluid image, can be expressed by applying the law of capacitance in the familiar formula.

6 Why Do Cats Land on their Feet?

In 1894, the French Academy of Sciences called for ‘a physical explanation for the fact that cats always manage to land on their feet even if they fall from very high up’. The mystery was finally solved by a doctor called Etienne Jules Marey who recorded the fall with sixty images per second. When the film was shown, some physicists still doubted that the rotation was possible without the cat pushing itself off from somewhere. But one of them unravelled the cats’ trick. What is this trick that cats use, which even physicists barely understand?

Cat anatomy is different from human anatomy in that the cat has a highly flexible spine, a surprising deformability, four elastically pliable legs and a long tail. Furthermore, the cat has almost 600 muscles, which enable its body to change shape quickly. The cat uses the same trick as figure skaters controlling their rotational velocity when performing a pirouette. However, the cat’s front and rear parts each perform a pirouette.

The simplest model of a cat consists of two angular momentum storage units whose moments of inertia can change significantly. It is not only by stretching and pulling in its legs that the cat changes the moments of inertia.

As Marey’s film has already shown, cats can greatly adjust their mass axially or distribute it radially both in their front and rear parts.

The actual rotation can be divided into four intervals and illustrated in a fluid image. In the first two intervals, the front part’s moment of inertia is small and the rear part’s moment of inertia is large. The mass of the front part is then shifted outwards, while the mass in the rear part is shifted as close as possible to the body axis.

In the first interval, the cat pumps angular momentum from the rear part to the front part by tensing the appropriate muscles. In the second interval, the cat lets the angular momentum flow back. Afterwards, the cat comes to rest in a completely twisted position and then abruptly changes its mass distribution. In the last two intervals, the cat pumps angular momentum into the rear part and then lets it flow back. As a result, the front part moves back slightly and the rear part performs the all-important rotation.

This rough model can be improved by assuming that the cat pumps angular momentum and changes the moments of inertia simultaneously. Let us therefore describe the angular momentum current as a cosine function and each of the two moments of inertia as a constant with a superimposed cosine function. In order to achieve the desired rotation, the frequency of the moment of inertia must be half as great the frequency of the torque.

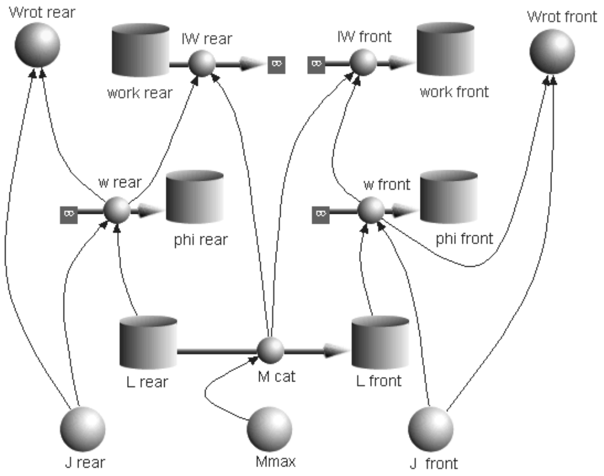

Figure 10: System dynamics model of a turning cat including angular momentum balance, kinematics and energy analysis. Rotational energy and work of the torque are calculated separately.

7 Water Rocket Simulator

A rocket can exchange linear momentum in three modes: conductive over the surface with the air (drag), throughout the whole volume with the gravitational field (gravitational force as a sink for momentum) and convective together with the mass of water. To transfer momentum convectively, each rocket requires energy. The water rocket stores the required energy in the compressed air.

Therefore, compressed air is the energy provider and water is the momentum carrier. Now the question is, in what proportion water and compressed air have to be bottled.

Model. The SD model consists of a momentum balance layer, a mass balance layer and a kinematic layer. The momentum balance pictorially shows that it makes no difference whether momentum is transported through the gravitational field (source-like), over the surface (conductive) or together with mass (convective). All three currents contribute equally to the rate of change of the momentum content.

