Revival of the Jumping Disc

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Abstract:
Snap discs made of bimetal have a lot of technical applications as thermostats. Jumping discs are a toy version of such snap discs. Besides giving technical information, we describe physical investigations. We show especially how, through simple measurements and calculations, you can determine the initial speed (~3.5 m/s), the acceleration (~30000 m/s^2) and the lower and upper snap temperature (~31 °C; ~99 °C). High speed videos give even deeper insight into the jump.

keywords:
bimetal, thermo-bimetal, snap disc, jumping disc, acceleration, physics toy

Introduction

In 1987, C. Isenberg published a short paper entitled 'The jumping disc' [1]. He discussed several features of this small toy and asked for further contributions. Afterwards, however, the jumping discs were no longer available, and this is probably the reason why no further reports have appeared in this journal. In 1988, one other publication appeared in 'The Physics Teacher' [2]. The reason for the disappearance of the jumping discs was that the owner of the only manufacturer in the United States had died and that its production had not been continued.

Now jumping discs are available once again (figure 1)[3], and they offer an interesting spectrum of experiments, among them very simple ones and others which are only possible with hi-tech equipment.

Figure 1. A jumping disc (Ø= 2.5cm) held between two fingers.

Physical-technical background

Thermo-bimetal snap discs are widely used as thermostats, for instance, to switch off the electric current automatically in water boilers when the temperature has reached a boil. Snap discs behave similarly to a phase change, i.e. when the temperature slowly changes and then reaches a critical point, the disc suddenly 'clicks'. There are other physics toys with similar behaviour, such as the plastic toy “popper” [4], the “clicker” or the “ping-pong snap-gun”. The latter has a metal guide strip which clicks suddenly when a critical bending moment is reached and the entire energy-input is applied to the ball positioned above the metal strip. The ball shoots up into the air. In this case, the change in state is caused by a mechanical influence while, in the case of the snap disc, the change comes about through temperature variation.

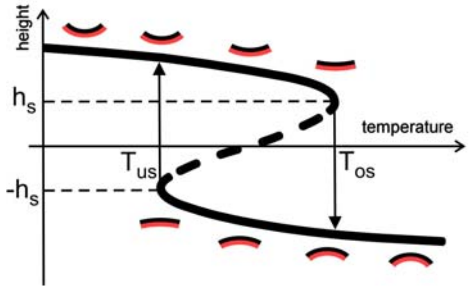

Figure 2. Qualitative characteristic of thermo-bimetal-snap disc. Bending of the discs is exaggerated. The active steel layer is black, the passive invar layer red.

The round snap discs, with a diameter of up to three centimetres, consists of two metal layers, one of invar (passive layer) and the other of steel (active layer), for instance, which are cold-welded together. Invar was developed by the French physicist Charles Guillaume back in 1897 and has, compared with steel, a very small coefficient of thermal expansion in the wide temperature range between -100°C and +160°C, and one that is, almost invariant, thus explaining the origin of its name. In the case of the jumping discs, the invar layer is visible and shiny. The steel layer is located below the printed advertising.

At low temperatures, snap discs have a concave shape which then snaps to a convex shape at high temperatures. During this process, the discs can exert a force great enough to activate a switch or make an electrical contact mechanically. As is common in discontinuous phase changes, the snap discs show considerable hysteresis behaviour (figure 2). With adequate materials and correct shaping, the lower and upper snap temperatures, T_{us} respectively $T_{os,}$ can be adjusted within a wide range.

The raw bimetal used in the jumping discs is produced by the German company Vacuumschmelze. If the printed advertising is removed, you can see the marking VAC 2036 or TB 1577. VAC stands for **Vac**uumschmelze (vacuum melting), and 2036 refers to the percentage of nickel in the bimetal layers [5]. The nickel content in the active steel layer is 20%, while the nickel content in the passive invar layer is 36%. By the way, the steel used is not stainless steel, which means that jumping discs can rust. In accordance with the German industry norm (DIN) 1715-1, the marking TB 1577 indicates a thermo-bimetal with good thermal sensitivity. The thickness of each layer is 0.15 mm, resulting in a total thickness of 0.30 mm. Since the properties of bimetals are extremely dependent upon their thickness, they must be manufactured with an accuracy of a few µm.

