Detection and analysis of metallic contaminants in dry foods using a microwave resonator sensor

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Abstract

Current systems for metal detection in dry food processing are limited by relatively large foreign objects and high-cost implementation. These issues are resolved here using a non-contact, cylindrical microwave cavity resonator sensor where food passes through the cavity and metallic objects are detected by a shift in the resonant frequency. Classic perturbation theory is applied to the basic set-up and numerical simulations are used to verify the design of the sensor. A cavity sensor was fabricated with a quartz tube symmetrically located for dry food flow and metal detection. Good performance is demonstrated for metal detection in a range of foods such as spaghetti, noodles, rice, wheat flour and soy milk powder. It is shown that the resonance frequency shift becomes larger when the foreign body gets closer to the cavity centre. The frequency variation is directly related to the volume of the object, and it is estimated that the minimum diameter of a detectable ball can be lower than 2 mm. For completeness it is also demonstrated that the set-up can be used to detect dielectric objects. A graphical user interface is developed for practical applications. This approach is low-cost, convenient, scalable and complementary to other metal contaminant detection approaches.

Keywords: Dry foods; foreign objects; microwave technique; resonance frequency; cavity perturbation

1 Introduction

Foreign objects can be introduced into food products during harvesting, processing and final packing. Among all the contaminants, metallic objects (e.g., screws, bolts, nuts, small fragments from equipment in the production line or cleaning tools) cause the most concern for manufacturers if they are undetected and become embedded in final products, posing a severe threat to human health. A brand can be severely affected by such incidents. In addition, metal contamination may potentially damage the machinery, leading to unwanted downtime. Hence, from the economic point of view, it is of great importance to detect metal objects in food. Many non-invasive techniques have been developed. However, each has its advantages and limitations, and only one technique cannot serve all the needs of the industry. For example, the X-ray (Einarsdóttir et al., 2016; Morita, Ogawa, Thai, & Tanaka, 2003) and nuclear magnetic resonance (NMR) instruments are expensive and need high power usage. For the conventional liquid-coupled ultrasonics (Zhao, Basir, & Mittal, 2003), waves cannot propagate well in the air, and this can be overcome if the food is immersed in water. This special arrangement is not desirable for some food types, especially dry foods. Instead, air-coupled ultrasonics can be applied, while the point scanning feature impedes fast inspection. Terahertz inspection needs intricate instrumentation (Wang, Zhou, Huang, Xie, & Ying, 2019) and it has a low signal-to-noise ratio (Kim et al., 2012). Near-infrared (NIR) spectroscopy, thermal imaging and optical techniques cannot readily examine subsurface foreign bodies. Three types of widely used low-frequency electromagnetic detection systems are pulse technology, ferrous in foil detection, and the balanced three coil system (Craig, 2004). The pulse technology is limited to finding relatively large pieces of metals, like nails and cans. Ferrous in foil detectors are more suited to ferrous metal contamination. In a balanced three coil system, a transmitter and two receiver coils are used, and complicated signal processing is involved. Therefore, there is continued search for efficient identification of metallic objects.

In recent years, microwaves-based detection techniques have received increased attention. The microwave frequencies range from 300 MHz (wavelength of ~1 m) to 300 GHz (wavelength of ~1 mm). In the analysis of the interaction with dielectrics, the complex permittivity (also called dielectric properties) is involved, and it can be characterised by $\varepsilon_0\varepsilon_r=\varepsilon_0(\varepsilon_r' - j\varepsilon_r'')$. ε_0 is the electric permittivity of free space (i.e., 8.854×10^{-12} F/m), and ε_r is the relative permittivity. ε_r' and ε_r'' are the real and imaginary parts of ε_r, respectively. ε_r' (commonly called dielectric constant) is related to the ability of energy storage. ε_r'' accounts for the energy dissipation. The microwave methods have several distinctive characteristics, such as low signal power consumption (few milliwatts), non-contact inspection, ease of experimental setup, good repeatability and no-ionising radiation. They have been successfully applied for material characterisation (Brinker, Dvorsky, Al Qaseer, & Zoughi, 2020; Cuenca, Slocombe, & Porch, 2017; Li, Haigh, Soutis, & Gibson, 2019), damage evaluation (Li, Haigh, Soutis, & Gibson, 2018; Li, Wang, Haigh, Soutis, & Gibson, 2021) and food analysis (Li, Haigh, Soutis, Gibson, & Sloan, 2017; Li, Meng, Haigh, Wang, & Gibson, 2021; Li, Haigh, Wang, Soutis, & Gibson, 2021b, 2021a; Sosa-Morales, Valerio-Junco, López-Malo, & García, 2010). However, for contamination monitoring, little research can be found in the literature. Urbinati et al. (2020) developed a microwave system where six monopole antennas were arranged above packaged jars. Machine learning was incorporated to interpret the 6×6 matrix of scattering parameters. It was found that a metal sphere with a diameter of 10 mm was accurately detected by the multilayer perceptron classifier. In this approach, complicated signal post-processing was involved, impeding its wide application.