The energy balance layer is not complet. In this model, only the dissipated energy is calculated from the performance of the air resistance. The calculation of the kinetic or potential energy is not very meaningful, because the mass of rocket changes during launch. An interesting problem is the convective energy transport. However, this problem is examined better in a stationary operating system, such as the jet engine.

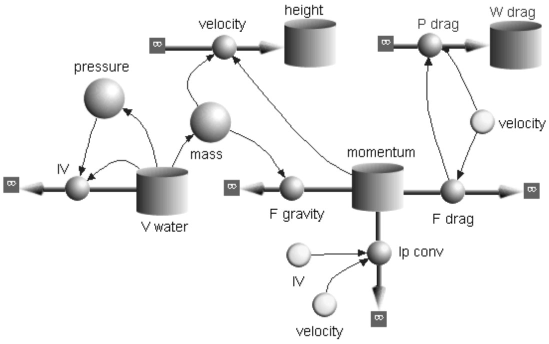

Figure 11: System dynamics model of a water rocket including liner momentum balance, kinematics and energy analysis (dissipated energy).

Results. The altitude of the water rocket is relatively easy to measure. However, this varies from shot to shot, because the trajectory is not always exactly vertical. A key question concerns the amount of water to be filled in. The simulation shows that one-third water and two thirds air leads to greatest altitude. This is also a good rule of thumb for the practitioner.

More important than the simulation of a most accurate trajectory is the knowledge gained for by students in terms of mechanics. Here they realize that forces are momentum currents with respect to a system. This is an important insight in mechanics which is denied by many physicists [9].

8 Thermodynamics

Classical thermodynamics describes systems in equilibrium, i.e. heat transfer is out of the scope of this theory. Furthermore, processes are discussed with energetic terms like heat, work, internal energy, and enthalpy, Helmholtz or Gibbs free energy. This description has a certain similarity with Lagrangian or Hamiltonian mechanics. In Systems Physics we introduce entropy first and then we add the constitutive laws for selected materials like ideal gas. In a final step we complete the theory by adding energy as a bookkeeper quantity [10]. This is the same approach as in all other topics of our course.

A body will move, rotate, be charged or get hot if we add energy to it. Energy is a bookkeeper quantity which says little about real processes. But if we add momentum to a body, we increase its velocity and if we add angular momentum to a rigid body, we increase its angular velocity. The same can be said for a thermodynamic system: if we add entropy to a body, it will raise its temperature or change its state of aggregation.

In everyday speech heat can be exchanged, stored and produced. In thermodynamics heat is defined as a quantity which can only be exchanged (the stored energy is called internal). This contradiction between the scientific and the common usage of the word heat can be resolved by using entropy for heat. Entropy can be exchanged, stored and produced. We try to give the students a picture of entropy as the basic quantity of thermodynamics which should be named heat and which acts as an energy carrier. Thus we draw the same picture as in hydraulics with volume and pressure or in mechanics with momentum and velocity or angular momentum and angular velocity.

The heat flowing through a reference surface can be seen as a flow of entropy or energy. Both quantities are connected by the temperature of the surface: the energy current through a reference surface is equivalent to the product to the absolute temperature of this surface and the entropy current through the same surface. In heat conduction, the energy current is always accompanied by a current of entropy. Or vice versa, each entropy current carries an energy current.

Entropy is like volume or momentum a fluidlike quantity which acts as an energy carrier. Temperature is the associate potential like pressure or velocity. With this picture in mind we can explain various thermally driven machines.

Let’s look at a heat pump which pumps entropy from the cold environment to the warm water of the heating. The heat pump has to add power to the entropy current because the entropy coming from outside is less charged with energy then the entropy going into the house.

Heat engines and heat pumps can be compared with a hydroelectric power plant. Entropy corresponds to the mass and temperature to the gravitational potential with the reference point at sea level. In a hydroelectric power plant water discharges only a part of its gravitational energy depending on the height of both reservoirs. This can be applied to a heat engine. This idea was first stated by Sadi Carnot [11].

