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Spinning Top Carousel

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Tops do not necessarily have to rotate on their tip or on a solid surface. In the toy presented here, two suspended tops use an ingenious friction coupling to make a support rod rotate by taking on the angular momentum from the tops.

The spinning top carousel shown in Figure 1 consists of a stand with a concave area at the top, a horizontal wooden support rod and two suspended spinning tops.

Fig. 1: Spinninng top carousel

Each of these classic hand-propelled wooden tops contains a thin, cylindrical magnet in its axis, and the flat surface of the magnet is at the peak of the top's handle.

In the concave area at the top of the stand, there is a short pin with a small steel ball about 2 mm in diameter.

At the bottom of each needle-shaped steel pin at the ends of the support rod, there is also a small steel ball about 2 mm in diameter. As shown in Figure 1, the two balls have picked up the spinning tops, each of which was initially rotating on its base [1, video] and is now held there through magnetic attraction.

Due to the attraction of the magnetic axes of the spinning tops, they are now hanging down like the pans of classical scales. Since the tops have the same weight, the system is balanced like well-balanced scales. Each of the tops has a mass of 14 g, which is dimensioned to keep them hanging tightly enough on the pin so that they will not drop off immediately, even if they rock slightly while rotating.

The real trick is to bring the two spinning tops, one after the other, to the highest possible speed by hand as quickly as possible, then to attach them quickly to the horizontal support rod and then to place the rod with the spinning tops carefully onto the stand. Up to 2000 rpm, a typical rotational speed for small, hand-turned tops, for example, can be reached on a smooth surface like a hollow shaving mirror. Since this procedure requires quite a bit of time and skill, the attached tops in our experiments usually spin at speeds of only around 1500 rpm.

The term carousel only makes sense after the support rod has been put on the stand, making the rod itself start to rotate with the still spinning tops. As the support rod with the two tops rotates faster and faster, the speed of the spinning tops decreases rapidly until they come to a fairly quick standstill. Afterwards, the system with the support rod loses speed due to friction until it also comes to a stand-still. Since it is almost impossible to spin both tops at exactly the same rotational speed and also to attach them simultaneously, one of the two tops usually comes to a standstill before the other. As long as one of the tops is still turning, it continues to propel the rotation of the support rod. Inertia causes this rotation to continue even after both tops have come to a standstill. By the way, blowing through a straw onto the hanging tops from the side is also a quite effective way of setting the system in rotation.

The main attraction of the toy is the first-hand experience of the amazing transfer of the spinning top's rotation onto the whole system. The system then exhibits two rotations, one around the axis of each of the tops and one around the central stand. Tops which are small globes, as in our self-construction in Figure 2, especially resemble a kind of planetary system in which rotations also interact with each other through gravitational coupling.

Fig. 2: In this self-built planetary top carousel two small terrestrial spheres rotate around a center.

Why does the support rod rotate?

Although the magnetic attachment of the support rod's steel ball to the top's magnetic plane involves very little contact surface and thus low friction, this friction is, nevertheless, strong enough to exert a small frictional torque with respect to the axis of rotation in the middle of the rod. The torque is maintained by the tops as long as they are still spinning; when combined with the rotating rod holding the tops, the speed is propelled up to a maximum. The tops then slow down very quickly. They not only transmit angular momentum and energy to the rotating rod, but also lose it through friction in their own magnetic attachment.

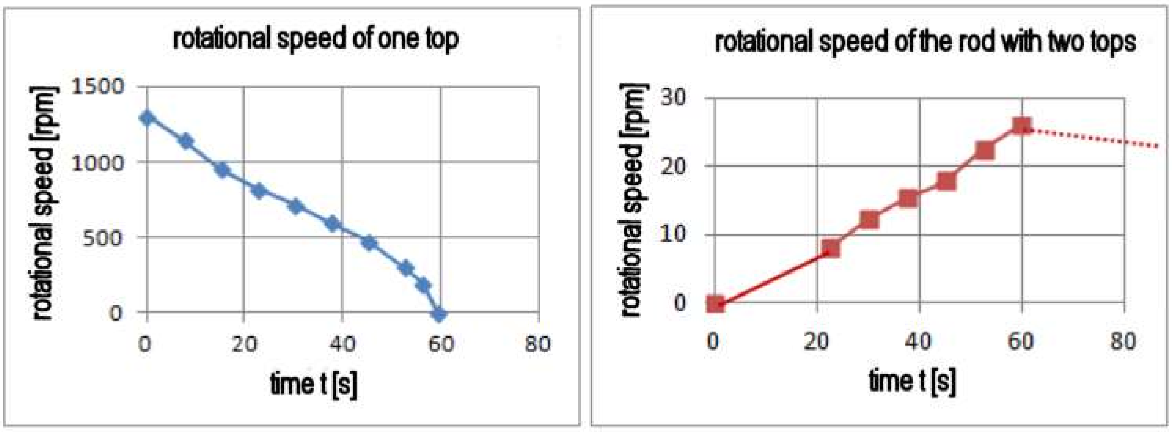

Fig. 3: Speeds of a gyro and the holding rod as a function of time, the measured values are based on video

To obtain a quantitative picture of the processes, we set one top in rotation while the other acted as a stationary counterweight (see also "Energy flow in the spinning top carousel" on p. 3). With the help of a video recording [2], we determined the speed of rotation of the top and of the support rod with the two tops as a function of time. Figure 3 shows the two tops plotted against each other. The speed of the spinning top decreases continuously until it comes to a standstill after about 60s, while the speed of the support rod increases continuously during the same time up to a maximum of about 26 rpm. Out of inertia, the support rod then rotates inertly for about another 100 s until it also comes to a standstill.

