

Measurement of radius of a metallic ball using eddy current testing based on peak frequency difference feature

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Abstract — This paper proposes a linear eddy-current feature to determine the radius of a metallic ball in a non-contact manner. An electromagnetic eddy-current sensor with two coils is placed co-axially to the metal ball during measurement. It is well known that the distance between the sensor and test piece (i.e. lift-off) affects eddy-current signals. In this paper, it is found that the peak frequency feature of inductance spectrum is linear to the lift-off spacing between the centre of coil and ball. Besides, the slope of peak frequencies versus lift-offs is linked to the radius of ball. The radius of metallic balls is retrieved from the experimental and embedded analytical result of the slope. Measurements have been carried out on 6 metallic balls with different radii. The radius of the metallic ball can be retrieved with an error of less than 2 %.

Index Terms — Eddy current sensor, lift-off variation, radius measurement, peak frequency feature, multi-frequency testing

I. INTRODUCTION

Conductive spherical balls are widely used in bearings applicable in robots, aircraft, automotive, and medical devices, for example, the spherical joint is used to support the flexible movements of the robots. Conductive spherical surfaces are used in screen EM interferences or used in certain containers/tanks for gas/oil storage/transportation. Hip replacement joint is an example of spherical surfaces in medical applications. Grinding balls are widely used in heavy industries. Moreover, the conductive coatings of the sphere object can also be estimated to ensure safety following this line of work. In addition, spherical balls are convenient to serve as calibration samples for material characterisation, in particular when the available sample size is limited. Normally, when using plate / cylindrical samples, there is a requirement that their sizes (planar dimension of a plate / height of cylindrical samples) should be significantly larger than the sensor coil dimension to eliminate edge effect.

Eddy-current (EC) is one of the most popular approaches exploited to inspect conductive materials. It is commonly used to assess the thickness of metal coating, to inspect the integrity of metal structures, to determine electrical conductivity and magnetic permeability of the material due to high sensitivity and good adaptability to tested objects [1-5]. This has become one of the main methods in non-destructive testing techniques. It is capable of testing the samples without contact with the samples while maintaining high precision and performance. As

the eddy current is measured, the alternating current is fed into the excitation coil to produce alternating magnetic fields and then induce eddy current in conductive samples. Thus, the transmitting coil receives a signal produced from the magnetic field produced from the exciting coil and the reflected signal from the sample. There are mainly two methods in the area of eddy current testing depending on the form of the excitation signal, i.e. pulsed eddy current (PEC), and multi-frequency eddy current (MEC). Multi-frequency eddy current testing has become a reliable technique for on-line and off-line measurements in our previous work. However, lift-off has a significant effect on the measurement's accuracy for either surface crack detection or material properties (conductivity, magnetic permeability, radius, thickness, etc.) measurements[6]-[11].

For certain cases, the examined objects can have a spherical surface and the radius of the sample may be determined by EC [12].

Several techniques have been proposed to address the issues caused by the lift-off effect. A hypothetical transformation model was applied in the PEC technique shows its effects in reducing the lift-off effect for planar geometry [13]. A new triple electromagnetic helix sensor was developed by Yin *et al.* and measurements were found to be resistant to lift-off variations [14]. Yin *et al.* showed that the phase signature is less sensitive to the lift-off of the non-magnetic metal plate compared with magnitude [15]. In addition, a compensation algorithm was developed by Lu *et al.* for reducing lift-off in thickness measurements for metallic plates. [16]. Yang *et al.* used a differential PEC probe and FFT transformation to classify the depth of the defect. It is found that the lift-off effect can be reduced under the lower band of frequency spectral and the depth can be extracted according to the peak amplitude [9]. This feature is further exploited in [17]. Abu-Nabah reduced the lift-off effect by using harmonic eddy current excitation and a GMR sensor configuration [18]. Other methods of using PEC and MEC is suggested to reduce the lift-off effect of the when measuring the thickness of the metallic film [20]-[21].

Our group have proposed the peak frequency, the zero-crossing, and the phase feature in the attempt to reduce the lift-off effect on sample property measurements [22]-[33]. A novel algorithm was proposed to solve the lift-off problem by estimating the thickness of metallic film based on the high-frequency characteristics of the sensor response [34]. A lift-off-

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tolerant pancake eddy current sensor was devised for the sensor to work at a larger range of lift-offs [35]. Another way to remove the lift-off effect is to work out the lift-off itself. When measuring at high frequency, eddy current thin skin effect can be exploited and a method based on the phase feature of the material can be used to achieve high accuracy [36]. The dual-frequency lift-off linearity, particularly at higher operating dual frequencies can be used to increase lift-off tolerance to 10 mm[37]. In addition to our previous work, the lift-off and sample parameters are explicitly retrieved from high-frequency features. However, these techniques only refer to the sample geometry of thin foils or slabs.