The primary objective of this study is to offer a novel approach for the detection of metals in food using microwave resonance. Dry foods are the food type of interest in the present work. The microwave energy is easily absorbed in moist samples and the resonance can be severely degraded. In comparison, in dry foods relating to a small ε_r'' value, lower energy is absorbed and consequently the signal penetration is deeper. It is noted that microwaves have very low penetration in metals, which behave more like reflectors and little electromagnetic energy is absorbed (Thostenson & Chou, 1999). By the insertion of a metallic object, a perturbation in the shape of a resonant cavity can be produced. Hence, here a low-cost cylindrical cavity resonator sensor is developed. The detection principle is described in detail, where the change of the resonance frequency is chosen as the primary indicator. Numerical simulation and experiments are carried out for verification. In the test, metallic objects in spaghetti are analysed first as an example, where the effects of the position, volume, quantity and shape of the object on the signal magnitude are thoroughly investigated. Finally, the detection performance for other dry foods including noodles, rice, wheat flour and soy milk powder is examined. The applicability of the sensor for dielectric contaminants is also studied.

2 Materials and methods

2.1 Samples under test

Five types of dry food samples bought from a local supermarket were measured, i.e., spaghetti, noodles, rice, wheat flour and soy milk powder. The diameter and length of the spaghetti strand were approximately 1.70 mm and 264 mm, respectively. Each noodle strand had a square cross section of approximately 1 mm×1 mm and a length of 184 mm. Metallic balls and wires, dielectric rods were used as foreign bodies, material types and dimensions of which are listed in Table 1. Some reference permittivity data of the samples are presented in Table 2. The sizes were measured with a digital calliper (Pro's Kit Co. Ltd., Shanghai, China), which had an accuracy of 0.01 mm.

2.2 Microwave resonator sensor

The resonant cavity sensor was made of aluminium, which has a high electrical conductivity and is reasonably priced. Its fabrication cost was around US$ 75. As illustrated in Figure 1, the sensor consists of a cylindrical wall and an endplate, which are mechanically connected by eight bolts and nuts. The radius of the cavity (*a*) is 47.5 mm, and the height (*d*) is 40 mm. Two SubMiniature version A (SMA) connectors are mounted on the endplate, and at the end of each connector a coupling loop is made for the excitation of the resonant mode designated, i.e., TE_{011} mode. For the air-filled cavity designed, the resonance frequency can be computed by

$$f_r = \frac{c}{2\pi}\sqrt{\left(\frac{p'_{01}}{a}\right)^2 + \left(\frac{\pi}{d}\right)^2} \tag{1}$$

where *c* is the speed of light in free space. p'_{01} =3.832 is the first root of the derivative of J_0, which is the Bessel function of first kind. Hence, by substituting the values of *a* and *d* into Equation (1), the theoretical f_r value is approximately 5.3721 GHz.

The TE_{011} mode has a degenerate mode (i.e., the TM_{111} mode) that shares the same frequency but exhibits different field distributions. To remove the mode interference, a hole with a diameter of 26 mm was drilled axially. The recess can be viewed as a short circular waveguide, and the cutoff frequency of the dominant mode (approximately 6.76 GHz) is higher than the resonance frequency. Thus, the electromagnetic energy can still be confined within the cavity.

