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ANALYSIS OF MRI SLOTTED TUBE RESONATOR INSIDE CIRCULAR CONDUCTING CYLINDER

Qiang Chen†, Kunio Sawaya†, Saburo Adachi†,
Hisaaki Ochi‡, Etsuji Yamamoto‡
†Department of Electrical Engineering, Tohoku University, Sendai 980, Japan
‡Central Research Laboratory, Hitachi Ltd., Kokubunji, Tokyo 185, Japan

1.Introduction MRI (Magnetic Resonance Imaging) system has been recognized as a new technique for medical diagnostic. In MRI system, an RF probe is used to emit a uniform RF magnetic field over a human body and receive response signals from the body. A conducting cylinder is usually located around the RF probe to minimize noises coming from the other equipments. Several kinds of probes, such as a saddle coil, a birdcage resonator and a slotted resonator (STR) [1] have been developed to use for different usages. Among these probes, the STR has gradually come to be employed since it can produce the uniform magnetic field and can suppress the electric field. However, the design of the MRI probe composed of conducting strips such as the STR has been made mainly by the experimental procedure. Although approximated analysis of the STR has been made [2], a more accurate and realistic analysis of the STR with shielding cylinder has been strongly desired to design more improved STR.

In this paper, the STR inside a concentric shield of circular cylinder which is assumed to be perfectly conducting and infinitely long is analyzed by using the dyadic Green's function inside a circular waveguide and the variational method. A use of three surface current modes expanding the surface current on the probe for variational analysis is proposed. Numerical results of the input impedance and the resonant frequency of the STR inside a shield of different diameters are presented and compared with the experimental data to show the effects of the circular shield and confirm the validity of the analysis.

2.Formulation Fig.1 shows the configuration of the STR inside a shield of conducting circular cylinder. The resonator is composed of six parts, i.e., two vertical strips called arms, two outer rings having radius of R_a called wings, and two inner rings with radius R_b called guard-ring. Four chip capacitors C_r are attached to the wings for tuning the resonant frequency and a capacitor C_m is attached parallel to the feed for the impedance matching. The conducting circular cylinder with radius a is located concentrically and is assumed to be infinite long for the analysis.

Since the structure of the probe is very complicated, the subdomain expansion technique requires a great amount of CPU time. Fortunately, the current distribution of the STR in free space has been analyzed previously[3]. Therefore, variational method is suitable here as the current distribution of the probe in free space is known. Referring to the current distribution of the STR in free space, we propose three kinds of surface expansion modes shown in Fig.2 and defined by vector functions as

$$\begin{cases} |\boldsymbol{f}_1| = 2 & \text{Mode 1} \\ |\boldsymbol{f}_2| = \cos 0.5\varphi & \text{Mode 2} \\ |\boldsymbol{f}_3| = \sin\varphi & \text{Mode 3} \end{cases} \tag{1}$$

where the direction of each vector is shown by arrows in Fig.2. The mode 1 is used to express the current of the exterior layer of the STR. In the previous analysis we found the current on the probe is very uniform and the flow of the current is looked like a uniform current loop. The loop current is especially strong at the resonant frequency and contributes to make homogeneous magnetic field in the interior region. Mode 1 is expected to play a main part to approximate the current. Mode 2 is used to express the current on the upper guard-ring, the upper wing, and feeding conductor. This mode is set to be unity at $\varphi = 0$, i.e, the feed point and to be zero at $\varphi = \pi$ to satisfy the property of continuity of the current. A use of the mode 3 is to expand the current on the lower guard ring which is isolated from other conductors.

