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Applicability of Reed Switch Type Rod Position Indicator for a Nuclear Reactor

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Control rod drive mechanism is an electromechanical equipment that provides linear movement to a control rod assembly to control the reactivity of a nuclear reactor. The rod position indication system for the SMART control rod drive mechanism provides a position signal of a control rod assembly. It is an electric circuit consisting of reed switches and precision resistors installed at regular intervals. Because the reed switch manufacturer arranges the magnetic properties of the reed switch in Ampere-Turns and it is an uncomfortable dimension for an analytical estimation, it is not easy for the reed switch users to estimate the operability of a reed switch application at the design stage. Furthermore, this dimension is not standardized among the manufacturers. The performance of a reed switch application needs to be analytically verified to reduce the development risk. The operability of a reed switch application has been proved to be affected by the electromagnetic field generated around the application or an adjacent reed switch itself. Thus, it is necessary to have an effective means for a reed switch operability analysis at the design stage because the operating magnetic properties from the manufacture may not be applicable for a numerical analysis. In this paper, a new analysis methodology for a reed switch operability is proposed, and the feasibility is discussed for the rod position indication system.

Keywords : control rod drive mechanism, reed switch, rod position indication system, electromagnetic interference

1. Introduction

Control rod drive mechanism (CRDM) is an electromagnetic equipment that controls the reactivity of a nuclear reactor by inserting or withdrawing control rod assemblies vertically from the core [1]. Figure 1 shows the basic configuration of CRDM applied to the SMART (*S*ystem-integrated *M*odular *A*dvanced *R*eac*T*or). The position of a control rod assembly is precisely monitored by a rod position indication system (RPIS), which consists of reed switches installed at regular intervals and an electric circuit composed of precision electric resistances. The reliability of a reed switch has been confirmed by reliability tests [2], a reed switch-type sensor has been adopted in a nuclear reactor [3-7]. The output voltage is proportional to the position of a permanent magnet as a target, which can be converted into the control rod position directly. An RPIS is installed outside the CRDM pressure vessel. Inside of a pressure vessel, a permanent magnet assembly is installed at the upper part of the extension shaft assembly which is directly connected to a control rod, and it plays a role as a target for an RPIS. Reed switches,

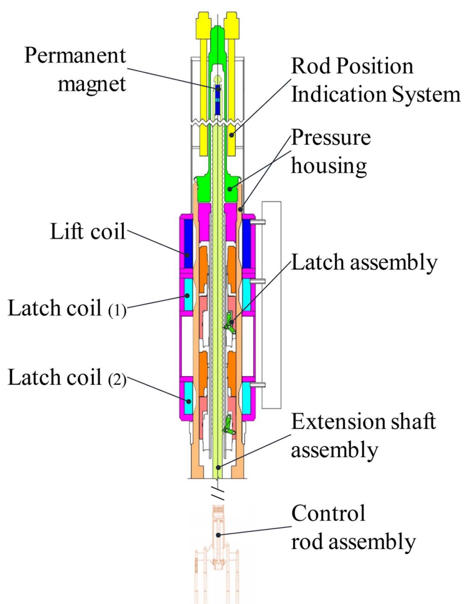

Fig. 1. (Color online) Configuration of SMART CRDM.

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positioned in the sufficient magnetic field affected zone by a permanent magnet assembly, are activated. The output voltage changes because electric current flows through an electric circuit section corresponding to the activated reed switches. The output of an RPIS is stepped and continuously linear within the control rod stroke range.

In an RPIS, discrete electrical contact signals as well as the position signal of the control rod assembly are generated. These limit the travel range of the control rod assembly to the electrical upper limit contact, the electrical lower limit contact and the dropped rod contact. These signals are generated at the upper and lower parts of an RPIS. In particular, in the lower part of an RPIS, the reed switches are installed densely because the position signal, the electrical lower contact signal, and the dropped rod contact signal are sequentially generated. It has been confirmed that the reed switch sensitivity changes owing to the magnetic mutual interference depending on the arrangement of the reed switches in this area, and an abnormal position indication signal can be generated. However, in the RPIS design, it is very difficult to arrange the reed switches so that the reed switch interference is completely excluded.