In a nuclear power plant, entropy which is coming from the reactor transfers part of its energy to the electric current. The rest of the energy is carried by the entropy to the environment. Because the cooling system is hotter than 300 Kelvin a large part of the energy coming from the reactor cannot be transferred to the electric current. With the waterfall picture designed by Carnot we can easily understand why most of energy coming from the reactor is transferred to the cooling system instead to the electric power net.

In a nuclear power plant, entropy is produced in the reactor. The rate of entropy production can be calculated using the entropy balance and the associated formula for the carried energy. As a result we get for the entropy production rate a simple formula: entropy production rate equals dissipated power divided by absolute temperature.

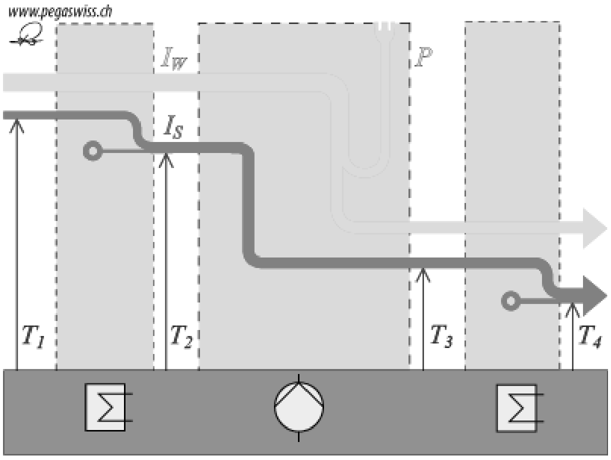

Figure 12: Schematic representation of an endoreversible heat engine.

The often heard argument that energy is converted into heat by dissipation can now be described more precisely using this relation: in a dissipative process entropy is produced and energy is reloaded from another fluidlike quantity to entropy.

Now we are able to explain heat conduction as a dissipative process. In heat conduction, entropy is flowing from a heat reservoir with high temperature through the conduction element to a colder reservoir. In doing this, energy is dissipated, which means that more entropy is produced. It can be shown that the energy flux remains constant: energy is increasingly distributed to a growing current of entropy. This phenomenon might be the reason for the odd definition of heat: in the middle of the 19th century physicists were looking for a thermal quantity which is conserved – and they found the bookkeeper and not the real actor.

As an example of a system with ideal and dissipative processes, we consider an endoreversible heat engine (Figure 12). This engine consists of an ideal heat engine with two heat exchangers. In both heat exchangers entropy flows downhill. The thereby released energy is used for entropy production. So the two heat exchangers reduce the usable gap i.e. the available temperature difference.

9 Heat Storage

In all branches of physics there are a lot of storage systems like reservoirs (mass), plastic bottles (volume), capacitors (charge), moving (linear momentum) or rotating (angular momentum) bodies. In thermodynamics the simplest accumulator is more complex. A homogeneous thermodynamic system can at least change entropy and volume. Therefore the system has two potential, temperature and pressure. To discuss and model such a system we have developed the Carnotor, a simple machine with two ports, a thermal and a hydraulic one (Figure 13). Carnotor is a portmanteau composed of Carnot and Motor (German word for engine).

The Carnotor consists of a double-acting cylinder filled with the substance to be examined on one side of the piston and an ideal fluid on the other side. To each port we can add a pump, a closing-off of or a big storage tank. With this equipment students can think about all four basic processes of thermodynamics (isochoric, isobar, isentropic, isotherm).

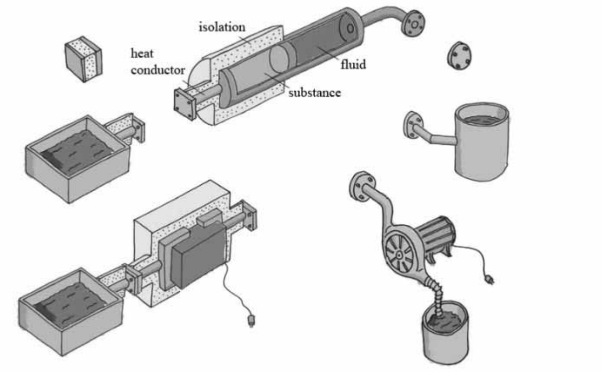

Figure 13: The Carnotor has two ports, one for heat and one for an ideal fluid. Both ports can be combined with a closing-off, a storage tank or a pump.

