Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia Engineering 32 (2012) 982 – 988

Procedia Engineering

www.elsevier.com/locate/procedia

I-SEEC2011

Jumping ring experiment: effect of temperature, non-magnetic material and applied current on the jump height

J. Taweepong, K. Thamaphat*, S. Limsuwan

Department of Physics, Faculty of Science, King Mongkut's University of Technology Thonburi, Bangkok 10140, Thailand

Elsevier use only: Received 30 September 2011; Revised 10 November 2011; Accepted 25 November 2011.

Abstract

The jumping ring experiment is an outstanding demonstration of Faraday's laws of electromagnetic induction and also of Lenz's law. A conducting non-magnetic ring is placed over the extended vertical core of a solenoid. When ac power is applied to the solenoid, the ring is thrown off or held in a state of levitation. This phenomenon happens because the induced current in the ring flows in the direction to counter that of the solenoid current. Consequently, two magnetic fields repel each other, giving rise to the jump effect. The induced current is corresponding to the jump height of a ring. In this work, the jump heights of brass, copper and aluminium rings subjected to different parameters such as temperature, vertical length of ring and applied solenoid current were investigated.

Keywords: Induced current; Jumping ring; Liquid nitrogen temperature; Lenz's law; Faraday's laws of induction

1. Introduction

The jumping ring experiment is an educational and fascinating demonstration in physics classrooms to illustrate the Faraday's laws of electromagnetic induction and Lenz's law as well. It is the basis for linear actuators for servomechanical purpose as well as induction heating and rail guns [1]. The jumping ring experiment was first exhibited by Elihu Thomson in 1887 at a meeting of the American Institute of Electrical Engineers and is therefore sometimes called Thompson's ring. It has been shown many times, since a notable example being that of Lord Rayleigh in 1891, at the Royal Institution in London, during a lecture to mark the centenary of the birth of Michael Faraday [2]. With modern sensors, electronics, and computers, students can investigate the factors that influence to the force on a conducting ring in an

* Corresponding author. Tel.: +66-2-4708961; fax: +66-2-4278785.
E-mail address: s903607@yahoo.com.

1877-7058 © 2012 Published by Elsevier Ltd.
doi:10.1016/j.proeng.2012.02.042

alternating magnetic field. The basic apparatus is illustrated in Fig. 1. It is made up of a conducting non-magnetic ring placed over the extended vertical core of solenoid or demountable transformer. When ac power is applied to the solenoid, the alternating current passing through the coil induced a current in a non-magnetic ring. The resulting force of repulsion makes the ring jump up. If the current is increased slowly, or the ring placed over the tube while the current is already flowing, the ring will levitate several centimeters above the acrylic former [2-3].

The jumping ring experiment is capable of development and experimentation. Several investigations have been reported [1-7]. In this work, the jumping ring apparatus is constructed and the jump heights of the aluminium, copper, and brass rings are considered when varying several parameters such as temperature, ring dimension, applied current to a solenoid.

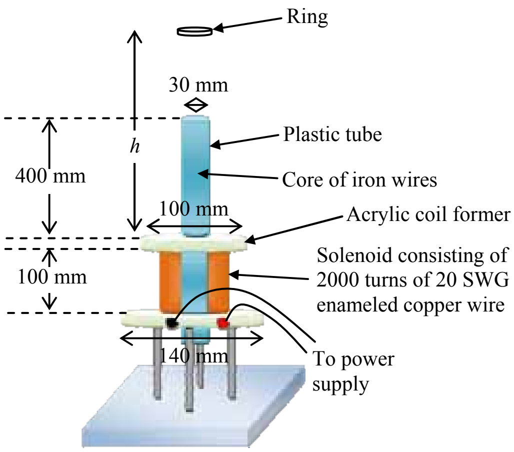

Fig. 1. Diagram of the jumping ring apparatus

2. Theory

When passing a sinusoidal current $I_s = I_0 \sin(\omega t)$ at a fixed frequency to a solenoid, an axial magnetic field with a radial component,

$$B_{\text{rad}} = \mu_0 n I_s K , \tag{1}$$

is induced [8]. Where n is number of wire turns per unit length of the solenoid, μ_0 is effective permeability of core of steel wires (see Fig. 1), and K is a geometrical constant. The strength of B_{rad} depends on the applied current I_s and the number of turns in the coil. The magnitude of the induced electromotive force (emf, ε) in a ring, which drives current through the ring I_r, is equal to the rate at which the magnetic flux Φ_B through that ring changes with time. The emf is described by Faraday's laws of electromagnetic induction,

$$\varepsilon = -\frac{d\phi_B}{dt} . \tag{2}$$

The minus sign indicates that the induced emf and the change in flux have opposite signs.