An RPIS is also affected by the electromagnetic field generated by the CRDM drive coils. In particular, it has been experimentally confirmed that the reed switches installed at the lower part of an RPIS can be affected by the CRDM drive coil.

Therefore, a review of the layout of the reed switches, which can ensure the normal operation of an RPIS in spite of the interferences of the reed switches or the electromagnetic fields from the drive coils, should be performed during the RPIS design phase. In this study, an analytical methodology, which verifies the design of the reed switch application at the design stage, is proposed.

2. Development of a Standard Reed Switch Model

2.1. Operating points of reed switches

It is difficult to apply a position sensor inside the pressure vessel because the high-temperature and high-pressure coolant circulates inside the pressurized light-water reactor. Therefore, it is general to measure the control rod assembly position by installing a position sensor outside the pressure vessel and installing a target, which can activate the position sensor, inside the pressure vessel. As a sensing element, the reed switch is suitable for applications in nuclear equipment requiring high reliability because the activation and deactivation of the contacts is fast and highly reliable. In the case of the SMART CRDM, several reed switches are arranged longitudinally at regular intervals. Inside the CRDM pressure vessel, a permanent magnet assembly, which serves as a target, is installed in an extension shaft assembly which is directly connected to a control rod assembly. A reed switch has a pair of magnetic reed blades, which are naturally not in contact with each other in the glass capsule, and reed blades are fixed by a glass capsule as shown in Fig. 2. When a magnetic field is applied to a reed switch, a counter polarity is formed at the overlapped part in each reed blade, and the reed blades are brought into contact and an electric current can flow through the reed switch.

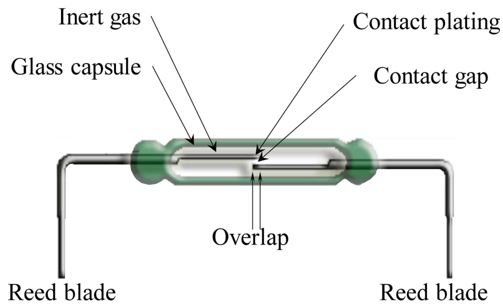


Fig. 2. (Color online) Configuration of a reed switch.

Because a glass capsule is formed after melting and shaping both ends of a glass tube, the fixing shapes of reed blades are not uniform. In addition, the contact gap between blades is not uniform. Even though the reed switch manufacturer classifies the reed switches that operate in a specific range, the operation point for each reed switch product is not uniform. The pull-in of a reed switch is the intensity of the magnetic field for a reed switch contact to be activated, and the drop-out means the intensity of the magnetic field for a reed switch contacts to be deactivated from activation.

In addition, a reed switch is installed after bending or cutting a reed blade, as shown in Fig. 2, which changes the pull-in and drop-out operating points.

The measure of the magnetic field strength required to operate a reed switch is generally expressed in Ampere-Turns (AT) by the manufacturers. They test the reed switches in standard test coils and provide the value in AT to the customer. However, there is no standardized test coil. All companies have their own test coils and therefore their own AT ranges specific to their test coils [8]. There are more reasons for the AT values to be inappropriate for the practical design process:

1) The AT value is not a physical quantity that determines the operating state of the reed switch in a space where the actual reed switch is installed.

2) When reed blades are bent or cut, the operating points of a reed switch change. Particularly when a reed blade is bent, it is impossible to measure the properties

using a standard test coil.

Therefore, this study proposes a physical quantity that represents the operating point of a reed switch, and suggests a method to evaluate the operability of an RPIS from a finite element electromagnetic field analysis.

2.2. Analysis model proposal for reed switch

Attraction generated between the reed blades is proposed as the physical quantity for the operating point of a reed switch [9]. Attraction for a specific reed switch model is evaluated, and it is compared with an operating point value. The model considers the actual shape of the reed blades. In this study, the model is called a standard reed switch.

The following procedure is applied to develop a standard reed switch model.

1) Perform pull-in and drop-out characteristic tests with actual reed switches using a permanent magnet which has known magnetic characteristics.

2) Produce a standard reed switch model reflecting the actual reed blade shape and material for an electromagnetic analysis.

3) Carry out an electromagnetic field analysis under the same conditions as the pull-in and drop-out characteristics test.

4) Evaluate the attractive force between reed blades.