The simplest thermodynamic system stores at least two quantities. Therefore it comprises two associated potentials. Such a system is more complex than a moving body or a capacitor.

Nonetheless, with the help of the Carnotor students can model real thermodynamic systems.

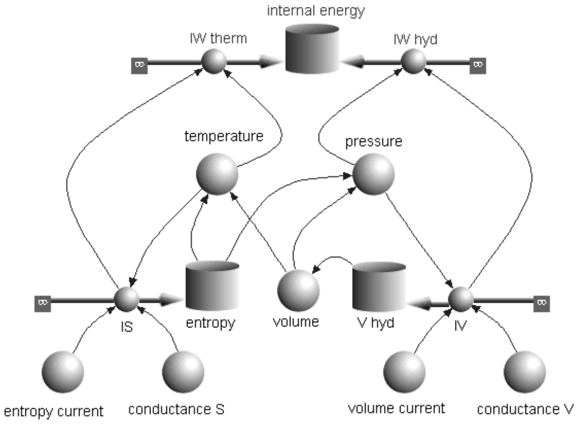

Figure 14: System dynamics model of the Carnotor whith the balances of entropy and volume, the two associated potentials and the energy balance.

In order to calculate pressure and temperature two constitutive laws are needed. As an auxiliary condition for these laws energy has to be conserved.

The system dynamic model of the Carnotor can be used as a basis for more complex systems like Otto or Diesel engine. One difficulty arises from modelling of the isobaric and isothermal processes. For both processes we need ideal conductance between Carnotor and storage tank, i.e. the numeric value of the conductance has to be infinite.

Therefore students have to make a compromise between idealization and calculability. That’s the difference between the quasi-static analysis of classical thermodynamics and simulation in time domain.

10 Stirling Engine

The Stirling engine was invented and patented by Robert Stirling in 1816. A Stirling engine operates by cyclic compression and expansion of air at different temperatures. The thermodynamic principle of the Stirling engine is dscribed by the Stirling cycle. This cycle differs from the Carnot cycle through the two isochoric processes which replace the isentropic processes. Both cycles have the same efficiency if entropy is only exchanged by the two isothermal processes. Therefore, the entropy released by isochoric cooling must be thermally buffered, so that this entropy is available for isochoric heating.

In contrast to the Stirling cycle, the Stirling engine operates with two chambers, one hot and one cold. A displacer piston pushes the gas periodically between the two chambers back and forth.

Our Stirling engine is a gamma type in which the power piston is mounted in a separate cylinder alongside the displacer piston cylinder.

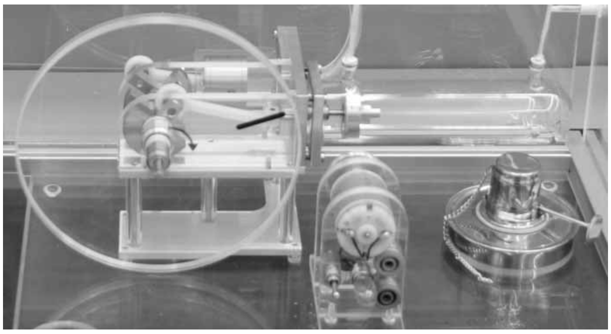

Figure 14: Stirling engine with flywheel (left), power piston (behind the flywheel), main chamber with displacer (right side).

Students can measure the temperatures in the warm and in the cold region as well as pressure and stroke of the working piston in function of time.

The temperature is measured directly at the glass cylinder. Therefore, a direct measurement of the gas temperature is not possible.

Model. We take the amount of substance of air as primary quantity. This quantity is pushed between the hot and the cold region by the pressure difference. As the second fluidlike quantity we take the energy and not the entropy. Later, we estimate the efficiency of the machine with the help of the entropy production. The mechanical part of the engine with pistons and flywheel is not modeled. Instead we give the two volumes in function of time. The rotational frequency comes from the measurement.