An induced current I_r has a direction such that the magnetic field in the ring B_r due to the current I_r opposes the change in the magnetic flux Φ_B [9]. This is known as Lenz's law for determining the direction of an induced current I_r. Because the ring current is opposite to the solenoid current, the two magnetic fields repel each other, giving rise to the jump effect. The upward force on a ring of radius a , which arises from the interaction between the current induced in the ring by the large axial alternating magnetic field of the solenoid and the radial component of the solenoid's fringing magnetic field [5, 8], is

$$F_{\uparrow} = 2\pi a I_r B_{rad} = 2\pi a \mu_0 n K I_r I_s \,. \tag{3}$$

By Faraday's laws of induction, the ring is an LR circuit with inductance L and resistance R. It can be shown that

$$I_r = \left(\frac{M I_0 \omega}{R^2 + \omega^2 L^2}\right)\left(R\cos\omega t + \omega L \sin\omega t\right), \tag{4}$$

where M is a mutual inductance between the ring and the solenoid. Substituting I_r in Eq. (4) into Eq. (3), it leads to

$$F_{\uparrow} = 2\pi a \mu_0 n K\left(\frac{M\omega I_0^2}{R^2 + \omega^2 L^2}\right)\left(R\sin\omega t\cos\omega t + \omega L \sin^2\omega t\right). \tag{5}$$

The term of $\sin\omega t\cos\omega t$ is equal to $\frac{\sin 2\omega t}{2}$, and represents a component of the force that oscillates with a frequency of 2ω. The $\sin^2\omega t$ term, which is equal to $\frac{1-\cos 2\omega t}{2}$, is equal to 1/2 when averaged over a cycle. Therefore, the time-averaged lifting electromagnetic force on the ring can be written as

$$F_{\uparrow} = \frac{\omega^2 L I_0^2}{R^2 + \omega^2 L^2}(\mu_0 n K M \pi a) \,. \tag{6}$$

Eq. (6) shows that the force on the ring is varied with the square of current in solenoid, frequency of AC power source, mutual inductance, ring inductance, ring resistance, ring dimension, and number of wire turns per unit length of the solenoid.

In 2008, Smith [3] explained that the optimum number of turns n, keeping all other variables constant, is

$$n = \frac{r}{\omega l}, \tag{7}$$

where l and r is inductance of a single turn and resistance of a single turn, respectively. Furthermore, he found that a ring material with the smallest resistivity (σ, $\Omega\cdot$m) and density (ρ, kg/m^3) production which give the greatest upward acceleration to the ring.

3. Materials and method

3.1. Construction of the jumping ring apparatus

A photograph of the constructed apparatus is shown in Fig. 2. Solenoid consists of 38 layers of 2000 turns of #20 copper wire wound around a plastic tube. The length of solenoid is 10 cm. The magnetic core is a close-packed set of 130 soft iron rods of 40 cm length and 2 mm diameter enclosed in a 30-mm-diameter plastic tube. In this work, different ring materials (copper, aluminium, and brass) of various vertical lengths (3, 6, 9, 12, 15, 18, 21, 24, 27, 30, 33, 36 and 39 mm), and fixed 3.5 cm inner diameter and 6.5 cm outer diameter, which were sliced from copper, aluminium alloy, and brass pipe, were determined (see Fig. 3). A conducting ring was placed over the extended core of a vertical solenoid and the jump height h was measured from the starting position of the ring.

3.2. Considering the chemical and physical properties of rings

Before jumping ring experiments, the chemical and physical properties of various rings were investigated. Due to the upward force corresponding to resistivity, the elemental purity and resistivity of rings were measured. The samples of copper, aluminium, and brass rings were selected to evaluate the purity of Cu, Al, and Cu and Zn, respectively, by standard test method for chemical analysis at the Department of Science Service, Ministry of Science and Technology (Thailand). Beside chemical analysis, the resistivity of rings was measured with a four-wire source meter Keithley, Model 2410 operated in current- reversal mode at a room temperature with three repetitions. Here, the presented results are average values.