Through the above procedure, pull-in and drop-out criterion are set in a force unit which is a physical quantity applicable to an electromagnetic field analysis, and on / off state of the reed switch can be judged.

The pull-in and drop-out characteristics test is a test to check whether the reed switch is activated or de-activated while approaching or moving away the permanent magnet to / from the reed switch as shown in Fig. 3. The distance between the center of the switch and the center of the permanent magnet (d) is measured for each case. Fig. 4 shows a simplified analysis model to extract the operating points.

2.3. Verification of the methodology

To evaluate whether a standard reed switch model is applicable to an actual reed switch operability analysis, a standard reed switch model for a specific reed switch was constructed, analyzed, and compared with the actual test results [10]. The specific reed switch for the CRDM RPIS supplied by Standex-Meder Electronics Inc. was considered. The information provided by the manufacturer is 27.5 AT on average for the pull-in characteristic with respect to the test equipment KMS-21.

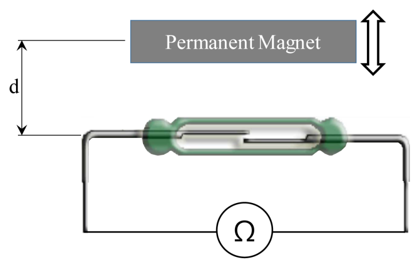


Fig. 3. (Color online) Pull-in and drop-out characteristics test.

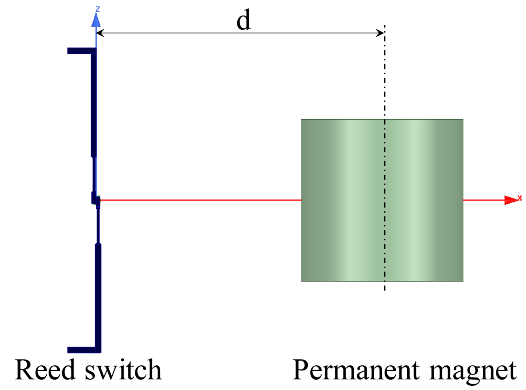


Fig. 4. (Color online) Standard reed switch and permanent magnet assembly model.

2.3.1. Analyzing of the reed switch design

The first step for developing the analysis model is to identify the material and shape of the reed blades. Since the reed blade shape of the target reed switch is the intellectual property of the manufacturer, the information is not provided to the reed switch user. Therefore, X-rays were taken, and the reed blade shape and initial gap were reproduced. Figure 5 shows an X-ray photograph in the direction where the initial gap between the reed blades can be confirmed. To understand the shape of the reed blade, X-ray photographs in the other direction are additionally required. The material information is provided by the manufacturer.

2.3.2. Development of the analysis model

Based on the acquired shape data, the reed switch analysis model is produced. The reed switch component applied to the actual position indicator is considered as the post-processed state. The reed blade is a cantilever shape supported by the glass capsule at point *A* in Fig. 5,

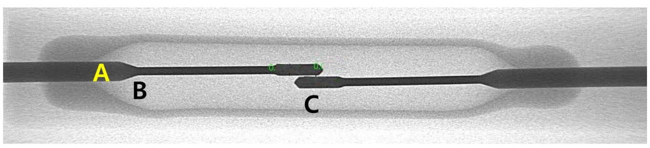


Fig. 5. (Color online) X-Ray image of a reed switch.

but in actuality, the reed blade is relatively thin at point *B*. Thus it can be assumed that point *B* acts as the cantilever fixing point. The reed blade magnetized by the electromagnetic field comes into contact at point *C*. The attractive forces generated between parallel reed blades are considered in this model.

2.3.3. Pull-in and drop-out characteristic test

The next step is to perform a pull-in and drop-out characteristic test of the same reed switch with the analysis model, as shown in Fig. 3. The characteristic extracted through the test is the distance (d) between the center of the permanent magnet and the center of the reed switch. The pull-in distance represents the initial distance (d) that the reed switch is activated while gradually reducing the distance from the position where the reed switch is not activated. The drop-out distance represents the distance at which the reed switch is first de-activated while moving the permanent magnet gradually away from the activated reed switch. Since the operating points of the reed switches are in a certain range of scattering, it is necessary to take the average of the values from several tests.