In this paper, the peak frequencies are found linear to the lift-off distance between the centre of coil and non-ferrous metal ball. With the capability of this method proposed, the integrity and quality of the objects in the examples mentioned can be tested in non-destructive and non-contact manner. Based on the peak frequency difference from two lift-offs, it can be applied to estimate spherical surfaces. For objects with plane surfaces, some investigations have been carried out to eliminate the lift-off effect, as reported in papers.[14][38]-[39]. Besides, the radius of metallic ball is retrieved by referring to the slope of peak-frequency versus lift-offs. Measurements have been carried out on six metal balls with different radii. The radius of metallic ball can be retrieved with an error of less than 2 %.

II. LINEARITY FEATURES AND RADIUS CALCULATION ALGORITHM

Fig. 1 shows the geometry of the air-cored EM sensor. The excitation coil and the receive coil are located co-axially above the spherical sample. These two coils have identical properties, i.e. size, turns and material.

A. Structure of the sensor

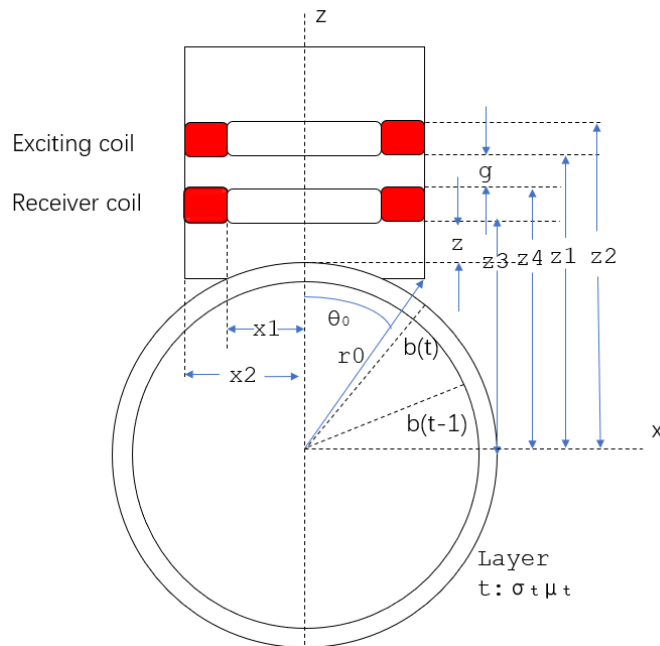


Fig. 1 Sensor structure

TABLE I
COIL PARAMETERS

Inner radius (x_1)	17.5 mm
Outer radius (x_2)	17.9 mm
The coil separation (g)	5.0 mm
The distance between the centre of the spherical sample and the lower/upper height of the excitation coil (z_1/z_2)	65.3 mm / 71.3 mm
The distance between the centre of the spherical sample and the lower/upper height of the receive coil (z_3/z_4)	52.3 mm / 60.3 mm
The distance between the sphere vertex and the lower height of the receive coil (z)	2.0 mm
The radius of the spherical sample (b_N)	140 mm or 160mm
Turns (N_1/N_2)	20 / 20

For the sensor setup, r_0 and θ_0 need to be mentioned particularly. Here r_0 denotes radial distance, and θ_0 denotes latitude. These two parameters can be used to locate the coil at space. The value of each parameter is shown in the table I. The conductivity value of each simulated metal is listed in table II.

TABLE II
METAL CONDUCTIVITY

Material	electrical conductivity (MS/m)
Copper	58.00
Brass	25.00
Aluminium	36.00
Zinc	17.40
Titanium alloy	0.59
Stainless steel	1.38

B. Analytical formulation

The inductance change of the air-cored sensor coil caused by the nonmagnetic, metallic spherical sample has been proposed [40]. The coil impedance Z can be represented by the sum of the coil impedance in free space Z_0 and the impedance change induced by the eddy currents within the spherical sample ΔZ .

$$Z = Z_0 + \Delta Z \quad (1)$$

As shown in equations (2)-(4), due to the phase difference between the voltage and current, the measured impedance between the excitation coil and receiving coil should be complex value, contains real part and imaginary part. The inductance change is defined as the ratio of the impedance change and the excitation frequency. The imaginary part of the inductance change reflects some properties of resistive components.

$$\Delta Z = \Delta R + \Delta jX \quad (2)$$

$$\text{Re}(\Delta L) = \text{real}\left(\frac{\Delta Z(f)}{j\omega}\right) = \frac{\Delta X}{\omega} \quad (3)$$

$$\text{Im}(\Delta L) = \text{imag}\left(\frac{\Delta Z(f)}{j\omega}\right) = \frac{\Delta R}{\omega} \quad (4)$$

Where $Z(f)$ represents the impedance of the coil in the presence of a metallic ball and $Z_0(f)$ is that of the coil in air.