Fig. 2. The experimental apparatus

(a) Copper rings (b) Aluminium rings (c) Brass rings

Fig. 3. A set of rings of various axial lengths sliced from copper, aluminum alloy, and brass pipe of fixed wall thickness

3.3. Jumping ring experiments

Experiments were performed in an attempt to understand the major factors such as applied voltage to a solenoid, ring mass and ring temperature affecting the jump height of rings. A set of copper, aluminium, and brass rings was produced. The mass was varied by making rings of different vertical length while keeping the same inner and outer diameters (see Table 1). The experiments were performed by placing the ring to be tested on to the acrylic coil former which was situated in front of ruler fixed to the wall behind. The power supply for the coil adjusted by VARIAC was set as 180 V, 200 V, and 220 V. The current through the solenoid was switched on, resulting in an instantaneous jump of the ring. It is important to appreciate that the solenoid current should be switched off immediately after the jump has occurred to avoid burning out the coil [2]. The maximum jump height of rings for room temperature (30 ºC) was then recorded. For the low temperature, the same procedure was followed, but this time the ring was cooled in liquid nitrogen contained in a dewar until the ring temperature as -45.93 ± 1.24 ºC and then quickly transferred to the acrylic former.

Table 1. Mass listed in order of vertical length of ring

Vertical Length of Ring (mm)	Mass (g)		
	Copper Ring	Aluminium Ring	Brass Ring
3	4.31	1.39	4.31
6	8.88	2.87	8.49
9	13.64	4.31	12.99
12	18.31	5.78	17.19
15	22.74	7.26	21.66
18	27.66	8.13	26.50
21	32.75	9.41	30.90
24	36.99	10.81	35.38
27	41.74	12.16	39.66
30	46.32	13.48	44.22
33	50.73	14.75	48.70
36	55.76	16.21	53.08
39	60.39	17.54	57.39

4. Results and discussion

The resistivity and elemental purity of rings are illustrated in Table 2. From Table 2, it shows the resistivity of aluminium ring > brass ring > copper ring. If the optimum number of wire turns per unit length of solenoid is used, therefore, a material with the smallest $\rho\sigma$ product will give the maximum acceleration to the ring. This also explains the enhanced jump height when the rings are cooled in liquid nitrogen.

Results of jump height as a function of mass for the copper, aluminium, and brass rings at room and cool temperature for applied voltage of 180, 200, and 220 V are shown in Fig. 4. The data confirm a peak jump height that grows, narrows, and shifts to smaller optimal mass when the rings were cooled. On the contrary, the response is much flatter at room temperature. The reasons for this were explained by Tjossem and Brost [5]. Clearly, at temperatures close to that of liquid nitrogen, there is a well defined