2.3.4. Analysis of attraction

The standard reed switch and the permanent magnet are modelled in ANSYS Electromagnetics Suite Release 19.0 [11] as shown in Fig. 4. One of the Samarium-Cobalt magnets is considered. The pull-in and drop-out distances obtained from the test are simulated, and the attractive force between the reed blades is estimated. These are the pull-in and drop-out threshold level for this standard reed switch.

The results obtained through the test and analysis for the target reed switch are as follows.

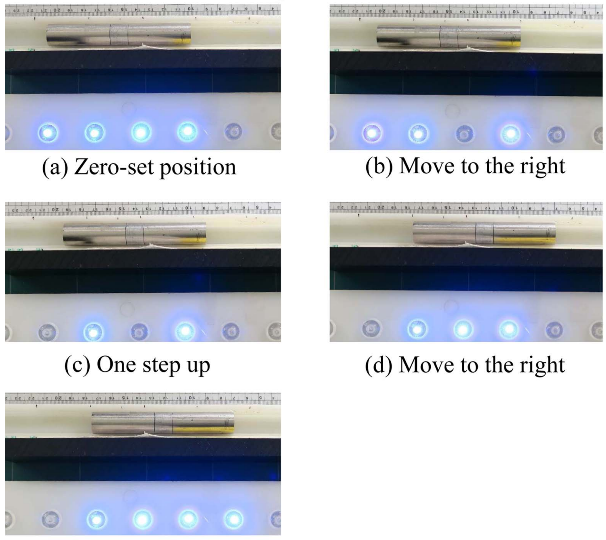
These figures are only adoptable for this specific standard reed switch, because the attraction level depends on each reed switch and its standard reed switch model.

2.3.5. Verification test

The methodology was verified by the RPIS function test on a function test bed [8]. The magnet assembly consists of two permanent magnets (Alnico No. 5) with facing the same magnet poles and a magnet spacer (carbon steel) between the magnets. This configuration helps to identity the position. LEDs are connected to each reed

Table 1. Pull-in and drop-out characteristics.

	Pull-in	Drop-out
Center Distance (mm)	59.4	72.4
Attraction (mN)	11.0	3.5



(a) Zero-set position (b) Move to the right (c) One step up (d) Move to the right (e) Two steps up

Fig. 6. (Color online) RPIS function test.

switch on the test bed, which light up when activated as shown in Fig. 6. Reed switches are not shown in the picture. A CRDM makes a control rod assembly move at a predetermined step size, and reed switches are installed every two CRDM steps. The test results show that two, three, or four reed switches are activated according to the position of the magnet assembly. This proves that the RPIS with the magnet assembly works as designed.

A finite element analysis was conducted to simulate the test. ANSYS Electromagnetics Suite Release 19.0 was used, and the analysis results are shown in Fig. 7. Ten reed switches and a permanent magnet assembly are simulated. An attraction of 11 mN between the reed blades was considered as the pull-in threshold level (the dashed red line) based on the previous research. The x-axis represents the reed switch position number. It means

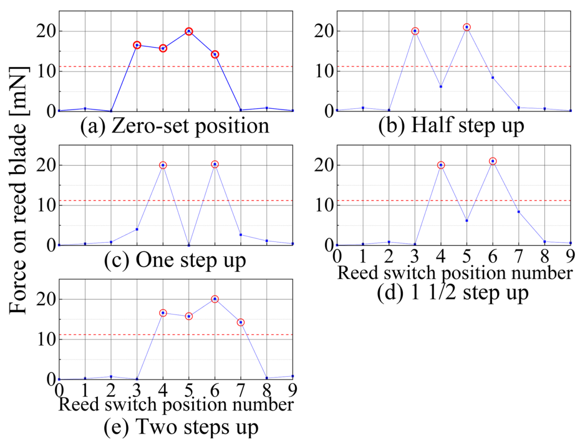


Fig. 7. (Color online) FE analysis results of reed switch activation.

that there are 10 reed switches in a concerning zone. The y-axis represents the reed blade attraction force on each reed switch. If this value is greater than the threshold pull-in level of a reed switch, it remains activated. If this value for an activated reed switch is lower than the threshold drop-out level of a reed switch, it becomes de-activated. The red-circled dot represents the activation state of a reed switch. The red-circled dots in Fig. 7 may coincide with the lighted LED in Fig. 6. The results almost coincide with the test results. However, Fig. 7(b) and (d) are not matched with Fig. 6(b) and (d) exactly. This disagreement may come from the scattering of the drop-out characteristics for each reed switch, even though every reed switch was sorted within a certain range. For example, No. 5 reed switch in Fig. 7(d) may be activated or de-activated because of the drop-out characteristic. Another mismatch comes from the manufacturing quality of the function test bed in Fig. 6. In fact, the reed switch operates much more concordantly for the actual prototype of RPIS.