Figure 15 shows the flowchart of this model. In the upper part you see the balance of the amount of substances. Using the ideal gas law the pressure is calculated of volume, amount of substance and temperature. The energy level consists of a thermal (top row) and a mechanical part (two pots below). The regenerator is modeled by means of three heat accumulator with identical heat capacity. The calculation of the entropy currents, the entropy production rate and the produced entropy is not shown in Figure 15. The produced entropy can be calculated for the heat transfers in the hot and the cold chamber as well as for the convective heat transport.

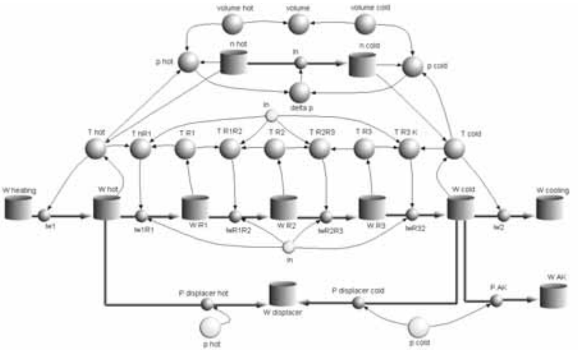

Figure 15: System dynamics model of a Stirling engine whith the energy balance (9 reservoirs) and the balance of amount of substance (two reservoirs on top).

Results. The theoretical efficiency (Carnot efficiency) is 50% at 600 K for the hot heat reservoir and 300 K for the cold heat bath. The simulation of this model gives 17%. Taking away the three heat store for the regenerator, gives only 6%. Large Stirling engines achieve an efficiency which is less than 0.5 times the Carnot efficiency. Small Stirling engines as ours achieve an efficiency that is close to zero. Therefore, the model presented here is not very valid.

But validity is not the primary goal of this laboratory course. In this modeling exercise, students will learn the basic laws of thermodynamics with a concrete example. And this goal is achieved much more than when the students solve a few simplified exercises.

An important learning objective is the correct interpretation of graphs. Figure 16 shows the pressure-volume diagram. In this diagram, the net work of the gas is equal to the area enclosed by the circle. This knowledge can also be applied to internal combustion engines and steam engines. Comparing the simulated data with the ideal cycle, we see two essential differences: expansion and compression processes are not isothermal and the four thermodynamic processes merge into one another.

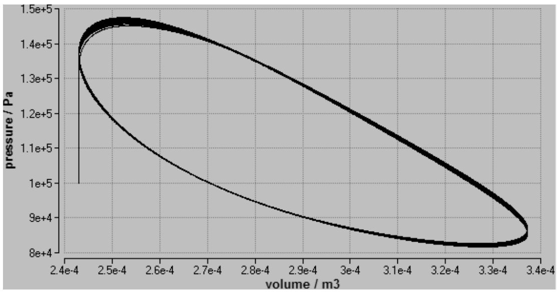

Figure 16: Simulated pressure-volume diagram of the Stirling engine.

This model of the Stirling engine allows many different studies. What happens with the effinciency if one increases the number of energy reservoirs for the regenerator? How increases the efficiency with the increase of temperature at the entrance of heat? Where is produced the most entropy? Will the entropy production decreases with increasing number of heat accumulators? The example of the Stirling engine clearly demonstrates how one can fulfill new learning objectives with modeling and simulation.

11 Summary

Systems Physics provides a consistent, coherent and relevant structure of physics. A huge number of dynamical systems can be modelled with the same heuristic approach. The equation of balance for fluidlike quantities like volume, mass, electric charge, momentum, angular momentum and entropy yields the backbone for such models. By adding the constitutive laws for accumulators and conductors we get the basic equations.

In a third step we can add energy as a second fluid-like quantity. The energy balance analysis is often useful but not necessary for simple systems. But energy conservation becomes an inevitable requirement in more complex systems like thermodynamic accumulators.