How well the system is propelled by the two tops depends largely on the frictional coupling. With the help of the magnetic hanging device, the direction of action of gravity is reversed. By changing the magnets, for example, the strength of the magnetic attraction and thus the frictional force between the parts attracted toward one other could be varied in a targeted manner. On the one hand, this gives you a fairly free choice of tops to attach. On the other hand, the frictional force, which is dependent on the attraction force and is largely responsible for the deceleration of the tops, can be made as small as possible. Of course, the fact that the friction must not fall below a certain optimal value must be taken into account because the transmission of the torque is dependent on a sufficiently high frictional force. This is a subtle optimization problem that has to be dealt with.

The spinning top carousel is a real challenge for further experiments, some of which are mentioned here:

- No matter how fast you spin one top or the other, it is the sum of the torque transmitted that determines the propulsion of the system.

- If one top is spun to the left and the other to the right, it is the difference between their individual torques that determines the speed and the direction of rotation of the system.

- The system remains still when the spinning speed and the friction in the opposite direction of the spinning tops are equally great.

- Friction can be reduced by carefully rubbing the magnets and/or steel balls with candle wax. It can, on the other hand, be increased by attaching a tiny piece of self-adhesive paper onto the magnet of the top axis.

Fig. 4: This self-construction consists of a balance-like arrangement of two disks suspended from a magnet with very low friction. The disks are concave, so that the rotating tops are trapped in them (see video [3]). Here, one top is replaced by an equivalent weight.

We were also interested in the idea of using the friction torque in a differently designed do-it-yourself construction (Figure 4). For this purpose, we glued two slightly roughened concave plastic discs onto a wooden disc attached to the bottom of a long, thin iron rod in the centre of gravity of this arrangement. The upper tip of the rod is suspended with low friction from a magnet. The whole construction rotates the same way as the spinning top carousel when fairly small spinning tops are placed on the plastic disks. Since the friction torque is very low, the masses used must also be small [3]. Here, too, some optimization was necessary before the system worked.

We hope that such ideas will inspire you, dear readers, to invent further designs and would appreciate receiving feedback.

Energy flow in the spinning top carousel

Using the dimensions of the individual parts of the spinning top carousel and the measurements of the speeds of the top and the system with the support rod (Figure 3), we derive an energy estimate for what happens when only one top is set in rotation and the other serves as a stationary counterweight. Considering the top as a homogeneous, cylindrical disk (d = 4.5 cm; m = 13.8 g), we calculated a moment of inertia of

$I_{K2ber} = 0{,}5 \cdot m \cdot (d/2)^2 = 0{,}5 \cdot 13{,}8\,g \cdot 2.25^2\,cm^2 = 35\,g\,cm^2$.

Our measurement turned out to be $I_{K2} = 37\,g\,cm^2$, so the simplified approximation fits quite well.

Now we need the moment of inertia of the support rod in relation to its center (l = 9.7 cm; m = 1.85 g), assuming that the rod is homogeneous and uniformly thick over its length. The result is

$I_{Stber} = ml^2/12 = 14.5\,g\,cm^2$.

One measurement resulted in: $I_{St} = 14.8\,g\,cm^2$. The moment of inertia of a top (m = 13.8 g) suspended from the rod at a distance of 4.25 cm from the center of the holding rod is now (with I_{St})

$I_K = 13.8\ g - 4.252\,cm^2 + 14.8\,g\,cm^2 = 264.1\,g\,cm^2$.

The total moment of inertia for the two suspended tops plus the rotating rod is

$I_G = 2\text{-}264.1\,g\,cm^2 + 14.8\,g\,cm^2 = 543\,g\,cm^2$.

The energy of a single rotating top at the beginning at a realistically achievable speed is

$E_{rot1} = 0.5 \cdot I_{K2} \cdot \omega^2 = 0.5 \cdot 37\,g\,cm^2 \cdot 136.32\,s^{-2} = 343\,687\,g\,cm^2 s^{-2}$,

with $\omega = 2\pi \cdot 1300$ rpm $= 136.1\,s^{-1}$, taken from Figure 3. As soon as one top has come to a standstill, the energy of the rotating rod with both tops at that moment is

$E_{rot2} = 0.5 \cdot I_G \cdot \omega^2 = 0.5 \cdot 543\,g\,cm^2 \cdot 2.72\,s^{-2} = 1979\,g\,cm^2 s^{-2}$,

with $\omega = 2\pi \cdot 26$ rpm $= 2.7\,s^{-1}$, taken from Figure 3.

Conclusion

Only an extraordinarily small amount (just under 0.6 %) of the rotational energy initially stored in the top is left in the rotational energy of the rod with both tops immediately after it has come to a standstill. With two rotating tops, we would get roughly 1.2 %. From the point of view of energy, the system is extremely inefficient, which is, of course, irrelevant for a toy.

References

1] Video on the functioning of an original spinning top carousel: https://t1p.de/Karussellkreisel1

2] Video with 240 fps for Figure 3: https://t1p.de/Karussellkreisel2

3] Video with 30 fps for Figure 4: https://t1p.de/Karussellkreisel3

4] Carousels with spinning tops in different variations are available from

Unique Wood Art, Kurt Jürgen Weigl, Daimlerstr.1, 71254 Ditzingen Schöckingen,

http://unikate-holzkunst.de

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