The variational expression of the input impedance can be represented by

$$\begin{aligned} Z_{in} &= \frac{1}{4\alpha_2^2}\Big[j\omega\mu \int_S\int_{S'} \boldsymbol{I}(\boldsymbol{R}) \cdot \overline{\boldsymbol{G}}(\boldsymbol{R}, \boldsymbol{R}') \cdot \boldsymbol{I}(\boldsymbol{R}')dS'dS \\ &\quad + 2\left(\alpha_1 - \cos(\frac{\pi}{4})\alpha_2\right)^2 Z_c + 2\alpha_1^2 Z_c\Big] \end{aligned} \tag{2}$$

where $\boldsymbol{I}(\boldsymbol{R}) = \sum_{k=1}^{3} \alpha_k \boldsymbol{f}_k(\boldsymbol{R})$, $Z_c = 1/j\omega C_r$, and $\overline{\boldsymbol{G}}(\boldsymbol{R}, \boldsymbol{R}')$ denotes the dyadic Green's function inside a conducting circular waveguide. According to the variational theory, the partial differential of Z_{in} respect to each coefficient φ_k should be zero. Thus, a simultaneous equation of three unknowns is obtained and the values of coefficients $(\alpha_k, k = 1 \sim 3)$ can be obtained numerically.

In the analysis described above, the most important and difficult work is the calculation of self and mutual impedances between three modes because it involves double integrals over the surface of the probe and a summation of double infinite series which are connected with the eigenfunctions appearing in the Green's function. The calculation seems almost impossible for its large amount of calculation. In this paper, we analytically evaluate the double integrals and obtain Z_{ij} expressed only by double summations.

3.Results

As an example, the STR used for human head is discussed here. The radius of wing R_a is 126mm and the radius of the guard-ring R_b is 124mm. The height of two slots in the tube is 230mm and the aperture angle is 87° which correspond to the width of the wings $W_1 = 35mm$ and the width of the arms $W_2 = 195mm$. The probe is 300mm in height and is made of 0.5mm thick copper strip. C_r and C_m are set to be 205pF and 164pF, respectively.

An experiment is also carried out and the input impedance is measured. Three circular copper circular cylinders about 1.5 meter long were used as the shields, with the radius of 200mm, 280mm and 325mm, respectively.

The behavior of the input impedance with radius ratio of $a/R_a = 2.19$ is shown in Fig.3. Experimental results are also plotted in the same figure. Although slight difference of the resonant frequency of about 160kHz is observed, the agreement between the theory and the experiment is satisfactory. Because the probe is used at the resonant frequency which required to be tuned to the spin frequency of the element to be imaged, it is important to know the shift of the resonant frequency when the radius of the cylinder is changed. Fig.4 shows the resonant frequency as a function of the ratio of a/R_a. Good agreement between the theory and the experiment is again obtained. It is noted that the resonant frequency increases rapidly when radius of the cylinder becomes less than $2R_a$.

5.Conclusion A slotted tube resonator has been analyzed by using of the variational method and the dyadic Green's function. Three surface current modes have been used to expand the surface current on the probe. Good agreement between theoretical and measured values has been obtained conforming the validity of the present method. By the presence of the cylinder shield, the resonant frequency increases rapidly when the ratio of a/R_a becomes less than about 2. The analysis seems to be valid and costs short CPU time although the resonator has a complicated strip structure. Other results such as Q factor and field distribution can also be obtained with this method. The slotted tube resonator should be further analyzed by taking account of a human body placed inside the resonator.

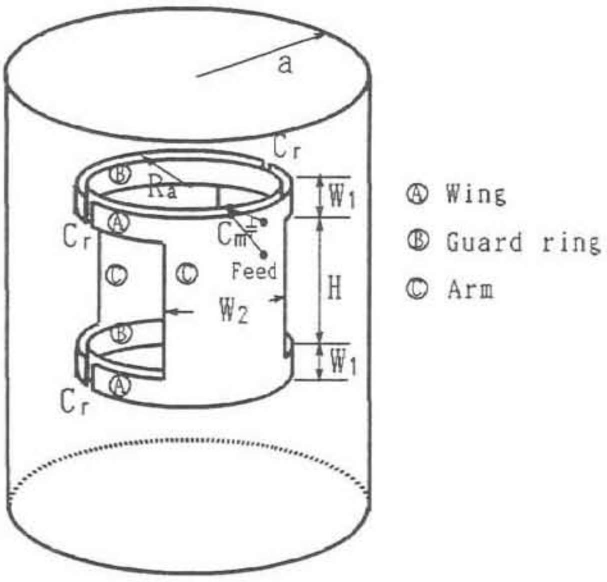

Fig.1 Geometry of slotted tube resonator
inside shield of conducting circular cylinder