Systems Physics differs in three respects from other physics courses at colleges. First, the structure is not historically i.e. we don’t teach along the well-trodden paths. Second, we use as many analogies as possible and develop the individual domains in a uniform manner: balance equation, constitutive laws and energy as a bookkeeper. Third, we explain the laws of physics by means of modeling and simulation and not primarily by means of subtle arithmetic problems.

Electricity and heat were originally understood to be a kind of fluid, and the names of certain quantities such as current are derived from hydraulic equivalents. Therefore, the hydraulic-electrical analogy is natural and used frequently.

In thermodynamics, there are two analogies to hydraulic, the entropic and energetic. We use the entropic analogy to represent the thermodynamics in its full beauty. Waterfall picture, entropy production and Carnotor are important stones in the large mosaic of thermodynamics. The energetic analogy we use only for the thermal RC circuits such as buildings to be heated or body to be cooled.

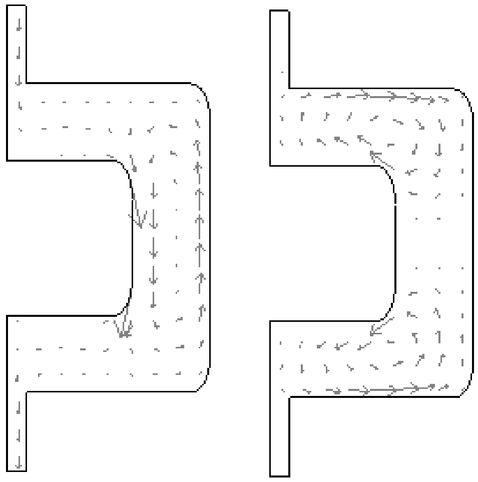

Figure 17: Momentum currents in a sheet metal under tensile stress. Each picture shows the current of a momentum component.

Mechanical-electrical analogies are introduced first by James Clerk Maxwell to explain electrical phenomena in familiar mechanical terms. However, as electrical network analysis matured it was found that certain mechanical problems could more easily be solved through an electrical analogy. Two pairs of power conjugate variables can be found: force and velocity for translational and torque and angular velocity for rotational mechanics. A deeper analysis shows that force and torque are analogous to the electric current and velocity and angular velocity are analogous to the electric potential. Each analogy has its limits. Unlike the electric charge momentum and angular momentum are vectors. Therefore, you always need a fixed coordinate system (world system) to decompose the two vector-like quantities in six fluidlike scalars.

Figure 17 shows, how you can create entirely new pictures with this idea. As a result of the tensile stress momentum flows through the piece of sheet metal (picture on the left side). Because this current is deflected, it generates eddy currents of the other components (picture on the right side). These in turn produce another eddy current of the first component (central part in the left picture). The momentum current coupling can be better explained if one also brings in the angular momentum. But that would be again a long story. This picture shows that the analogy goes much further than is assumed first. But you have to understand the continuum mechanics thoroughly in order to apply these ideas correctly.

Analogies are also important in regard to the further education of engineers. Thus one finds in textbooks on control systems the same analogy as in the Systems Physics [12]. Another line of development leads directly to the modeling tools of the latest generation such as Modelica [13]. Systems Physics has the potential to become the backbone of an entire engineering education. In such a program, we could start with a simple system dynamics tool. Then, with advancing knowledge, students could develop entire Modelica libraries. Based on past experience, we know that such training would be more sustainable than the usual formula based instruction. Unfortunately, the possibilities of this type of learning are still too little exploited.

Despite the good acceptance by the students and the excellent preparation in terms of modelling and simulation, Systems Physics isn't widely accepted.

Several reasons prevent the widespread acceptance of this approach. Most opposition comes from other teachers who don't accept that momentum can flow through material or that entropy can be seen as another word for heat. Tradition is another obstacle to progress in education. If all curricula would change, hundreds of textbooks and formulary had to be rewritten and thousands of teachers had to be re-educated.

Nevertheless, the development of Systems Physics was a real adventure. It has provided a deep insight into classical physics and paved the way for the wide application of modelling and simulation in teaching physics. Last but not least I would like to thank my friend Hans Fuchs for the innumerable fruitful discussions in developing this approach and Elisabeth Dumont for further discussion.

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