3. Application of Standard Reed Switch Model

3.1. Mutual magnetic interference check

Reed switches are installed closely in the lower part of the RPIS as mentioned above. To arrange a plurality of reed switches in a limited space, the reed switches are tilted at an angle with respect to the direction of the magnetic field and layered. This may cause an interference between reed switches and a sensitivity change. The influence of the arrangement of reed switches on the position indicator sensitivity can be analyzed to establish the design criteria to compensate it based on the new methodology [12]. Unbent reed switch models and a permanent magnet are considered. Two different cases are evaluated as follows:

Case 1) Installed closely and in parallel (Fig. 8(a))

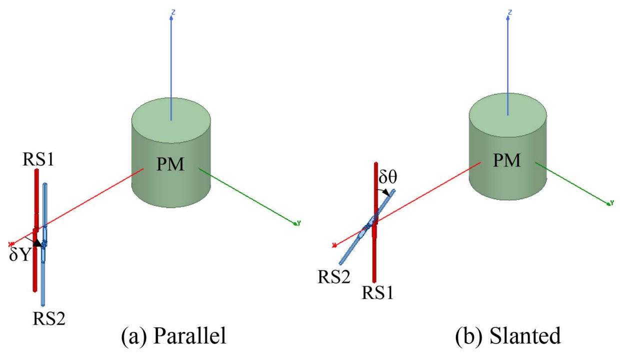


Fig. 8. (Color online) FE analysis model for interference check.

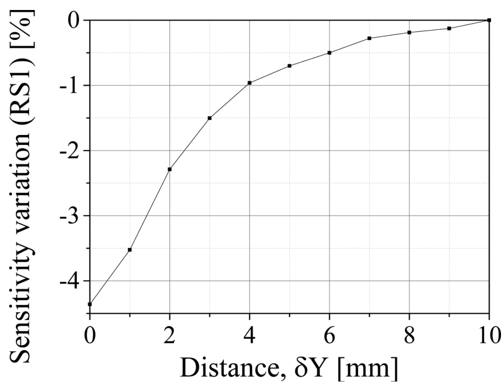


Fig. 9. Sensitivity variation of RS1 (Case 1).

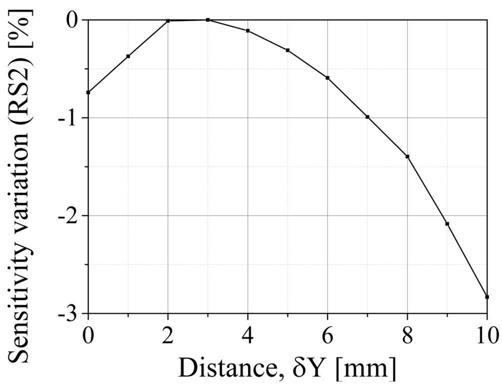


Fig. 10. Sensitivity variation of RS2 (Case 1).

Case 2) Installed closely and slantwise (Fig. 8(b))

RS1 is fixed with respect to the permanent magnet (PM), and RS2 is initially located 2.5 mm further from the permanent magnet center. RS2 moves along the Y axis for Case 1 and rotates around X axis for Case 2. When RS1 is installed alone, the attractive force is estimated as 19.72 mN.

Reed blade attraction for Case 1 is summarized in Figs. 9 and 10. When RS1 and RS2 are located aligned with the centerline of the permanent magnet (δY = 0), each reed switch interfere with each other and the reed blade attraction of RS1 diminish about 4.4 % compared to the attraction without RS2. It means that the electromagnetic field around RS1 is interfered with RS2. As RS2 moves away from RS1, interference gradually reduces and fades away to less than 1.0 % when δY is over 4 mm, and it may be negligible. However, the interference effect should be examined carefully through a sensitivity test. The reed blade attraction of RS1 reaches maximum when δY is 3 mm because interference decreases. The attraction reduces after the peak point because the center distance from the permanent magnet is increases.