2.3 Cavity perturbation caused by dielectrics and metals

When a dielectric sample like food is inserted into a resonant cavity, material perturbation is introduced. The fractional change in the resonant frequency can be estimated by (Collin, 2000)

$$\frac{\omega_2 - \omega_1}{\omega_1} \approx \frac{-\int_{V_c}\left(\Delta\varepsilon\left|\bar{E}_1\right|^2 + \Delta\mu\left|\bar{H}_1\right|^2\right)dv}{\int_{V_c}\left(\varepsilon\left|\bar{E}_1\right|^2 + \mu\left|\bar{H}_1\right|^2\right)dv} \tag{2a}$$

$$\omega_1 = 2\pi f_1 + \frac{j\pi f_1}{Q_1} \tag{2b}$$

$$\omega_2 = 2\pi f_2 + \frac{j\pi f_2}{Q_2} \tag{2c}$$

where ω_1, f_1 and Q_1 are the complex angular frequency, resonance frequency and quality factor before the perturbation, respectively. ω_2, f_2 and Q_2 are the complex angular frequency, resonance frequency and quality factor after the perturbation, respectively. ε and μ are the electric permittivity and magnetic permeability of the medium in the unperturbed cavity, respectively. In the present case, ε and μ are equal to ε_0 and magnetic permeability of free space $\mu_0=4\pi\times10^{-7}$ H/m, respectively. $\Delta\varepsilon$ and $\Delta\mu$ are the permittivity and permeability changes introduced by the sample, respectively. Thus, $\Delta\varepsilon$ can be expressed as $\varepsilon_0[(\varepsilon_r'-1)-j\varepsilon_r'']$. The dielectrics are generally non-magnetic, so $\Delta\mu$ is equivalent to zero. $\bar{E}_1$ and $\bar{H}_1$ are the original electric and magnetic fields, respectively. V_c is the volume of the cavity. For the original cavity, at resonance the electric energy stored in the cavity volume is equal to the magnetic energy stored, i.e.,

$$\int_{V_c} \varepsilon\left|\bar{E}_1\right|^2 dv \approx \int_{V_c} \mu\left|\bar{H}_1\right|^2 dv \tag{3}$$

Hence, the resonance frequency $\Delta f_r = f_2 - f_1$ can be given by

$$\Delta f_r \approx -\frac{(\varepsilon_r'-1)f_1}{2}\frac{\int_{V_d}\left|\bar{E}_1\right|^2 dv}{\int_{V_c}\left|\bar{E}_1\right|^2 dv} \tag{4}$$

where V_d is the volume of the dielectric object. It is indicated that a lower resonance frequency can be produced by the food, and the frequency change is larger for a higher dielectric constant. When the food contains a metallic object, the volume of the cavity is slightly reduced, causing additional shape perturbation. The resultant resonance frequency change can be approximated by (Pozar, 2012)

$$\frac{\Delta f_r}{f_1} \approx \frac{\int_{V_m}\left(\mu\left|\bar{H}_1\right|^2-\varepsilon\left|\bar{E}_1\right|^2\right)dv}{\int_{V_c}\left(\mu\left|\bar{H}_1\right|^2+\varepsilon\left|\bar{E}_1\right|^2\right)dv} \tag{5}$$

where V_m is the volume of the metallic object. Resonance frequencies f_1 and f_2 correspond to food without and with a metallic object inside, respectively. For the TE_{011} mode, as the electric field intensity around the axis is relatively low, the magnetic field is more affected. Therefore, the resonance frequency would be increased when a metallic object appears. Considering the extreme case where the contribution by $\bar{E}_1$ is ignored, the expression for Δf_r can be simplified as

$$\Delta f_r \approx \frac{V_m f_1}{2}\frac{\left|\bar{H}_{1,\mathrm{avg}}\right|^2}{\int_{V_c}\left|\bar{H}_1\right|^2 dv} \tag{6}$$

where $\left|\bar{H}_{1,\mathrm{avg}}\right|$ is the average magnetic field intensity in the metallic object region. Δf_r is directly proportional to V_m, suggesting that the detection is more sensitive to a larger object.