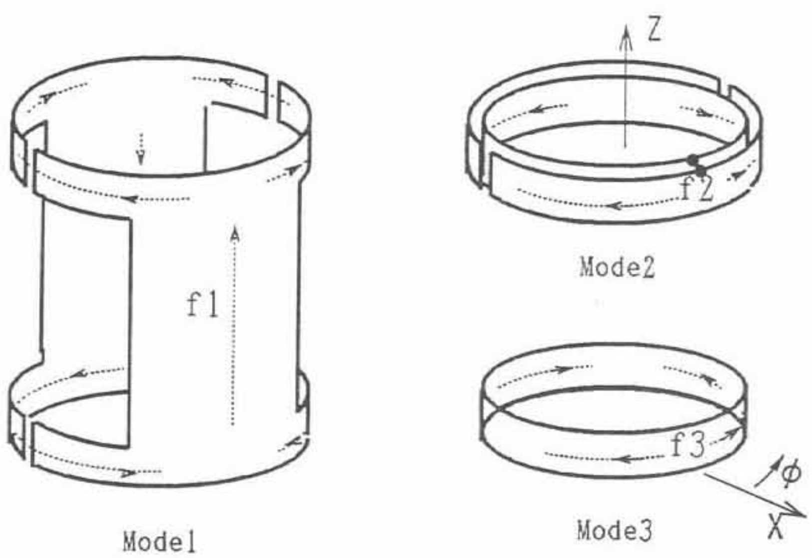

Fig.2 Three expansion modes of surface current on slotted tube resonator

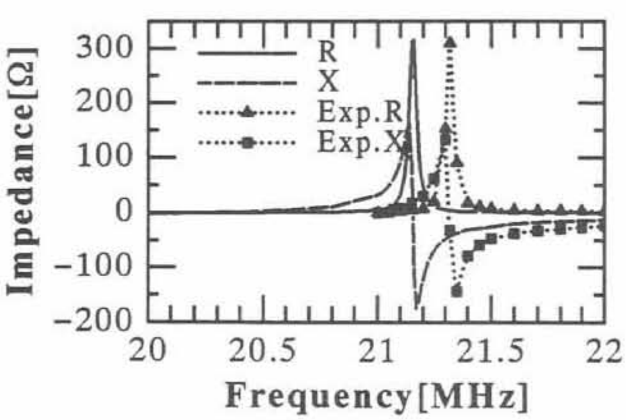

Fig.3 Input impedance of slotted tube resonator as a function of frequency for a/R_a=2.19

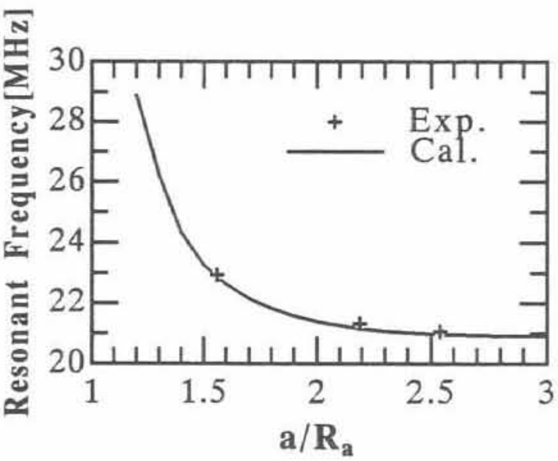

Fig.4 Resonant frequency versus the radius of the circular shield

Reference

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