The reed blade attraction variation for Case 2 is summarized in Figs. 11 and 12. The reed blade attraction of

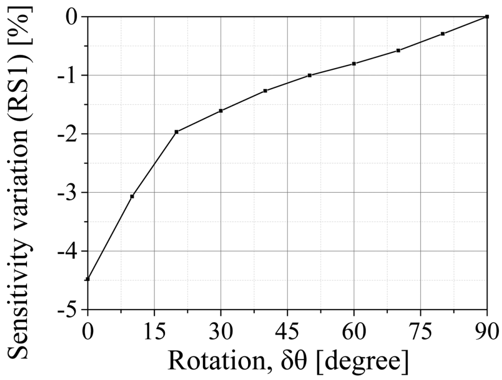


Fig. 11. Sensitivity variation of RS1 (Case 2).

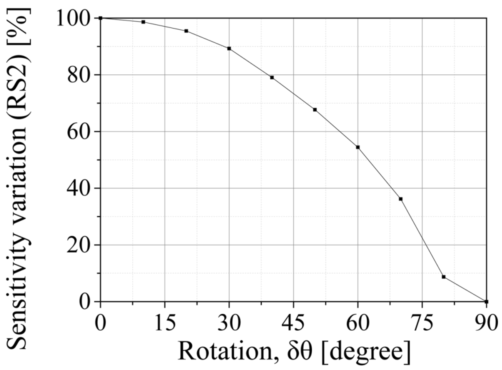


Fig. 12. Sensitivity variation of RS2 (Case 2).

RS1 increases along with increment of δθ because magnetization of the RS2 reed blades decreases as shown in Fig. 12. When δθ is equal to 90°, almost zero reed blade attraction for RS2 is estimated because the reed blades stand perpendicular to the magnet field direction from the permanent magnet and no polarity difference is generated.

When a reed switch rotates with respect to the centerline of the permanent magnet as shown in Fig. 13, the sensitivity may change. Reed blade attraction for this case

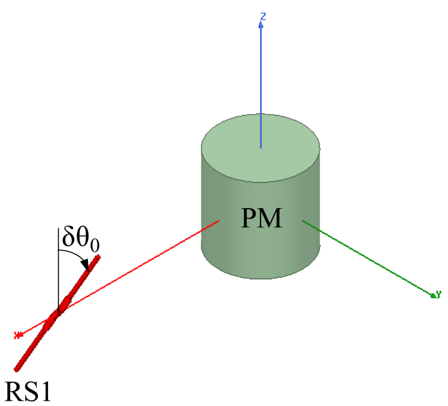


Fig. 13. (Color online) FE analysis model for sensitivity check with respect to rotation.

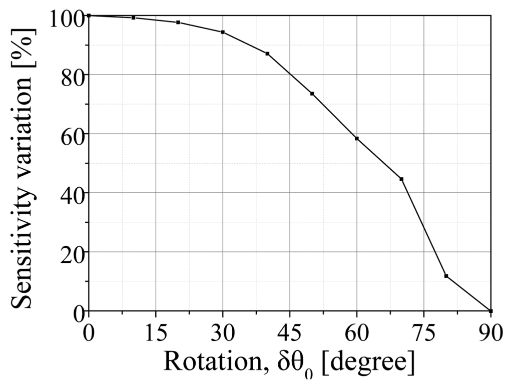


Fig. 14. Sensitivity variation due to installation angle.

is summarized in Fig. 14.

It was found that the rotation of a reed switch makes a greater reduction in the sensitivity. Thus, the arrangement of reed switches shall be studied thoroughly before designing the position sensors with reed switches. When a reed switch rotates 90°, the same polarities take place on each reed blade and no attraction is generated.

3.2. Electromagnetic interference consideration

Both the permanent magnet assembly and the operating coils can affect the electromagnetic field around the reed switches. Reed switch activation due to the coils may cause a malfunction of the RPIS. This phenomenon was proved to be possible through a CRDM performance verification test when the supply current to the lift coil increased. In this study, the electromagnetic influence from the lift coil is analyzed to establish the design criteria to arrange the RPISs without disturbing the operability [13].