Using the shape perturbation theory, the resonant mode can be checked with a metallic wire positioned along the cavity axis. The wire has a small radius r and a length longer than the cavity height. r can be estimated from the resonant frequency shift by substituting the expressions of the electric and magnetic fields of the desired resonant mode into Equation (5). For the TE_{011} mode, r can be given by

$$r \approx a\sqrt{2\zeta\frac{\Delta f_r}{f_1}} \tag{7}$$

where the coefficient ζ is expressed as

$$\zeta = \left[1+\left(\frac{\pi a}{dp'_{01}}\right)^2\right] J_0^2\left(p'_{01}\right) \tag{8}$$

If the r value calculated is close to the real value, the resonant mode can be confirmed.

2.4 Experimental setup

The setup for the food examination using the microwave resonator sensor is shown in Figure 2. The sensor was connected to a portable N9951A Fieldfox microwave analyser (Keysight Technologies, Penang, Malaysia) by two coaxial cables. A LAN cable was used to link the analyser to a personal computer (PC). As a two-port measurement, the transmission coefficient (S_{21}) data were extracted. In the test, the default signal power (i.e., 0.032 mW) was adopted.

A frequency span of 20 MHz with 401 points was used, so that the frequency resolution was 0.05 MHz. The intermediate frequency bandwidth (IFBW) was set to 100 Hz to reduce the noise floor and accurately measure the non-resonance region. The analyser setting produced a long sweep time of around 10.3 s. To shorten the time for rapid online monitoring, the number of points can be set lower and/or IFBW value can be set higher without significantly decreasing the detection accuracy, as only the resonance frequency value is needed and the peak signal is orders of magnitude larger than the non-resonance region. For a frequency range of 5.324-5.334 GHz with 101 points (the corresponding frequency resolution was 0.10 MHz, which was still enough for discrimination) and an IFBW value of 10 kHz, the sweep time was approximately 66 ms.

For easy positioning of the sample, a 160 mm long quartz tube with an inner diameter of 12 mm and an outer diameter of 14 mm was used. The food sample was filled into the tube and inserted into the resonant cavity through two cuboid-shaped tube holders. Each tube holder had a central hole with a diameter of 14 mm and was attached to the top and bottom surfaces of the cavity.

3 Results and discussion

3.1 Electromagnetic simulation

CST® software is employed for the feasibility study. The cavity model built is given in Figure 3 (a), and the electric and magnetic field distributions are presented in Figure 3 (b-d), where the patterns produced match those of the ideal TE_{011} mode, validating the cavity design. The magnetic field intensity is the highest at the cavity centre, where the presence of a metallic object can cause a relatively large perturbation. It is also shown that the magnetic field intensity is high around the axis, but the electric field intensity is relatively low. Hence, a perturbation can be more easily generated by a metal than a dielectric.

Three representative cases are considered, i.e., an empty cavity, insertion of a quartz tube and a copper sphere. The relative permittivity data of fused quartz, $3.75\text{-}j1.5\times10^{-3}$, is from the built-in material library. The resonance frequency of the empty cavity simulated is 5.3634 GHz, which is in good agreement with the theoretical value (an error of 0.2%). As seen in Figure 4 (a), with the introduction of a quartz tube, the resonance frequency is shifted to 5.3432 GHz due to material perturbation. A copper sphere is further created at the cavity centre, and the resonance peak shifts upwards with increasing sphere diameter (D=1, 2, 3, 4, 5 mm). The perturbation of the magnetic field around the sphere is shown in Figure 4 (b) and (c), where only the field lines close to the sphere surface are distorted and the small perturbation condition is satisfied. The effect of the diameter on the resonance frequency shift is plotted in Figure 4 (d), where a linear correlation with a high coefficient of determination R^2=0.999 is given and the intercept of the fitted equation obtained is small compared with the dynamic range of the frequency shift. The findings agree well with the theoretical analysis (i.e., Equation (6)).

3.2 Experimental results

3.2.1 Examination of the resonant mode

The resonant mode was checked with the LWb wire, and another similar tube holder with a central hole of the same diameter as the wire was made. For the empty cavity, one resonance peak was observed over 5.34-5.38 GHz, and the resonance frequency measured was 5.35362 GHz (only 0.4% lower than the theoretical value). When the wire was inserted, the peak shifted to 5.36264 GHz. Using the cavity dimensions and resonance frequencies measured, the radius computed was 1.55 mm, and the resultant error was well within 5%, demonstrating that the resonance frequency measured corresponded to the TE_{011} mode and the degenerate mode was successfully suppressed.