Due to the presence of the spherical sample, the impedance change can be expressed as,

$$\Delta Z = \frac{j\pi\omega N_1 N_2}{(z_2 - z_1)(z_4 - z_3)(x_2 - x_1)(x_4 - x_3)} * \sum_{n=1}^{\infty} \frac{b_t^{2n+1}}{n(n+1)} \frac{V_{11N}NOMI + V_{21N}NOMK}{V_{11N}DENI + V_{21N}DENK} P_{1,n,s} P_{2,n,s} \quad (5)$$

Where

$$NOMI = i_n(a_N b_N)[(n+1)\mu_N - 1] - a_N b_N i'_n(a_N b_N) \quad (6)$$

$$NOMK = k_n(a_N b_N)[(n+1)\mu_N - 1] - a_N b_N k'_n(a_N b_N) \quad (7)$$

$$DENI = i_n(a_N b_N)(n\mu_N + 1) + a_N b_N i'_n(a_N b_N) \quad (8)$$

$$DENK = k_n(a_N b_N)(n\mu_N + 1) + a_N b_N k'_n(a_N b_N) \quad (9)$$

$$a_t = \sqrt{j\omega\mu_t\mu_0\sigma_t} \quad (10)$$

$$P_{n,s} = \int_{\theta_{21}}^{\theta_{12}} \sin\theta_0 P_n^1(\cos\theta_0) \int_{r_{o1}(\theta_o)}^{r_{o2}(\theta_o)} \frac{1}{r_o^{n-1}} dr_o d\theta_0 \quad (11)$$

$$V(N) = T(N, N-1)T(N-1, N-2)...T(2, 1) \quad (12)$$

$$T(t+1, t) = \begin{bmatrix} T_{11}(t+1, t) & T_{12}(t+1, t) \\ T_{21}(t+1, t) & T_{22}(t+1, t) \end{bmatrix} \quad (13)$$

Here equation (10) is related to the skin depth. The formula of skin depth is:

$$\delta = \frac{1}{\sqrt{\pi f_0 \mu_t \mu_0 \sigma_t}} = \frac{\sqrt{2j}}{a_t} \quad (14)$$

Other parameters, N denotes the total shell number of the multi-layered spherical sample. The t^{th} shell has a constant conductivity σ_t and the relative permeability μ_t ; $i_n(a_N b_N)$ and $k_n(a_N b_N)$ denote the modified spherical Bessel function of the first and second kind respectively; $i'_n(a_N b_N)$ and $k'_n(a_N b_N)$ denote the derivatives of the respective modified spherical Bessel functions. The interface between shells t and $t+1$ is located at a radial distance b_t ; ω denotes the excitation frequency; μ_0 denotes the permeability of free space; μ_N denotes the permeability of outermost spherical shell; $P_n^1(x)$ denotes the first order of Legendre function; $V(N)$ is a two-dimensional matrix and V_{ijN} denotes the element in the i^{th} row and j^{th} column. The expressions of T matrix for different cases are introduced in the appendix.

As shown in equation (11), $P_{n,s}$ contains double integration considering the rectangular cross-section of the coil. It can be substituted with a single integration loop, which gives $n \neq 2$:

$$P_{n,s} = \int_{\theta_{12}}^{\theta_{11}} \frac{\sin\theta_0 P_n^1(\cos\theta_0)}{n-2} \left(\frac{\sin\theta_0}{x_1}\right)^{n-2} d\theta_0 + \int_{\theta_{11}}^{\theta_{21}} \frac{\sin\theta_0 P_n^1(\cos\theta_0)}{n-2} \left(\frac{\cos\theta_0}{z_1}\right)^{n-2} d\theta_0 + \int_{\theta_{21}}^{\theta_{22}} \frac{\sin\theta_0 P_n^1(\cos\theta_0)}{n-2} \left(\frac{\sin\theta_0}{x_2}\right)^{n-2} d\theta_0 + \int_{\theta_{22}}^{\theta_{12}} \frac{\sin\theta_0 P_n^1(\cos\theta_0)}{n-2} \left(\frac{\cos\theta_0}{z_2}\right)^{n-2} d\theta_0 \quad (15)$$

$n = 2$:

$$P_{n,s} = \int_{\theta_{12}}^{\theta_{11}} \sin\theta_0 P_n^1(\cos\theta_0) \ln \frac{x_1}{\sin\theta_0} d\theta_0 + \int_{\theta_{11}}^{\theta_{21}} \sin\theta_0 P_n^1(\cos\theta_0) \ln \frac{z_1}{\cos\theta_0} d\theta_0 + \int_{\theta_{21}}^{\theta_{22}} \sin\theta_0 P_n^1(\cos\theta_0) \ln \frac{x_2}{\sin\theta_0} d\theta_0 + \int_{\theta_{22}}^{\theta_{12}} \sin\theta_0 P_n^1(\cos\theta_0) \ln \frac{z_2}{\cos\theta_0} d\theta_0 \quad (16)$$

Where: $\theta_{ij} = \arctan(x_i/z_j)$. It denotes four angles of the rectangle corners. This parameter is mainly used to transfer double integral to a 1-D integral.

