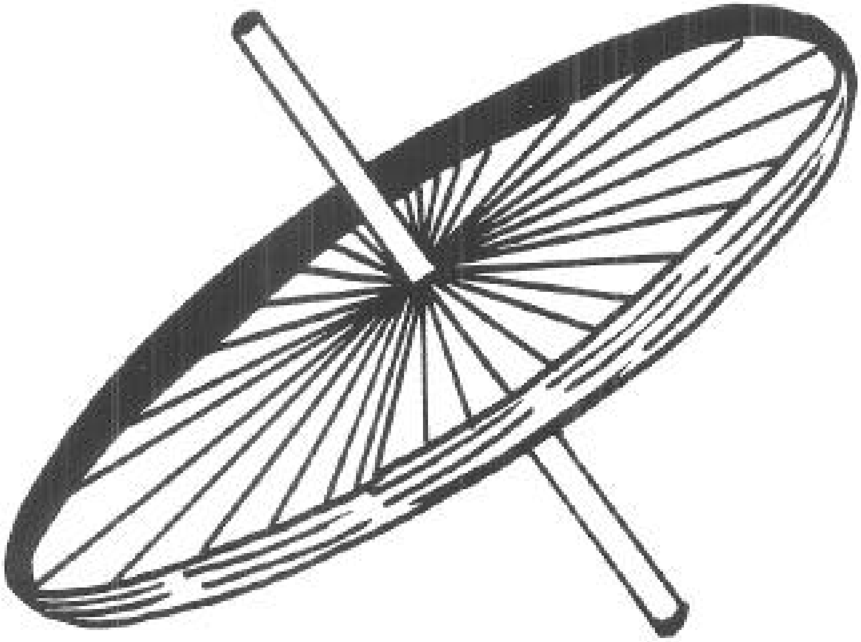
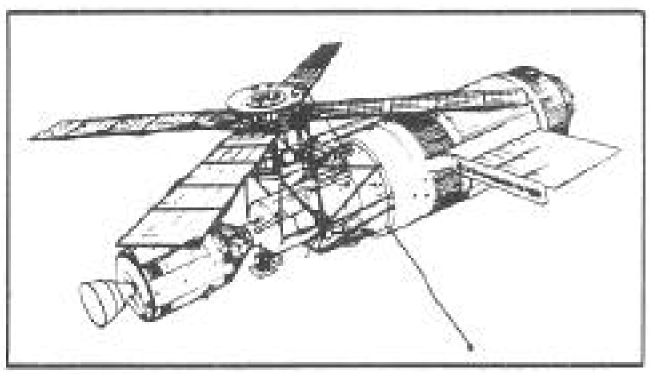
A Teachers Guide for the Videotape
Segment 7

Starts at 12:26:27
Run Time 02:09:03

GYROSCOPES





FILM FOOTAGE FROM NASA SKYLAB MISSIONS

National Aeronautics and Space Administration

Edited and Produced for the AAPT
by Thomas Campbell
and Robert Fuller

I. Introduction

A rotating gyroscope may serve as an important guidance device because of its tendency to remain stable in space. The type of motion referred to as "gyroscopic" motion, which includes this stability in addition to other special features, can be seen in many objects. Consider, for example, a frisbee. If the disk is thrown without rotation the air produces a resistant force which causes it to flip end over end, so that its mechanical energy is quickly frittered away. But if it is simultaneously thrown and given a spinning motion, angular mementum provides stability to the spinning disk, and its initial orientation tends to be preserved.

What is the nature of this stability of objects such as rotating gyroscopes and spinning frisbees? How does the motion of a gyroscope in a weightless environment such as that of Skylab compare to the motion of a gyroscope on earth? The experiments shown in this film help provide answers to these questions.

II. Background Physics

This film concerns the dynamic aspects of the motion of a gyroscope. Let us consider the object sketched in Fig. 1.