3.2.2 *Characterisation of a metallic ball in spaghetti*

The quartz tube was partially filled with 17 spaghetti strands to mimic the real scenario where the food shall freely flow in the production line. The height of the spaghetti was around 6 mm (i.e., the radius of the tube). First, a BD5 ball was placed below the spaghetti at a position just outside the cavity, i.e., P0 as illustrated in Figure 5 (a). After the measurement at this position, the tube together with the spaghetti and ball was moved to the other ten positions (denoted by P1-P10). The distance between the adjacent positions was 5mm. Starting from P3, the ball entered the cavity. At P7 the ball was located closest to the cavity centre. During the movement, the length of the spaghetti part in the cavity was always equal to the cavity height.

The resonant responses for all the positions are given in Figure 5 (b). The frequency decreased when the spaghetti was placed into the empty cavity. The frequency changes with respect to P0 are computed and presented in Figure 5 (c). Three consecutive measurements were done for each case, while the resonance frequency extracted remained the same due to the low IFBW value used, demonstrating good repeatability of the sensor. Therefore, error bars are not plotted in the figure. The highest frequency shift Δf_r was seen at P7 as would be expected. For comparison, the spaghetti without the presence of the ball were measured at the eleven positions as well, and the maximum difference between the frequencies was 0.15 MHz, indicating a relatively low noise.

The P0 case is different from the spaghetti-only case, as there is a resonance frequency difference of 1.75 MHz. At P0 the ball did not affect the magnetic field distribution in the cavity, but the spaghetti were lifted upwards due to the relatively high stiffness of the spaghetti. As indicated by the simulation, when the centre of the material is closer to the cavity axis, the electric field intensity inside becomes smaller. Therefore, according to the material perturbation theory, the frequency becomes higher than that of the spaghetti-only case. Hence, it is suggested that the sensor can detect the presence of a metal when it is close to but still not in the cavity.

As shown in Figure 5 (c), smaller balls (i.e., BD2, BD3 and BD4) are also detected. A smaller object produces a lower Δf_r, which agrees well with Equation (6). A similar linear relationship is found between the maximum Δf_r at P7 and the cube of the diameter D, i.e., Δf_r=0.0421D^3-0.1223 with R^2=0.9909. Considering the signal noise, the minimum diameter of a ball that can be detected in the spaghetti is around 1.86 mm.

3.2.3 *Effect of the ball quantity on the signal responses*

Taking the BD3 ball as an example, the effect of the ball quantity was studied. The balls were in contact and aligned in parallel to the cavity axis. Initially, the centre of the balls was at P0. The differences between the resonance frequencies at P0 and P7 are listed in Table 3, where the placement of more balls leads to a greater frequency shift. The responses for a large number of balls were evaluated using the LWa and LWb wires, where the latter had the same diameter as the BD3 ball. The frequency shift caused was higher than any of the ball cases as expected. In comparison, the LWa wire had a smaller diameter, and a lower Δf_r was obtained.

3.2.4 Detection of a short wire in spaghetti

Same as the balls, short wires were measured at P0 and P7. The corresponding resonance frequency differences are presented in Table 4, where lower responses are seen for smaller dimensions. In the test, the wire was parallel to the magnetic field, and the cross-sectional area was smaller than the diameter of a ball of the same volume (e.g., SWb2 and BD4), thereby inducing weaker perturbation. Thus, it is indicated that ball-shaped objects can be more easily identified than stick-shaped objects.

3.3 Discussion

3.3.1 Detection of a metallic object in other dry foods

Same as the setup in the spaghetti cases, the sensor performance for the other dry food samples was examined. For each sample, the two cases with food only and with a BD3 ball at P7 were considered. The resonant responses obtained are presented in Figure 6, where the Δf_r values for noodles, rice, wheat flour and soy milk powder are 2.75 MHz, 3.68 MHz, 2.93 MHz and 2.03 MHz, respectively. Thus, the ball can be readily detected in these foods as well. For the noodles, the effect of the ball size was also studied at P0 and P7, and the Δf_r values for BD2, BD3, BD4 and BD5 were 0.20 MHz, 0.95 MHz, 2.75 MHz and 5.85 MHz, respectively. For the same ball, the value of Δf_r is slightly higher than that in the spaghetti case, indicating better detection sensitivity. The trend of the frequency shift with respect to the ball size (the relationship between Δf_r and D^3 is Δf_r=0.0487D^3-0.2922 with R^2=0.9987) is consistent with that for spaghetti.

