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METHODOLOGICAL NOTES

DEMONSTRATION WITH CONDUCTING GYROSCOPE IN A MAGNETIC FIELD

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WHEN a massive conductor moves in a magnetic field, eddy currents are produced in the conductor, and their magnetic moment, interacting with the external field, influences the motion of the conductor itself. This phenomenon, which is important for geomagnetism[1] and for the motion of artificial satellites in the earth's magnetic field,[2] is of general physical interest.[3] The theory of motion of a conducting gyroscope in a magnetic field was considered in papers by E. N. Kuznetsov.[4]

Certain features of the behavior of a conducting gyroscope in a magnetic field can be observed in sufficiently simple experiments and explained within the framework of elementary gyroscope theory. For these experiments one uses a free symmetrical gyroscope made of a bulky conductor, balanced on a Cardan suspension (the diameter of the gyroscope brass disc is 110 mm and its thickness is 20 mm). The gimbals of the Cardan suspension are slotted, to prevent induction currents from flowing in them when they move in the field. The gyroscope is placed between the poles of an electromagnet, the field intensity of which is 1000 Oe at a gap length of 200 mm. There are no magnetizing parts in the gyroscope. The gyroscope is set in rotation by a string wound on its axis, and therefore its angular velocity does not exceed 1000 rpm. In the first experiment, a rather interesting phenomenon was observed—orientation of the axis of the gyroscope's own rotation along the force lines of the magnetic field. The magnet is de-energized and the axis of the gyroscope is set at an angle 40–50° to the direction of the field, and the gyroscope is then set in motion. The magnetic field is then turned on, and the axis is seen to change its position until it is parallel to the magnetic field. The experiment should be repeated with the direction of gyroscope rotation and (or) field reversed. In all cases the gyroscope axis turns in the shortest way in the direction of the magnetic field, describing the arc of the acute angle between its initial position and the field direction.

It turns out that the gyroscope angular momentum vector assumes a position parallel or antiparallel to the magnetic field vector, depending on whether the angle between them in the initial position was acute or obtuse. Thus, the rotation axis of a conducting gyroscope becomes oriented along the force lines of the magnetic field but, unlike the magnetic compass needle, it does not indicate the direction of the vector of the magnetic field. An illustrative explanation of this phenomenon can be provided by the following experiments with special initial conditions.

In the second experiment, the gyroscope axis is set perpendicular to the field prior to application of the field. After the magnetic field is turned on, the gyroscope is decelerated and stops rapidly; its axis remains stationary. This experiment is best considered in a stationary reference frame with origin at the mass center of the gyroscope (Fig. 1). Let the magnetic field vector **H** be directed along the Z axis and the angular momentum vector **N** along the Y axis. In such an arrangement, three-dimensional eddy currents are produced in the brass disc of the gyroscope; the direction of these currents on the visible side of the disc is shown by the arrows in the figure. The magnetic moment of these currents $\mathbf{P}_m$ is proportional to the angular velocity of rotation ω and to the magnetic field intensity **H**, and is directed along the X axis. When the direction of the gyroscope rotation or of the magnetic field is reversed, the magnetic-moment vector direction is also reversed. In all these cases, when the gyroscope axis is perpendicular to the field, the gyroscope is acted upon by a mechanical moment $\mathbf{M} = \mathbf{P}_m \times \mathbf{H}$, directed opposite the angular momentum vector and causing only deceleration of the gyroscope. The magnitude of the mechanical moment is proportional to the square of the field intensity.*

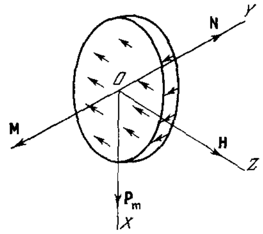

FIG. 1

The third experiment is performed with the initial position of the gyroscope axis along the force lines of the magnetic field (along the Z axis). After the magnet is turned on, no change in the rotation speed of the gyroscope or in the position of its axis is observed. The result of the experiment does not change if the direction of the gyroscope rotation or the direction of the magnetic field is reversed. The rotation of the gyroscope is gradually slowed down only by the friction forces, just as in the absence of a field. This is connected with the fact that when the gyroscope axis is directed along the field and the rotation speed is constant, there are no eddy currents; the magnetic and mechanical moments are then equal to zero.

*At gyroscope rotation speeds greatly exceeding those used in these experiments, the distribution of the eddy currents should change in such a way [3], that the magnetic moment vector is inclined in a direction opposite to the vector **H**. The effects described here should then become weaker.