In the free space, the impedance $Z_0(f)$ can be calculated as

$$Z_0 = jX_0 = \frac{j2\pi\omega\mu_0 N_s^2}{(z_2 - z_1)(z_4 - z_3)(x_2 - x_1)(x_4 - x_3)} \int_0^\infty \frac{1}{a^6} J^2(x_2, x_1) [a(z_2 - z_1) + e^{-a(z_2 - z_1)} - 1] da \quad (17)$$

where

$$J(x_2, x_1) = \int_{ax_1}^{ax_2} x J_1(x) dx \quad (18)$$

Here $J_1^{(x)}$ is the Bessel function of the first kind and first order.

Further, after obtaining the impedance change due to the spherical sample, the peak frequency can be extracted by searching the minimum value of the imaginary part from the ratio of impedance change and the excitation frequency.

$$a = \min\{\text{Im}((\Delta Z(f))/j\omega)\} \quad (19)$$

Where, a represents the peak frequency where the local minimum of the imaginary part of the inductance change is located. In order to calculate the peak frequency, it is found that, in a specific frequency range, the curve of imaginary part of the inductance change can be approximated as a quadratic function. The peak frequency can be calculated by finding the stationary point from the derivatives of the quadratic function.

C. Linearity feature

In this section, different setups (materials, radii and thicknesses) of sphere balls have been simulated. The metal ball is a double layered sphere (i.e. it is a hollow sphere: the inner sphere is made of air/ the shell is made of metal), the value of thickness of metal ball is the difference between the inner radius and the out radius. It can be seen from Figs. 2-4 that for different materials, radii and thicknesses, the peak frequency in (16) is

linear to the lift-off distance. For metal balls with different radii, the slope of the peak frequency will decrease as the radius increases. For metal balls of different materials, the slope of the peak frequency changes more obviously, and it will decrease as the electrical conductivity of the material increases.

Fig. 5 presents the relationship between conductivity and slope of peak frequency versus lift-offs. It can be noted that, for different kinds of metals, as the conductivity increases, the value of the slope of the peak frequency versus lift-offs decreases. A slope can be worked out from the relationship between the peak frequency and lift-off, i.e., two peak frequencies can be obtained from two lift-offs, then a slope can be calculated. For spheres with different conductivity, the slope is different. Figure 5 illustrates the relationship between conductivity and the slope. It is obvious that the conductivity is inversely related to the slope of peak frequency. The conductivity of copper is 58 MS/m and the slope rate is approximately 5, whereas the titanium metallic ball has conductivity of 0.58MS/m and highest slope. Besides, the slope of the peak frequency will decrease as the thickness of the metal ball increases. Based on this, the slope of the peak frequency can be used to detect the material, radius, and thickness of the metal ball.

Therefore, based on the linear relationship of peak frequency with lift-offs, the inverse radius calculation can be deduced by using the slope rate, shown in Fig.6 which describes the calculation process of obtaining the radius of the metallic ball. The first step is to measure the peak frequency at two lift-offs. Then, the slop rate can be calculated by using two differences (ΔZ and Δf), shown in the second and third step of the process chart. Consequently, by comparing the measured slope rate with the theoretical ones, the radius of ball can be obtained.

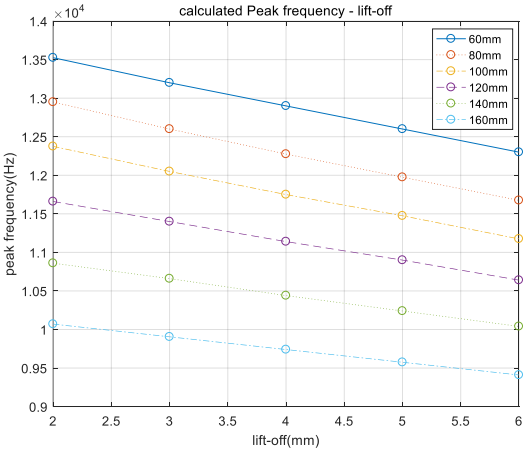


Fig.2. Comparisons of theoretical peak frequencies for the different size of stainless-steel ball at a range of lift-offs