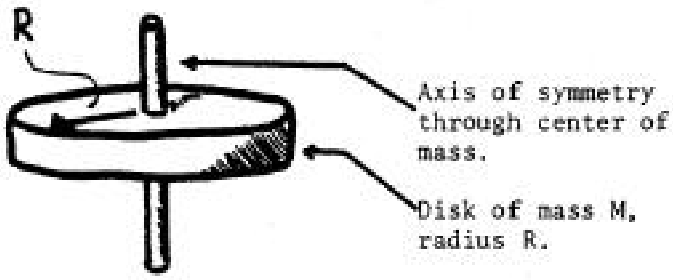


Figure 1

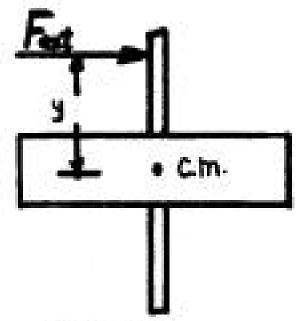


Figure 2

A. Disk not rotating.

First let us consider the system with no initial rotation. If placed at rest with respect to our reference frame it will remain at rest if no external forces are applied. But suppose an impulsive force $\vec{F}$ is applied perpendicular to the symmetry axis at a distance y from the center of mass, imparting an impulse $\vec{F}\Delta t$ to the system. (See Fig. 2.) What is the subsequent motion of the disk-axis system?

We have both translation and rotation to consider.* To describe the translation the fundamental equation is

$$\vec{F} = M\, d\vec{v}_{cm}/dt,$$

where $\vec{v}_{cm}$ is the velocity of the center of mass and $\vec{F}$ is the net external force. Since the initial velocity relative to our coordinate system is zero, we may integrate this equation to obtain

*See references, Section V

$$\vec{v}_{cm}(\text{final}) = \frac{1}{M}\ \vec{F}\ \ \Delta t,$$

for the translational velocity given the system by the applied impulse. For a body free to move in a plane, as this one is, the rotation is described by

$$\vec{L} = I_{cm}\ \vec{\omega},$$

where $\vec{L}$ is the angular momentum about an axis passing through the center of mass, I_{cm} is the moment of inertia of the body about that axis and $\vec{\omega}$ the angular velocity about the same axis. The equation of motion for the rotation may be written

$$\frac{dL}{dt} = d(I\omega)_{cm}/dt = \tau = \frac{d(yF)}{dt}$$

where the external torque, τ is equal in magnitude to yF for this simple case. The direction is given by the cross product $\vec{r} \times \vec{F}$, and is into the plane of the paper. For an impulsive force the equation may be integrated to give

$$\omega(\text{final}) = \frac{1}{I}\ yF\ \Delta t,$$

since the initial angular velocity is zero. The composite motion produced by the impulse is illustrated in Fig. 3. Note that the final linear velocity of the center of mass is in the direction of the applied impulse, and the angular velocity is about an axis through the center of mass and <u>into</u> the plane of the paper.

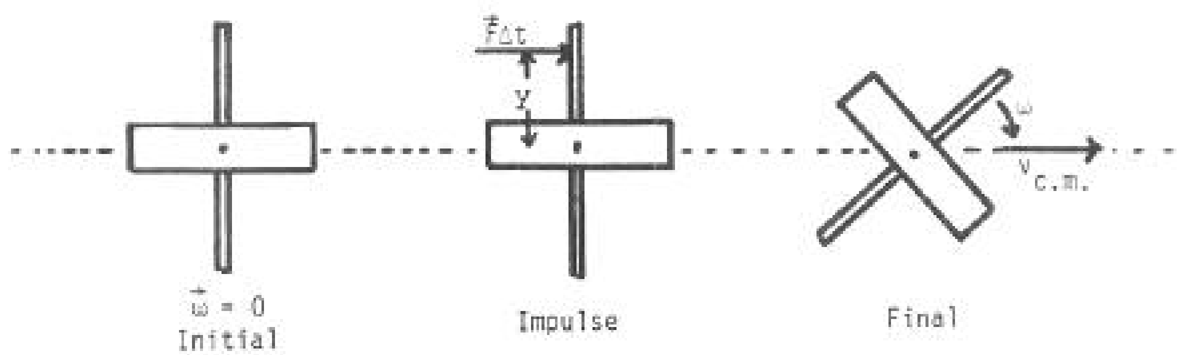


Figure 3

B. Disk rotating.

Now let us consider the case in which the disk is initially rotating about its symmetry axis with the direction of the angular mement $\vec{L}$ up. Because of conservation of angular momentum the rotating disk displays a stability not shown in situation A. An impulsive force applied as indicated in Fig. 2 will again result in an impulsive torque on the system, just as before, but the change in angular momentum is so small in comparison with the initial angular momentum that no perceptible change in the direction of spin occurs. At the same time, since the system had no initial translational velocity, the change in $\vec{v}_{cm}$ is readily apparent.