The jumping discs are produced from raw bimetal by unique machines from the Austrian company Wurmb [6], which also manufactures apparatus to measure the thermal and mechanical properties of snap discs.

A German patent from 1929 gives an exact description of the snap disc as a toy or for use in advertising [7].

From technical use to playful application

The toy version of the jumping disc is characterised by the feature that it can reach temperatures of up to 40 °C when rubbed between your dry fingers. This temperature is sufficient to click the disc into its other – unstable at normal room temperature – configuration, in which it can remain temporarily until it cools down. If the disc is then placed concave-side down on a hard, cool surface quickly enough, it will snap back into the stable configuration and jump up about 60 cm (±10 cm). A repetition of the experiment with the same disc results in a noticeable variance in height, and there can be even greater divergences between different discs.

If placed on the surface convex-side down, the disc jumps as much as about 20 cm into the air. This phenomenon will be discussed later.

C. Isenberg [1] proposes performing an experiment to determine the lower snap temperature T_{us} through quasi-static cooling of the disc in a water beaker. This can be done easily and results in a snap temperature of about 30 °C. The upper snap temperature T_{os} of about 100 °C cannot normally be determined with boiling water but rather on a slowly heating hotplate with an adequate thermometer (e.g. a contactless thermometer) (figure 3). Wurmb [6], the company manufacturing snap discs, states that the critical temperatures are 31 °C and 99 °C, with a tolerance of ±4 °C.

(Be careful: heating up to more than 240 °C, for example, by means of a gas flame, will change the snap temperatures. In particular, the critical temperature T_{us} will change in a way that you cannot achieve with rubbing between your fingers. Heating up to more than 600 °C changes the properties of invar irreversibly. After this, the snap discs will no longer work at all.)

Figure 3. Jumping discs on a small hotplate, with a contactless thermometer on the right.

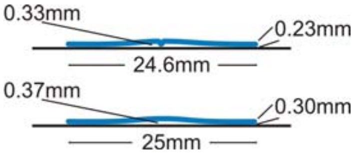

Figure 4. Shapes of original (at the top) and new jumping disc in taut position (not true to scale).

Figure 5. Measurement of force for bending the disc.

From the measurement of the jump height h and the mass m (= 1.235 g ±0.003 g), you can calculate the potential energy E (= $m \cdot g \cdot h = 0.001235\text{kg} \cdot 10\text{ms}^{-2} \cdot 0.60\text{m} = 7.4 \cdot 10^{-3}$ J). The initial jumping speed can be calculated with

$$v = \sqrt{2gh} = \sqrt{2 \cdot 10ms^{-2} \cdot 0.60m} = 3.5\ ms^{-1}.$$

Air resistance can be disregarded because of the low speed, as can rotational energy due to rotations. An additional experiment shows that there is even more energy in the disc. If some small metal sheets only a few square millimetres in size and with a thickness of 0.3 to 0.4 mm are put under the centre of the clicked disc, the disc jumps up to 85 cm high! By using this trick, the disc can be accelerated along the whole distance of the bent disc. For this reason, the original discs had a notch of about 0.3 mm in the centre of the disc (figure 4). The question arises of what happens to the energy which does not contribute to the jump without the metal sheets. We can only guess that the energy is dissipated due to the juddering and therefore inelastic collision upon the impact of the centre of the disc on the surface.

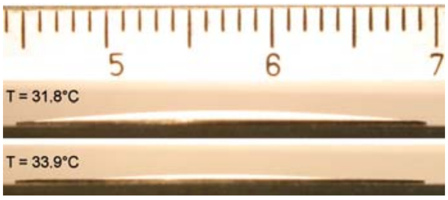

Figure 6. Shape of disc below (at the top) and above lower critical snap temperature.
(thickness of edge of disc = 3 mm).

The initial acceleration, which can be estimated from the force F = 34 N (±5 N), necessary to bend the disc is extremely great. To determine this force, the disc is laid flat on a plane surface, and then the centre of the disc is loaded with weights until it bends (figure 5).