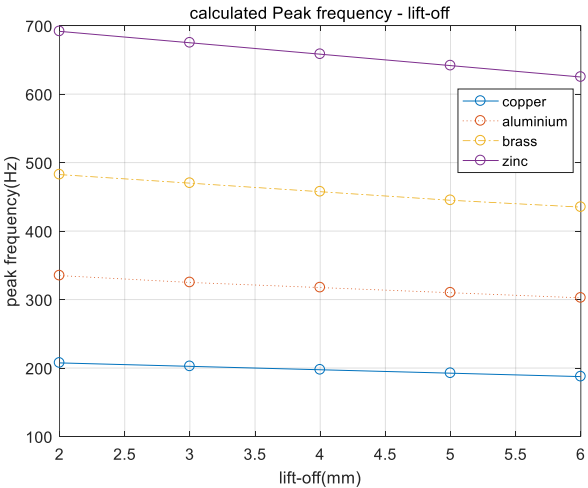


Fig.3 Comparisons of theoretical peak frequencies for the different balls of different materials at a range of lift-offs(thickness is 1mm and radius is 160mm)

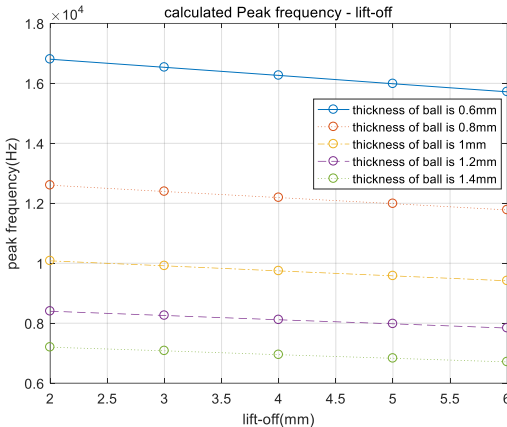


Fig.4. Comparisons of theoretical peak frequencies for the different thickness of stainless steel ball at a range of lift-offs(the radius is 160mm)

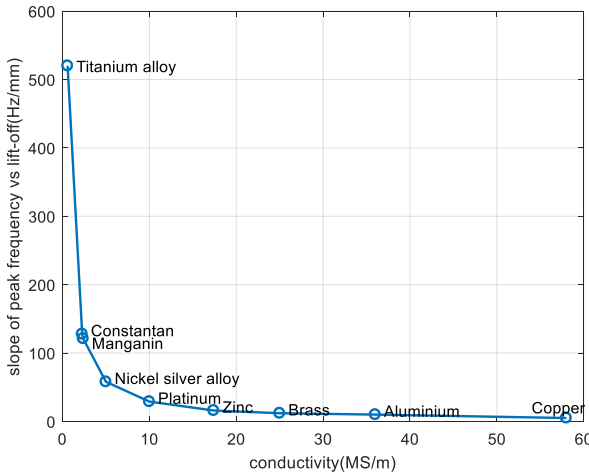


Fig.5. The relationship between conductivity and slope of peak frequency versus lift-off.

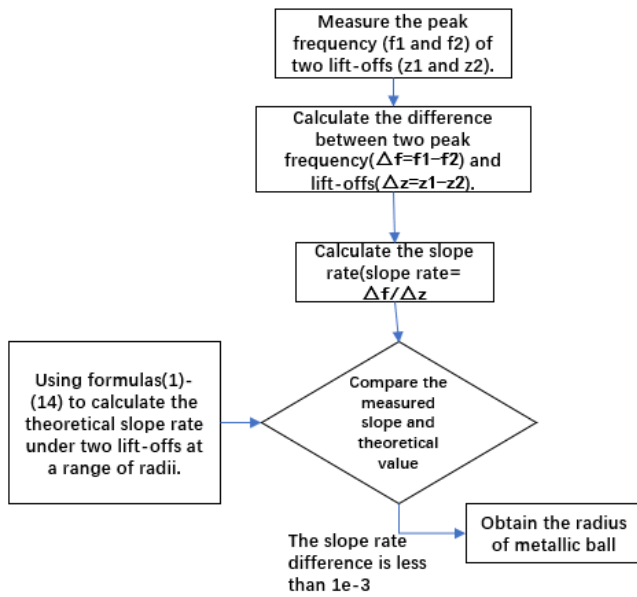


Fig.6 The calculating process of obtaining the radius of metallic ball

III. EXPERIMENTS AND RESULTS

A. Experiment and simulation setup

To evaluate the radius calculation algorithm due to the lift-off variation based on the linearity feature of peak frequency versus lift-offs, simulations and experiments have been carried out on 6 metallic balls with different radii.