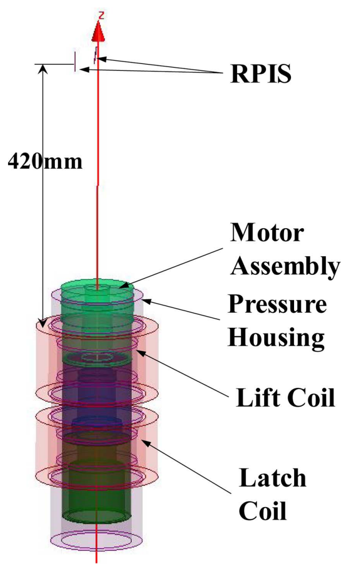


Fig. 15. (Color online) FE analysis model for the coil and reed switch.

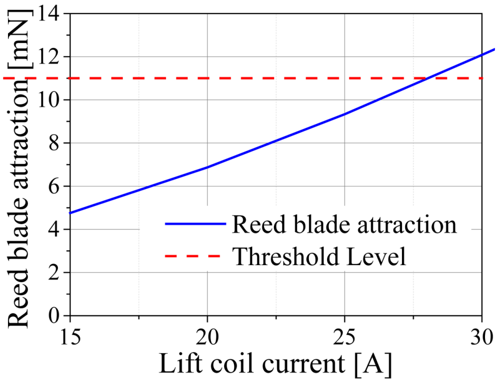


Fig. 16. (Color online) Reed blade attraction according to the lift coil current supply.

The attractive force can be produced above the threshold level by the electromagnetic field from the current through the CRDM lift coil. A 3D analysis model is shown in Fig. 15. It is assumed that the latching coil current is fixed as 25 A, and the lift current is variable.

It was easily found that reed blade attractive force increases along with the supply current increment as shown in Fig. 16. Because the postulated threshold attraction level (pull-in level) was 11 mN (the red dashed line), the reed switch may be activated at this position by the lift coil current of over 28 A. This estimation confirms that the current CRDM design for the RPISs and the coil arrangement are satisfactory without a malfunction of the RPIS because of the coil operation.

4. Conclusion

The new methodology for a reed switch analysis is proposed to take the reed switch arrangement into account at the design stage. The internal design of a reed switch needs to be investigated, although the information may be not provided by the manufacturer. However, this methodology could be efficient once a standard reed switch model is established. The feasibility of this methodology was demonstrated by comparing the test and analysis results, and it was concluded that the methodology can be applied for the RPIS design and arrangement. The quantitative results from this research cannot be applied to the other reed switches if a reed switch design is different. However this methodology can be applied to estimate the reed switch tilting effect and mutual interference quantitatively for a specific reed switch at the design stage.

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References

[1] J. S. Lee, G. M. Lee, and J. W. Kim, J. Magn. **21**, 4 (2016).
[2] R. K. Saraf and I. B. Ram, Microelectron. Reliab. **17** (1978).
[3] Westinghouse Electric Co., US Patent 6,380,734 (2002).
[4] H. Huh, J. I. Kim, and K. J. Kim, Trans. of KIEE **52D**, 8 (2003).
[5] J. Y. Yu and S. Choi, J. KPVP **3**, 4 (2007).
[6] J. Y. Yu, J. H. Kim, H. Huh, M. H. Choi, and D. S. Sohn, Trans. of ASME PVP/KPVP Conference (2010).
[7] J. Y. Yu, J. H. Kim, H. Huh, M. H. Choi, and D. S. Sohn, ICONE (2009).
[8] Reed Technology, Standex-Meder Electronics Inc.
[9] Y. B. Park, J. W. Kim, and J. S. Lee, J. KMS **26**, 5 (2016)
[10] J. S. Lee, Y. B. Park, J. W. Kim, and H. J. Park, ICEAA (2017).
[11] Ansys Electronics Desktop 19.1 [Online]. Available: http://www.ansys.com
[12] J. S. Lee, G. M. Lee, and J. W. Kim, EMSA (2018).
[13] G. M. Lee, J. S. Lee, Y. B. Park, and J. W. Kim, ICM (2018).