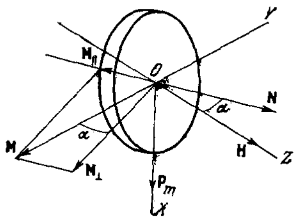

FIG. 2

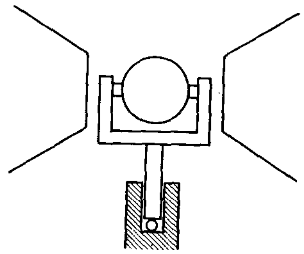

FIG. 3

In the general case, the initial position of the vector N makes an angle α ($0 < \alpha < \pi$) with the vector H, corresponding to the first experiment (Fig. 2). In the same reference frame, at the chosen directions of the vectors N and H, the vector of the magnetic moment P_m is directed along the X axis, and its magnitude decreases with decreasing angle α. The mechanical moment M is best resolved into components parallel to the gyroscope axis, $M_{\parallel} = P_mH \sin\alpha$, and perpendicular to it $M_{\perp} = P_mH \cos\alpha$. $M_{\parallel}$ is directed opposite to the vector N and decreases its magnitude, causing deceleration of the gyroscope. $M_{\perp}$ changes the direction of the vector N, thus explaining the rotation of the gyroscope axis towards the field direction, as observed in the first experiment. This rotation of the axis can be regarded as a precession of the gyroscope about an axis perpendicular to the plane in which the vectors N and H lie. The angular velocity of the precession, $\Omega = d\alpha/dt = P_mH \times \cos\alpha/N$. When the gyroscope axis is oriented along the field, the magnetic and mechanical moments vanish, and the precession stops. Considering also cases when the initial directions of the vector N and (or) vector H are reversed, it is easy to verify that the motion of the gyroscope axis will always follow the shortest path towards the direction of the force lines of the magnetic field. The vector N should become parallel to the vector H, if the angle α between them was acute in the initial position, and antiparallel if this angle was obtuse.

All these features of the behavior of a conducting gyroscope were observed in the first experiment. The choice of the initial position of the gyroscope axis ($\alpha = 40-50°$) is convenient because in this position the deceleration is weakened to a sufficient degree and the gyroscope has time to become oriented along the field, retaining its own rotation.

The lack of motion of the gyroscope, observed in the second experiment when its position was perpendicular to the field, is connected with the fact that in this position the component $M_{\parallel}$, which causes deceleration of the gyroscope, is maximal, while $M_{\perp}$ is equal to zero. In this case, the freely rotating gyroscope has time to stop before the inaccurate setting of its axis perpendicular to the field comes into play. If one degree of freedom is eliminated from the gyroscope, by tying together the gimbals of the Cardan suspension, then at a definite position of the remaining two mutually perpendicular axes relative to the field it is possible to observe the same phenomena. Therefore, for a lecture demonstration, it is possible to use successfully a gyroscope of simpler construction with two degrees of freedom, for example in the form of a copper ball of 30 mm diameter (Fig. 3).

[1] W. M. Elsasser, Phys. Rev. 72, 821 (1947).
[2] V. V. Beletskiĭ, Kosmicheskie issledovaniya (Cosmic Investigations) 1 (3), 339 (1963).
[3] L. D. Landau and E. M. Lifshitz, Elektrodinamika sploshnykh sred, Fizmatgiz, 1959 [Electrodynamics of Continuous Media, Addison-Wesley, 1960].
[4] E. N. Kuznetsov, Izv. AN SSSR (Mekhanika), No. 4, 124 (1965); Dissertation (Moscow State University), 1966.

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OXYGEN LIQUEFIER FOR DEMONSTRATIONS

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THE significance and role of low temperatures in science and engineering increases continuously. However, in so far as we know, lecture demonstrations at which low temperatures and gas liquefaction are attained are practically nonexistent. We describe a small air liquefier, operating with a compressed-air flask. If a flask containing 40 liters of compressed air with initial pressure 150 atm is available, it is possible to obtain within 4 min liquid air in the Dewar of the instrument.