The sensor configuration in experiments and simulations is listed in Table I. The simulations were programmed in MATLAB. The Zurich impedance analyser with frequency sweeping mode is applied to obtain the experimental data during the measurements. The experimental schematic diagram is shown in Fig.7. The spherical samples are stainless steel balls with the conductivity of 1.37 MS/m and the thickness of 1 mm. As shown in Fig. 8, from the simulation, the peak frequency is no longer linearly decreasing when lift-off distance is larger than 30mm. Besides, in practical measurement, the sensor probe is placed close to the tested object to obtain a better performance. Therefore, the lift-off is chosen from 2 mm to 6 mm in the steps of 1 mm.

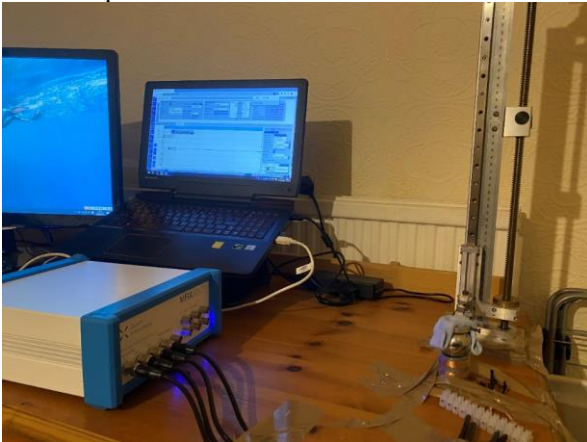


Fig. 7. The impedance analyser for the eddy current testing of metallic ball

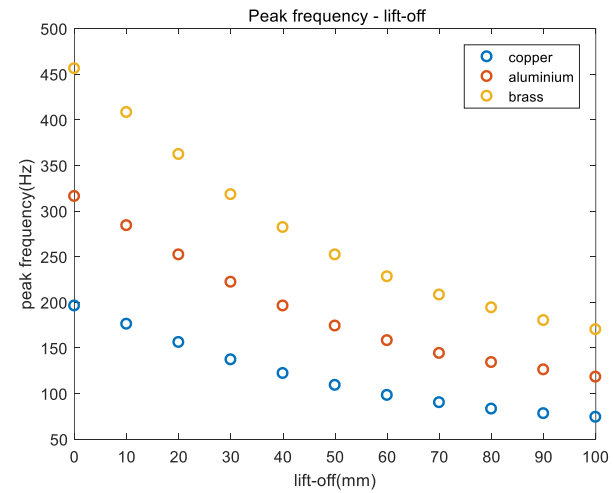


Fig. 8. Peak frequency of different metal in different lift-off distance

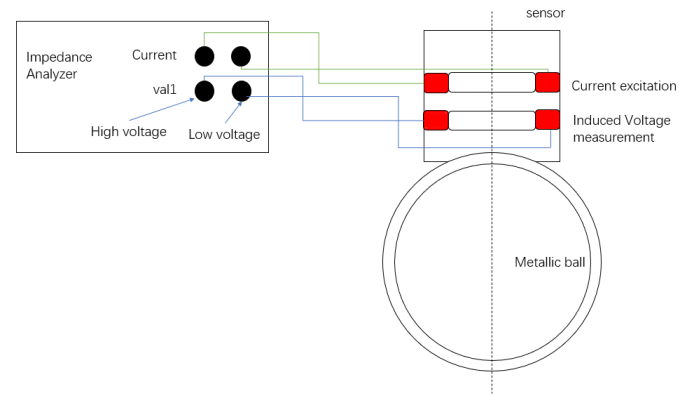


Fig.9. Experimental schematic diagram



Fig.10. Interface of impedance analyser

B. Results

As shown in Fig. 11 and Fig. 12, for the coil-sample system, both the real and imaginary parts of the inductance change was measured under the multi-frequency spectra and the lift-off spacer was from 2 mm and 6 mm. Experimental curves agree with simulation results. From both sets of results, it is found that the magnitude of both real part and imaginary part of the inductance change decreases as the lift-off increases. Besides, there exists a minimum value in the imaginary part and the

corresponding frequency (named as peak frequency) is used to investigate the effect due to the lift-off. It can be seen that the shift of the peak frequency is not severe. The difference of peak frequency from the lift-off of 2 mm and 6 mm is only ~ 1 kHz. Fig. 13 illustrates the inversely proportional trend between the peak frequency and the lift-off under different radii of metallic balls. Besides, due to more interaction between the magnetic field and the spherical ball, the peak frequency decreases as the radius increases. There is a slight difference in the peak frequency between the simulations and experiments which is due to the estimation of the peak frequency from the limited number of the frequency number. Moreover, the slope of metallic spherical sample increases with larger radius. By utilizing this feature, the radius of the metallic sphere can be deduced from different slopes shown in Fig. 13. In measurements, the slope of the tested sample can be calculated by the two lift-offs testing. Then the inversion tool is used to match the simulation with the experiment. Therefore, the radius of the spherical sample can be estimated, and it proves to be robust with a reasonable variation of 2%.

