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Surfatron: catch the wave of accelerators

Extension activity: The mechanical Surfatron

Introduction

The use of a mechanical and virtual Surfatron in parallel not only provides more insight into the physics of waves and particle acceleration, but also highlights the beauty and power of computer simulations in scientific research.

The mechanical Surfatron consists of a pipe twisted around a cylinder that is free to rotate around its longitudinal axis (see figures 1 and 2). As the cylinder rotates, the pipe behaves like a one-dimensional travelling wave. A ball inserted into the pipe at the right time can be accelerated forward, following the same mechanisms as those described in the article, coming out of the other end with a higher speed.

Both ends of the pipe must be aligned with the axis of the cylinder. Two funnels at each side of the cylinder are used to curve the pipe smoothly from the axis to the surface of the cylinder. The amplitude of the wave is set by the diameter of the cylinder, the wavelength is determined by the number of turns of the pipe around it, and the wave frequency is the angular speed of the cylinder.

The cylinder can be turned manually (e.g., attaching a handle at one end of the apparatus) or using a motor. To calibrate the angular speed of Surfatron, one can use the stroboscopic effect by drawing a series of equally spaced lines along the perimeter of the cylinder so that, when the lines are illuminated with a strobe light at a given frequency and the device is spinning at the desired speed, the lines appear stationary.

The output energy of the ball can be determined by measuring the distance it covers from a particular height. A fun way to do it is by placing a glockenspiel or xylophone directly in front and underneath the pipe exit so that the higher the energy of the ball, the higher the note it hits. This would be the mechanical analogue of an electron spectrometer.

How to build a mechanical Surfatron

Materials

- A rigid cylindrical tube approximately 1 m long and 15 cm in diameter
- A flexible pipe, 3 m long with 1 cm inner diameter
- Two funnels with broad ends of the same diameter as the rigid tube and narrow ends of the same diameter as the outer diameter of the flexible pipe
- Two bearings, with inner diameters not smaller than the outer diameter of the flexible pipe
- Planks of wood or metal for the support structure
- Steel balls, approximately 7 mm in diameter
- Tools: drill, hacksaw, screwdriver, glue, tape, screws

Figure 1. Top: Manually operated mechanical Surfatron built in a professional workshop, featuring stroboscopic lines for frequency calibration. Bottom: Home-made version
Image courtesy of Ricardo Torres

Optional

- Washing machine motor
- Rubber belt
- Strobe light (available as a free mobile app)
- Glockenspiel or xylophone

Building instructions

1) Drill a hole in each funnel, near the middle of the broad side so that the pipe can pass through it.
2) Stick the funnels to each side of the tube. Introduce the pipe into the funnel through the holes and extract it through the narrow end. Twist the remaining part of the pipe around the tube (one turn is enough), and do the same with the other end of the pipe to the other funnel. Be careful not to strangle the pipe and avoid sharp bends, otherwise the ball may get stuck inside. Cut the excess length of the pipe with a hacksaw.
3) Make a frame to support the apparatus, so that the narrow ends of the funnels can rest on the bearings and the cylinder with the pipe around it can rotate freely without touching the ground (figure 2).
4) Cut a piece of the leftover pipe and fix it in front of the input end of the moving contraption to use it as an injection device.
5) Fix a piece of wood or metal to the narrow end of the output funnel to use as a handle to turn the contraption. Alternatively, you can fix a washing-machine motor to the supporting structure and use a rubber belt to transmit the motion from the motor's axis to the funnel, as shown in figure 2.