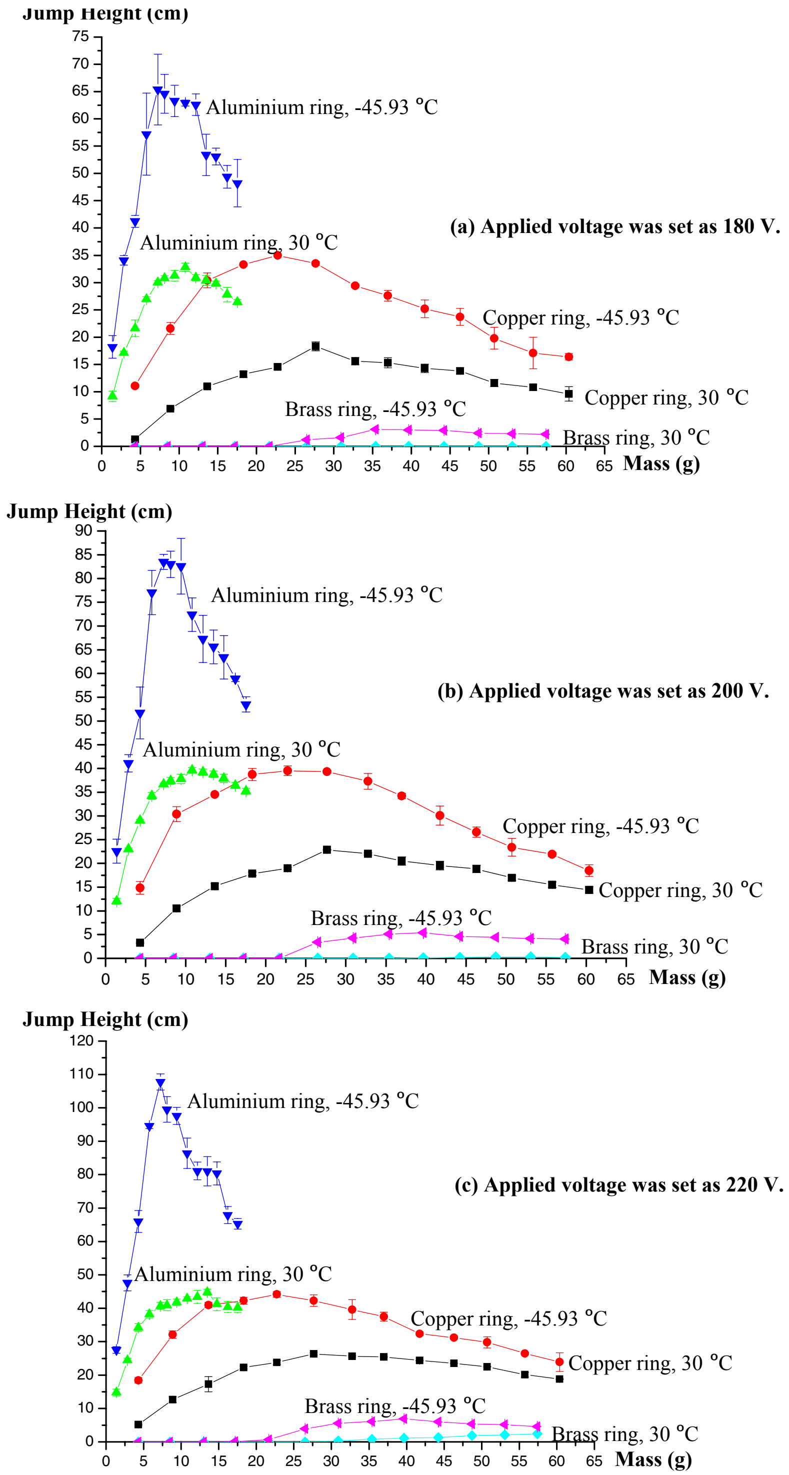

Fig. 4. The jump heights of copper, aluminium and brass rings at cool and room temperature for (a) 180 V; (b) 200 V; (c) 220 V

maximum jump height corresponding to an optimum mass to produce this effect for all materials. By lowering the temperature of the ring, its electrical resistance decreases and hence the induced ring current is increased. This, in turn, increases the strength of the magnetic field B_r, thereby causing the ring to jump higher. The present of other defects, such as impurities, will also result in an increase in resistance, caused by distortion of the crystalline structure within material. This will affect the flow of electrons, as well as the orientation of atoms, making direct collision more likely [2].

At the same applied voltage and temperature, aluminium ring achieved the highest jump height when comparison with other materials. The cause of this phenomenon is the value of $\rho\sigma$. Anyway, at the same temperature, the jump height increased with increasing of applied voltage because the upward force is proportional to the square of current in the solenoid [8].

Table 2. Composition and resistivity of rings

Material	Resistivity (10^{-6} Ωm)	Analyzed Element	Purity Percentage
Copper	1.17	Cu	99.92
Aluminium	1.37	Al	99
Brass	1.29	Cu	58.3
		Zn	38.19

5. Conclusion

The jumping ring apparatus is described. It is a striking demonstration of Faraday's laws of electromagnetic reduction and also Lenz's law. It can be constructed with inexpensive parts, and others are often found unused in laboratory. The jumping ring experiment is therefore suggested to demonstrate for introductory students or a more involved laboratory tool for advanced student.

Acknowledgements

The present study was financial supported by the Faculty of Science, King Mongkut's University of Technology Thonburi.

References

[1] Tjossem PJH, Cornejo V. Measurements and mechanisms of Thomson's jumping ring. *Am J Phys* 2000; **68**: 238-244.
[2] Baylie M, Ford PJ, Mathlin GP, Palmer C. The jumping ring experiment. *Phys Teach* 2009; **44**: 27-32.
[3] Ford PJ, Sullivan RAL. The jumping ring experiment revisited. *Phys Educ* 1991; **26**: 380-382.
[4] Sumner DJ, Thakkrar AK. Experiments with a 'jumping ring' apparatus. *Phys Educ* 1972; **7**: 238-242.
[5] Tjossem PJH, Brost EC. Optimizing Thomson's jumping ring. *Am J Phys* 2011; **79**: 353-358.
[6] Tanner P, Loebach J, Cook J, Hallen HD. A pulsed jumping ring apparatus for demonstration of Lenz's law. *Am J Phys* 2001; **69**: 911-916.
[7] Smith JMB. The jumping ring and Lenz's law - an analysis. *Physc Educ* 2008; **43**: 265-269.
[8] Hall J. Forces on the jumping ring. *Phys Teach* 1997; **35**: 80-83.
[9] Halliday D, Resnick R, Walker J. *Fundamentals of physics*. 6th ed. New York: John Wiley & Sons, Inc.; 2001.