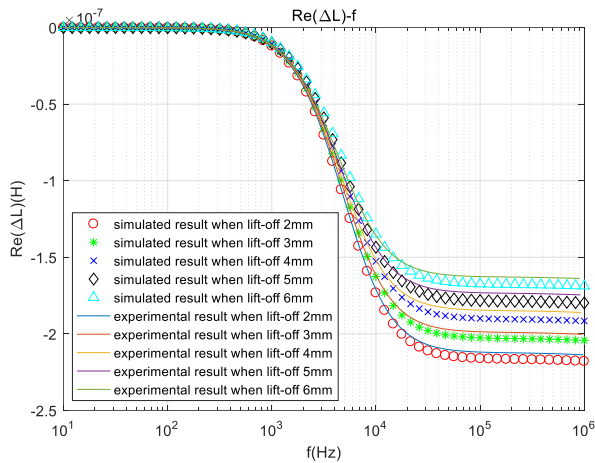


Fig. 11. Simulation and experimental results of real part of ΔL for stainless ball with radius of 160 mm and thickness of 1-mm at a range of lift-offs

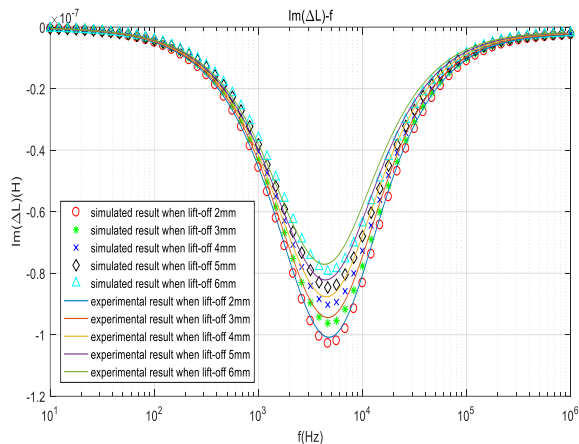


Fig. 12. Simulation and experimental results of imaginary part of ΔL for stainless ball with radius of 160 mm and thickness of 1-mm at a range of lift-offs

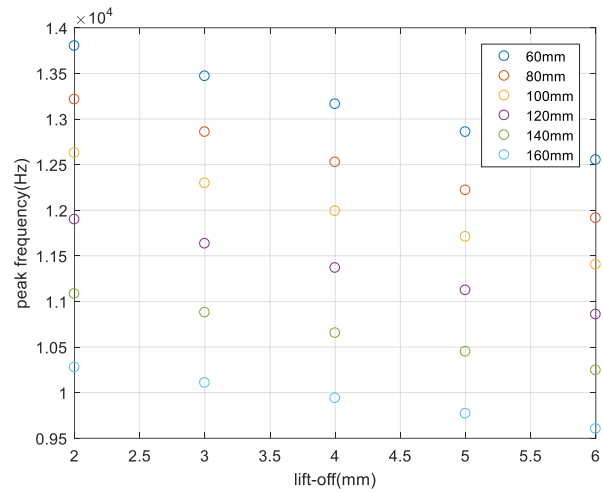


Fig.13. Comparisons of measured peak frequencies with thickness of 1-mm stainless steel ball at a range of lift-offs

TABLE III
RADIUS MEASUREMENTS FOR DIFFERENT RADIUS AND LIFT-OFFS

Lift-off point1 (mm)	Lift-off point2 (mm)	Actual radius (mm)	Slope of peak-frequency versus lift-off	Radius calculated from original as calculated (mm)	relative error
2	3	140	-204	142.8	2.0%
3	4	140	-225	141.7	1.2%
4	5	140	-204	140.8	0.5%
2	3	160	-169	159.6	0.8%
3	4	160	-168	158.7	0.8%
4	5	160	-169	158.6	0.8%

IV. CONCLUSIONS

In this paper, it is found that the peak frequency feature of inductance spectrum is linear to the lift-off spacing between the centre of coil and ball. Besides, the slope of peak frequencies versus lift-offs is linked to the radius of ball. Thus, the proposed approach is using the sensor probe to measure the slope of peak frequencies under different lift-off from receive coil. Then applying the radius calculation formula which is proposed in paper to obtain the radius of metallic balls. The results from the experiments show that the radii of samples can be predicted accurately within the error of 2 %. The shortcoming of this experimental design is that the sensor needs to be measured twice to get a set of experimental data values. Therefore, a triple-coil sensor will be designed in future, in which three coils (two excitation coils and one receiving coil) with same radii are co-axially arranged in different lift-off planes. Based on this sensor setup, the measurement method applied in this paper can be optimized. By utilizing two transmitter-receiver combinations and the proposed algorithm, the radius of metallic ball can be obtained by measuring once.