The assumption of a uniform acceleration results in:

$$a = \frac{F}{m} = \frac{34N}{1.235 \cdot 10^{-3}kg} = 27500\ ms^{-2} = 2750g \quad (g = 10\ ms^{-2})$$

To get an idea of the dimension, compare this with the acceleration of a bullet, which is only a hundred times greater. The plastic popper [4] has an acceleration of thirty times less!

With an adequate digital camera, the hotplate already mentioned and a thermometer, you can measure quantitatively the bending of the disc against the temperature. The disc in the photo was laid flat on the hotplate and photographed directly from the side. In figure 6, two situations are shown. In the

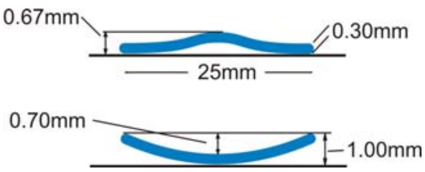

Figure 7. Shape of jumping disc in clicked position (at the top) and after relaxation near lower critical snap temperature (not true to scale).

lower part, you can see the disc cooling from high temperatures before reaching the lower snap point. At the top, the disc is shown heating up from low temperatures after the snap state. From pictures like this, the shape of the disc can be determined with an accuracy of at least 0.1 mm (figure 7).

The distance the disc is accelerated without metal sheets under the centre is about s = 0.70 mm (figure 7). This will be analysed more precisely later. With the following calculation, the time for the initial jump process can be roughly estimated:

$$t = \sqrt{2 \cdot s / a} = \sqrt{2 \cdot 0.0007 m / 27500 ms^{-2}} \approx 2.3 \cdot 10^{-4} s = 230\ \mu s$$

With an adequate high-speed video camera [8], the initial part of the jump can be documented. In figure 8, the separate phases of the jump, taken with a camera with 16,000pictures/second, are shown. The resolution of the camera is very limited at this speed. The difference between each picture is 62 µs. The start of the jump takes place relatively slowly. In the picture at 250 µs, levitation of the disc is very constricted but clearly visible above the surface. In the picture at 312 µs, the disc already has contact with the surface. Then the disc is shown above the surface and jumps up with a speed of 3.6 m/s, as can be derived very accurately from the video. This is consistent with the value of 3.5 m/s calculated at the beginning of jump height.

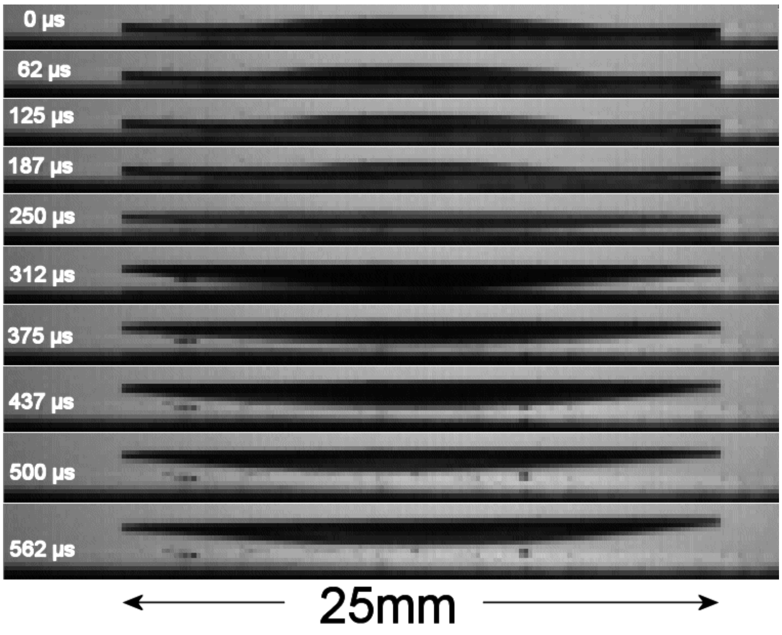

Figure 8. Start of a jumping disc taken with a video camera with 16,000 pictures per second

Together with the measurements concerning the shape of the disc, some reflections and estimations can be made.