3.3.2 Examination of a dielectric object in spaghetti

The sensitivity to a dielectric object was investigated using short Plexiglas rods. The Δf_r values computed at P1-P10 for four rods with varied lengths are presented in Figure 7, where the frequency decreases as the rod is closer to the cavity centre. This trend of the frequency variation is opposite to that for a metallic object, facilitating the differentiation of metallic and dielectric objects. The primary reason is due to the fact that here material perturbation is involved. Compared with the results of the metallic balls given in Figure 5 (c), the signal magnitudes for the rods are five times lower, though the volumes are comparable. Therefore, it is suggested that the Plexiglas material is less detectable.

3.3.3 Development of foreign object detection software

As shown in Figure 8, MATLAB GUI-based software is programmed for easier identification of a foreign body. First, six parameter values are input for analyser setting and analyser-computer communication, i.e., IEEE GPIB address, start frequency, stop frequency, number of points, IFBW value and signal power. S_{21} data from a reference case (e.g., a foreign body-free case) are taken. Continuous scanning is then performed until the current resonance frequency shift is over the detection threshold defined. A warning message box pops up when a foreign object is found, and the specific object type (metal or dielectric) is also provided.

4 Concluding remarks

A new microwave resonant system has been introduced for the detection of metals in dry foods. The low-cost sensor requires very low signal power and is sensitive to both ferrous and non-ferrous containments. The presence of a metallic object perturbs the magnetic field in the TE_{011} mode resonant cavity and causes an increase in the resonance frequency. In the evaluation of metallic balls in spaghetti, it has been revealed that the frequency shift is proportional to the volume of the ball, which is in good agreement with the theoretical analysis and numerical simulation. The minimum diameter of a detectable ball can be lower than 2 mm. For the same volume, an object with a larger cross-sectional area can be identified more easily due to the stronger perturbation. Good detection performance has also been shown for other types of dry foods. The sensor can also be applied for the detection of dielectric containments. For the low electric field intensity around the axis and small difference of the permittivity between the dry food and the foreign object, the detection signal is relatively low compared with a metal of the same volume. A GUI-based programme has been developed for convenient implementation. The comparison between the proposed sensor and the existing research for foreign body detection in dry foods is presented in Table 5.

In future work, the speed of the moving food on the effectiveness of the sensor system is to be tested. Methods like gold plating on the inner surface of the cavity, use of more frequency points and minimisation of the recess size will be adopted to improve the sensor performance. In addition, bespoke low-cost sensor electronics will be developed for industrial use. For a real production line, the cavity can be scaled up to ensure high throughput, and the technique can be combined with other non-invasive sensors for enhanced performance.

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Tables

Table 1 Details of the foreign objects used in this study

	Ball				Long wire		Short wire						Short rods			
Material	Q235 steel				Copper		Copper						Plexiglass			
Diameter (mm)	2.00	3.00	3.98	5.02	1.70	2.97	2.66	2.66	2.18	2.18	1.70	1.70	3.12			
Length (mm)	-	-	-	-	201.00	201.00	20.03	10.16	20.20	10.04	20.10	10.16	4.06	6.20	7.90	20.25
Code	BD2	BD3	BD4	BD5	LWa	LWb	SWa1	SWa2	SWb1	SWb2	SWc1	SWc2	PRa	PRb	PRc	PRd

Table 2 Reference permittivity data of the food samples and dielectric rod under investigation

Material	Rice	Wheat flour	Ground soybean	Plexiglas	Water
Reference	(A. Prasad & P. N. Singh, 2007)	(Nelson, 1984)	(Stuart O. Nelson & Tian-su You, 1989)	(Hippel, 1995)	(Mason, Hasted, & Moore, 1974)
ε_r	2.32-j0.34 (2.45 GHz)	3.35-j0.34 (11.67 GHz)	4.02-j0.22 (11.5 GHz)	2.60-j0.01 (3 GHz) 2.59-j0.02 (10 GHz)	73.40-j18.16 (5 GHz)
Temperature (ºC)	24	22	24	27	25
Moisture content (%)	11	8.5	7.5	N/A	N/A