On the other hand, if a large torque is applied to the system a change in angular momentum will be easily seen. One way to increase the torque is to increase the time Δt during which the force $\vec{F}$ is applied. This can be accomplished by using a "couple" of forces as shown in Fig. 4. The net external force provided by a force-couple on the system is zero; thus no translational velocity is introduced and the center of mass of the disk remains in one place. As a result of the lack of translational velocity the astronaut can apply the forces over a longer period of time, and produce a significantly larger torque at right angles to the original angular momentum. The direction of the applied torque is into the plane of Fig. 4, and therefore the vector L will reorient itself to point slightly into the page. Note that the change in angular momentum is a vector in the direction of the applied torque.

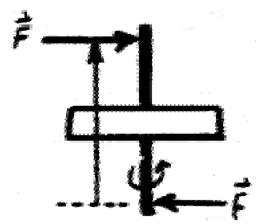


Figure 4

III. Film Synopsis

Section 1. Gryoscope not spinning (no angular momentum).
Scene 1: Astronaut Carr is shown in Skylab's orbital workshop illustrating the motion of a gyroscope.
Scene 2: Title "Gyroscopes"
Scene 3: Close-up shows Carr's striking "nonspinning" gyroscope with a soda straw. (Note: Gyroscopes' gimbal is in place.)

Section 2. Gyroscope Spinning (Angular Momentum Present.)
Scene 1: Carr holds gyroscope using the gimbal as a "handle" and spins by pulling a string wrapped around the gyroscope shaft. Carr then releases the gyroscope from the gimbal. This leaves the gyroscope with its spin vector ($\vec{\omega}$) pointing upward. In the sequence which follows, Carr performs the following noteworthy experiments and/or demonstrations.

a) Translation - a push or force on the gyroscope produces translation but no noticeable tumbling rotation.

b) Illustration Spin Direction - Carr illustrates direction of spin with right hand rule. He then holds schematic sketch which further illustrates the gyroscope's spin and position of the spin vector ($\vec{\omega}$).

c) Force Couple Applied - Close up of Gyro shows Carr exerting a force couple (see note below) which produces a change in the gyroscope's orientation in space.

As Carr provides the external torque, the gyroscope's orientation changes from spin UP to spin IN. (These directions of UP, and IN are relative to your screen picture.)

d) Force Couple Reversal - Next Carr reverses the direction of the applied torque. The gyroscope responds to this applied torque by turning from Spin-In to Spin-Out.

Scene 2: Additional Sequence - The last sequence shows the gyroscope again turned by the application of a soda-straw torque.

IV. Questions and Exercises

To assist you in solving the problems given below, the following data concerning the gyroscope pictured in the film is given.

Mass = 200 grams

Radius = 6_{cm}

Axis length = 8 cm (Total Length)

1. Scene 3 of Film Section one shows a non-spinning gyroscope receiving an impulse. To analyze this filmed sequence do the following:

a) Place a large white sheet of paper (or newsprint) on the wall as a projection screen.

b) As the scene runs from beginning to end, stop frame the projector several times while using a stopclock to measure the time interval between successive stopframes. Each time the motion is stopped trace the outline features of the gyro showing the location of the center of mass and the gyro's axis.

c) From the data you collected, determine the velocity of the center of mass, the direction of motion of the center of mass, and find the rate of rotation of the gyro about its center of mass. (Note: For prerequisite or background information not found in these films notes, see Human Momenta, another AAPT Skylab film.)

2. Obtain an inexpensive gyroscope (on sale in most large toy departments) and recreate the scenes of Section 2 for a spinning gyroscope.

A. In what ways does your gyroscope respond the same as the gyro featured in the film? In what ways is it different?

B. When your gyroscope is placed on a table and tilted slightly, it begins to move in a periodic motion known as "precession." What is the cause of this precession? Does the gyro shown in the film precess?

3. Using data collected from question 1, calculate the impulse imparted to the gyroscope by the straw. (You should correct the measured film time using the following relation, real time = 18/24 film time.)

4. Suppose that the gyroscope filmed aboard Skylab was 100 times more massive. Carefully describe the motion of astronaut Carr, assuming he is not touching Skylab's interior, as he applies the soda-straw torque of film Section 2, Scene 1, Section C.

5. Large massive gyroscopes were used aboard Skylab to control its attitude in space. Use the results of question 4 to explain qualitatively how this might be done.

V. References

Sears and Zemansky, University Physics, Fourth Edition Chapter 9 Addison-Wesley, 1970

Halliday and Resnik, Fundamentals of Physics, John Wiley & Sons, 1974

PSSC College Physics, Chapter 19, Raytheon, 1967

Grant R. Fowles, Analytical Mechanics, 2nd Edition, Holt, Rinehart & Winston (1970) especially Section 8.9