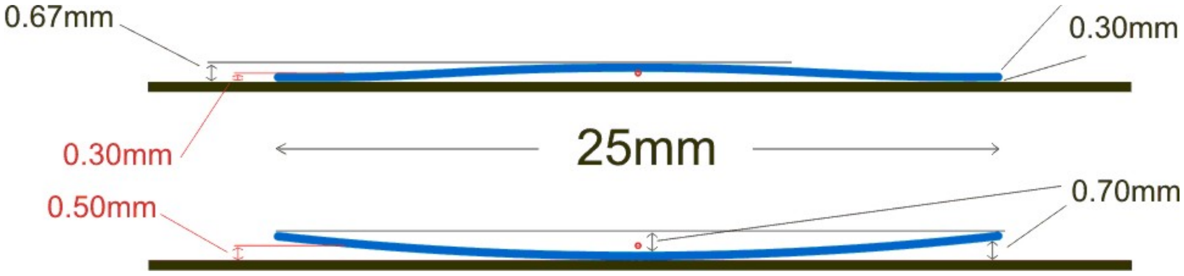

Figure 9. True- to- scale representation of a jumping disc just before and after the jump. The centre of mass is marked by a red point.

The upper part of figure 9 shows the true-to-scale shape of the disc shortly before start. The centre of mass (red point) can be located at a distance of about 0.30 mm (±0.05 mm) from the surface, which can only be estimated due to the irregular form of the disc. At the beginning of the snap process, the centre of the disc moves downwards, which takes about 250 µs. Within this time, the disc falls down only $0.5 \cdot 10 ms^{-2} \cdot (0.25 \cdot 10^{-3} s)^2 = 0.3\ \mu m$ due to gravitation. Therefore, the edge of the disc must move upwards because the centre of mass remains at almost constant height. The phase at 250 µs shown in figure 8, where the disc levitates above the surface, demonstrates this clearly. The centre of the disc moves further downwards until it touches the surface at about 260 µs (±10 µs). It is only now that acceleration of the disc begins, continuing until the disc is bent completely. At about 330 µs (±10 µs), the disc lifts off the surface. The centre of mass can now be located more precisely at about 0.50 mm (±0.05 mm) above the surface because the centre of mass of a thin spherical cap is found at exactly half of the height.

With the data above and with the assumption of uniform acceleration, acceleration can be calculated in two ways:

1) with speed and time

$$a = \frac{v}{t} = \frac{3.6ms^{-1}}{70\mu s} = 51430\ ms^{-2}\ (\pm 15000\ ms^{-2}) \approx 5100g$$

2) with speed and distance

$$a = \frac{v^2}{2s} = \frac{(3.6ms^{-2})^2}{2 \cdot 0.2mm} = 32400\ ms^{-2}\quad (\pm 21000\ ms^{-2}) \approx 3200g$$

Due to the simplifications made here, congruence can only be expected within a certain order of magnitude.

Figure 9 also shows that the disc jumps up if it has been placed on the surface the 'wrong way', this means convex-side down. In this case, the edge of the disc accelerates downwards, touches the surface and consequently the disc jumps upwards. This effect is even stronger if the disc is put on a ring with a diameter of about 23mm, such as on the neck of an open bottle, as described by McNeil [2].

Acknowledgements

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References

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[3] www.jumpingdisc.com *and* www.grand-illusions.com

[4] Lapp D 2008 Exploring 'extreme' physics with an inexpensive plastic toy popper *Physics Education* **43** 492-3

[5] http://www.vacuumschmelze.de/dynamic/en/home/products/materialsampparts/physical/thermobimetals/vacoflex.php

[6] http://wurmb.at/ . Many thanks for providing helpful information.

[7] Ein aus zwei übereinanderliegenden Metallen bestehendes Plättchen *(A small disc consisting of two metals lying upon one other)* 1929 *Patent no*. 487164, Reichspatentamt, Deutsches Reich.

[8] The video *jumping_disc.avi* can be downloaded from *stacks.iop.org/physed/44/612*. The video was made with a high-speed camera from Xcitex Incorporated (*www.xcitex.com*) and analysed with the associated software MiDAS. But it is also possible to view this video file with other video software. The video contains only 40 frames!

Christian Ucke is a physicist and retired from the Technical University Munich in Germany in 2007. He has been interested in the physics of toys for more than twenty years and has published papers mainly in German about this theme. These publications can be seen on his homepage
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