Table 3 Effect of the object quantity on the resonance frequency difference between P0 and P7

	Number of the BD3 balls					LWa	LWb
	2	3	4	5	6		
f_r at P0 (GHz)	5.32395	5.32395	5.32395	5.32390	5.32390	5.32445	5.32460
f_r at P7 (GHz)	5.32685	5.32820	5.32915	5.32995	5.33045	5.32800	5.33220
Δf_r (MHz)	2.90	4.25	5.20	6.05	6.55	3.55	7.60

Table 4 Resonance frequency shifts caused by the insertion of short copper wires in spaghetti

	SWa1	SWa2	SWb1	SWb2	SWc1	SWc2
Volume (mm^3)	111.31	56.46	75.40	37.47	45.62	23.06
f_r at P0 (GHz)	5.32645	5.32645	5.32630	5.32560	5.32560	5.32545
f_r at P7 (GHz)	5.33040	5.32810	5.32880	5.32670	5.32675	5.32620
Δf_r (MHz)	3.95	1.65	2.50	1.10	1.15	0.75

Table 5 Comparison between the proposed methodology and the existing detection methods

Non-invasive method	Food products	Foreign bodies	Advantages	Limitations
X-ray (Kwon, Lee, & Kim, 2008)	Instant ramen, macaroni and spaghetti	Balls made of stainless steel, Teflon, aluminium, rubber, glass and ceramic	• High image resolution • Good penetration	• High cost • High power usage • Ionising radiation
Air-coupled ultrasonics (Pallav, Hutchins, & Gan, 2009)	Chocolate	Hazelnut, mint	• Non-contact inspection	• Raster scanning required • Low signal-to-noise ratio
Terahertz (Ok, Kim, Chun, & Choi, 2014)	Milk powder	Steel nuts and washers, square and circular polymer samples, insects	• Reasonable penetration • Non-contact inspection	• Intricate experimental setup • Low signal-to-noise ratio • Raster scanning required
Near-infrared spectroscopy (Yin, Hameed, Xie, & Ying, 2021)	Toast bread	metal, plastic and hair	• Full-field imaging • Reasonable image resolution	• Image processing required for better interpretation • Poor penetration
Thermal imaging (Ginesu, Giusto, Margner, & Meinlschmidt, 2004)	Raisins, almonds and nuts	Wooden sticks, stone, metal chips and cardboard pieces	• Full-field imaging	• Relatively high power usage • Poor penetration
Present work	Spaghetti, noodles, rice, wheat flour and soy milk powder	Metallic balls and wires, dielectric rods	• Low power consumption • Easy signal interpretation • Low cost • Volumetric sensing	• Limited penetration for high-moisture materials

Figure captions

Figure 1 Cross section of the microwave resonator sensor developed for food examination (not to scale)

Figure 2 Schematic diagram of the experimental setup for the detection of metallic contamination in dry foods using microwave resonance

Figure 3 Numerical simulation of the electric and magnetic fields in the microwave sensor at resonance: (a) cross-sectional view of the empty cavity model; (b) electric fields in the transverse plane; (c) electric fields in the *y*-*z* plane (pointing out of the paper on the left-hand side and pointing to the paper on the right-hand side); (d) magnetic fields in the *y*-*z* plane

Figure 4 Effect of a metallic sphere on the microwave resonance studied by simulation: (a) signal responses for the cavity with and without a sphere; (b) magnetic field distribution in the presence of the sphere; (c) close-up view of the magnetic field around the sphere; (d) variation of the resonance frequency shift with respect to the diameter (*D*) of the sphere

Figure 5 Evaluation of a metallic ball in spaghetti using the microwave resonator sensor: (a) schematic diagram of the eleven positions along the axis for the study of the position effect; (b) resonant responses for the BD5 ball; (c) resonance frequency shift due to the movement of the ball from the original position into the cavity

Figure 6 Resonant responses for other dry foods with and without a metallic ball placed at P7

Figure 7 Resonance frequency shifts caused by dielectric rods at varied positions in the cavity

Figure 8 Self-developed GUI-based software for easy online detection of a foreign object in dry food (here a BD3 ball is placed in spaghetti)