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V. APPENDIX

Case 1: $\sigma_{t+1} \neq 0$ and $\sigma_t \neq 0$

$$T_{11}(t+1, t) = \left[\frac{i_n(a_t b_t)}{\mu_t} [k_n(a_{t+1} b_t) + (a_{t+1} b_t) k'_n(a_{t+1} b_t)] - \frac{k_n(a_{t+1} b_t)}{\mu_t} [i_n(a_t b_t) + (a_t b_t) i'_n(a_t b_t)] \right] / DEN \quad (20)$$

$$T_{12}(t+1, t) = \left[\frac{k_n(a_t b_t)}{\mu_{t+1}} [k_n(a_{t+1} b_t) + (a_{t+1} b_t) k'_n(a_{t+1} b_t)] - \frac{k_n(a_{t+1} b_t)}{\mu_t} [k_n(a_t b_t) + (a_t b_t) k'_n(a_t b_t)] \right] / DEN \quad (21)$$

$$T_{21}(t+1, t) = \left[\frac{i_n(a_{t+1} b_t)}{\mu_t} [i_n(a_t b_t) + (a_t b_t) i'_n(a_t b_t)] - \frac{i_n(a_t b_t)}{\mu_{t+1}} [i_n(a_{t+1} b_t) + (a_{t+1} b_t) i'_n(a_{t+1} b_t)] \right] / DEN \quad (22)$$

$$T_{22}(t+1, t) = \left[\frac{i_n(a_{t+1} b_t)}{\mu_t} [k_n(a_t b_t) + (a_t b_t) k'_n(a_t b_t)] - \frac{k_n(a_t b_t)}{\mu_{t+1}} [i_n(a_{t+1} b_t) + (a_{t+1} b_t) i'_n(a_{t+1} b_t)] \right] / DEN \quad (23)$$

$$DEN = \frac{a_{t+1} b_t}{\mu_{t+1}} [i_n(a_{t+1} b_t) k'_n(a_{t+1} b_t) - i'_n(a_{t+1} b_t) k_n(a_{t+1} b_t)] \quad (24)$$

Case 2: $\sigma_{t+1} \neq 0$ and $\sigma_t = 0$

$$T_{11}(t+1, t) = \frac{b_t^n}{\mu_{t+1}} [k_n(a_{t+1} b_t) [1 - (n+1) \mu_{t+1}] + a_{t+1} b_t k'_n(a_{t+1} b_t)] / DEN \quad (25)$$

$$T_{12}(t+1, t) = \frac{1}{b_t^{n+1} \mu_{t+1}} [k_n(a_{t+1} b_t) (1 + n \mu_{t+1}) + a_{t+1} b_t k'_n(a_{t+1} b_t)] / DEN \quad (26)$$

$$T_{21}(t+1, t) = -\frac{b_t^n}{\mu_{t+1}} [i_n(a_{t+1} b_t) [1 - (n+1) \mu_{t+1}] + a_{t+1} b_t i'_n(a_{t+1} b_t)] / DEN \quad (27)$$

$$T_{22}(t+1, t) = -\frac{1}{b_t^{n+1} \mu_{t+1}} [i_n(a_{t+1} b_t) (1 + n \mu_{t+1}) + a_{t+1} b_t i'_n(a_{t+1} b_t)] / DEN \quad (28)$$

Case 3: $\sigma_{t+1} = 0$ and $\sigma_t \neq 0$

$$T_{11}(t+1, t) = \frac{1}{b_t^n \mu_t} [i_n(a_t b_t) [1 + n \mu_t] + a_t b_t i'_n(a_t b_t)] / (2n+1) \quad (29)$$

$$T_{12}(t+1, t) = \frac{1}{b_t^n \mu_t} [k_n(a_t b_t) [1 + n \mu_t] + a_t b_t k'_n(a_t b_t)] / (2n+1) \quad (30)$$

$$T_{21}(t+1, t) = -\frac{b_t^{n+1}}{\mu_t} [i_n(a_t b_t) [1 - (n+1) \mu_t] + a_t b_t i'_n(a_t b_t)] / (2n+1) \quad (31)$$

$$T_{22}(t+1, t) = -\frac{b_t^{n+1}}{\mu_t} [k_n(a_t b_t) [1 - (n+1) \mu_t] + a_t b_t k'_n(a_t b_t)] / (2n+1) \quad (32)$$