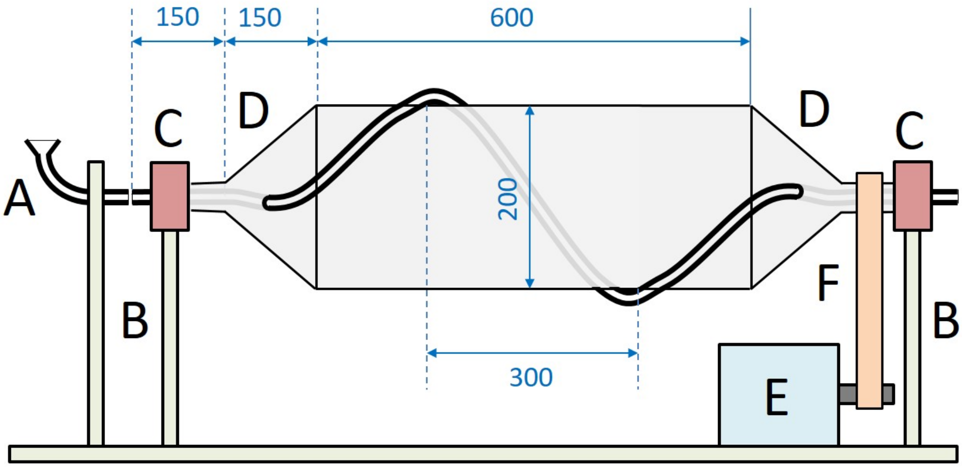

Figure 2. Schematics of the mechanical Surfatron. A: injector; B: support structures; C: bearings; D: funnels; E: motor; F: belt. All distances in mm are approximate.
Image courtesy of Ricardo Torres

Frequency calibration

The angular speed of the cylinder, which defines the frequency of the wave, can be calibrated with a stroboscope. To make the stroboscope, cut a narrow strip of paper of the same length as the circumference of the cylinder. You will have to draw a series of equally spaced parallel lines on the strip along the transverse direction (see figure 3). The distance, Δ_n, between the lines depends on the target frequency, that is, the frequency, F_n, that you want to calibrate; the frequency of the strobe light with which you will illuminate the lines, or sampling frequency, F_S; and the outer diameter, D, of the cylinder, according to the following relationship:

$$\Delta_n = \pi D \frac{F_n}{F_S}.$$

For example, if you want to adjust the angular speed to 60 rpm (1 Hz) for a cylinder with an outer diameter of 15 cm, with a sampling frequency of 100 Hz, the line separation must be 4.7 mm.

Paste the strip of paper around the side of the cylinder and illuminate it with a strobe light at a set frequency as the cylinder rotates. You can download a free mobile app like Strobily to use your mobile phone as a strobe lamp with adjustable frequency. When the cylinder spins at the target frequency, the corresponding set of lines will look stationary. If the frequency is slightly higher or lower than the target frequency, the lines will appear to move forward or backwards, respectively.

You can draw different sets of lines to adjust the angular speed of Surfatron to different frequencies, as in figure 3.

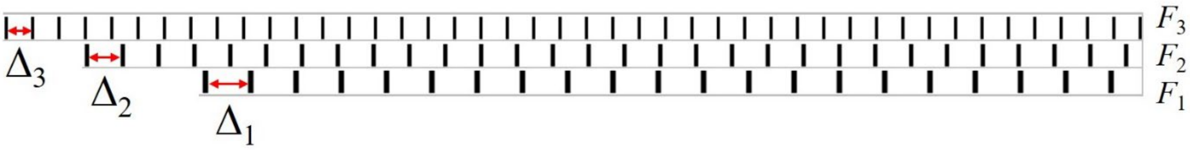

Figure 3: Stroboscope to calibrate the angular speed of the mechanical Surfatron to frequencies F_1, F_2, and F_3
Image courtesy of Ricardo Torres

Using the mechanical Surfatron

1) Open online Surfatron to familiarize yourself with the motion of a ball in a travelling wave.
2) Get the mechanical Surfatron turning at a given frequency by operating the handle or switching on the motor.
3) Drop the ball into the injector, observe its motion inside the pipe, and measure the output energy with a glockenspiel or similar.
4) Try to obtain the maximum output energy by varying the rotational speed of the tube and the time the ball is inserted.

Discussion

The ball accelerates for as long as it stays on a downward portion of the pipe, whereas it will slow down if it slips into the upward side. Therefore, to achieve maximum acceleration, one has to aim to get the ball on a downward slope for the whole length of the tube.

If the ball goes faster or slower than the wave, it will eventually slip into the upward slope, losing speed; this phenomenon is called dephasing. The key to achieve maximum acceleration is then to adjust the rotation speed of the tube so that the phase velocity of the wave matches the average speed of the ball.

A plasma accelerator works in much the same way as Surfatron, using a travelling plasma wave to accelerate electrons. The mechanical Surfatron lets students experience some of the challenges faced by scientists developing and operating particle accelerators, that is, synchronising the particle beam with field oscillations, and avoiding dephasing to extract the maximum energy from the apparatus.

The virtual Surfatron can be used alongside its mechanical counterpart to gain insights into the motion of the ball inside the pipe (with the caveat that the virtual Surfatron treats the ball as a point-like particle, ignoring its moment of inertia). Similarly, scientists use computer simulations to better understand the outcome of their experiments and even anticipate new results by varying parameters that may be difficult to manipulate in practice, like the wave amplitude in the mechanical Surfatron.