Figure 1 shows a photograph of the liquefier (without the flask). The operating principle of the instrument is based on the use of the Joule–Thomson throttling effect. Figure 2 shows a longitudinal section through the liquefier. Its construction consists essentially of a heat exchanger and a throttling valve, which are placed in an ordinary glass Dewar with inside diameter 50 mm (1—flange; 2—packing gasket of rubber; 3—packing of cotton thread; 4—foamed plastic filler; 5—thin-wall cylin-

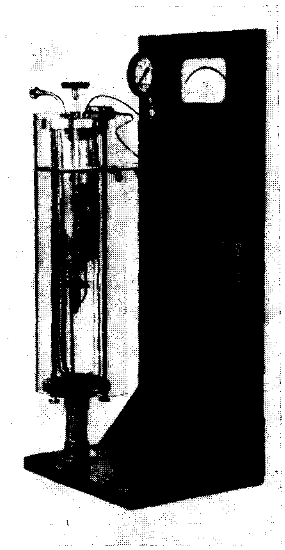

FIG. 1. Over-all view of liquefier.

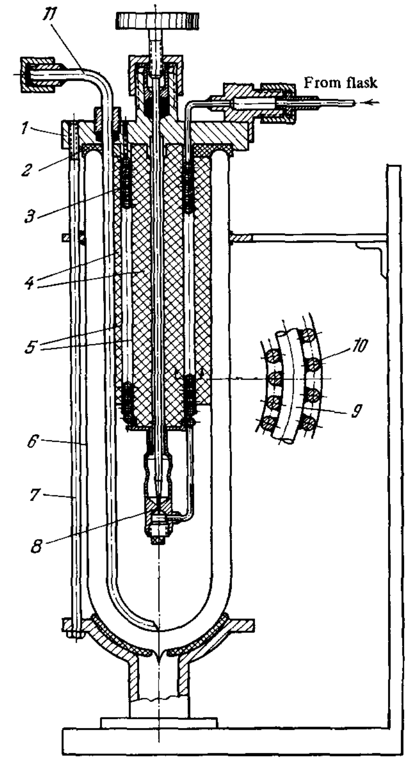

FIG. 2. Longitudinal section through liquefier.

ders of stainless steel; 6—glass door; 7—bolt; 8—throttle valve; 9—heat-exchange tube; 10—rib of copper wire; 11—siphon).

An effective coiled counterflow heat exchanger is made of five ribbed tubes wound helically in one layer between two thin-walled cylinders made of stainless steel. The diameter of the helical winding of the tubes is 30 mm, the total number of turns is 90. The tubes have an inside diameter 0.7 mm and an outside diameter of 1 mm. The ribs of the tubes are made by winding on them a round copper wire which is subsequently soldered to the tube. The wire diameter is 0.5 mm and its pitch is 1.5 mm. The throttle valve is of the usual design with a steel needle blocking an aperture of 1 mm diameter in a brass body.

Compressed air from the flask connected to the liquefier flows through the tubes of the heat exchanger to the throttle valve, is throttled in the Dewar, being cooled thereby as a result of the Joule–Thomson effect, and then returns to the heat exchanger, passing in the space between its tubes, cooling the direct flow, and finally escaping to the atmosphere through an opening in the flange. The accumulation of cold by the heat exchanger gradually lowers the temperature of the direct flow of the gas, and after 3–4 minutes the throttling of liquid air from the valve begins and its gradual accumulation in the Dewar, as can be observed through gaps in it. The instrument has a manometer for monitoring the pressure in the Dewar and a millivoltmeter to measure the thermal emf of a thermocouple inserted in the lower part of the Dewar—to demonstrate visually the cooling process and then the liquefaction. The liquefied air can be forced out from the Dewar through an open siphon by producing pressure in the Dewar by slight flow of air through the throttle valve. For normal operation of the liquefier, pure air is required, containing no moisture, oil, etc. We took compressed air from a commercial nitrogen liquefier, and the instrument operated many times without clogging the heat exchanger. A supply of air in the flask with a capacity of 40 liters with initial pressure 150 atm is sufficient to obtain 150 g of liquid air. The instrument can also liquefy any other gas whose inversion temperature is higher than room temperature, for example, nitrogen or oxygen.

In addition to demonstrating the cooling processes, followed by liquefaction of the gas in the Dewar, this instrument can be used to reveal, by means of the thermocouple readings, the integral effect of throttling from any pressure to 1 atm. To this end it is necessary to keep the siphon open to permit the emergence of the gas from the Dewar, bypassing the heat exchanger. One of the instruments constructed at our Institute is successfully used in the Physics Department of the Moscow State University and at the Khar'kov Polytechnic Institute.