Chapter 1 Introduction

1.1 Classifications of the CRMS

1.1.1 Control rod position measurement sensor

Control rod is the only moveable device in the pressure vessel of the nuclear reactor. On the one hand, the power regulation of the nuclear reactor is conducted with the step-up or step-down of the control rod. On the other hand, the start-up or shut-down of the nuclear reactor is also achieved by the control rod (Paul, 2019). In particular, the scram performance which includes the scram time, control rod position is critical to ensure the safety of the nuclear reactor during the shut-down process (Sumner et al., 2010). Therefore, the accurate and reliable measurement of the control rod position is an essential task of the nuclear reactor.

The measurement of the control rod position is commonly accomplished by the control rod position measurement sensor (CRMS). Firstly, the CRMS should provide the accurate and reliable position of the control rod. Secondly, the CRMS must display the scram time of the control rod. Hence, the CRMS is the key equipment to ensure the safety and operation of the nuclear reactor.

Currently, the CRMS of the nuclear reactor can be classified into several types. Firstly, these include the non-inductance type and inductance type by the principle of CRMS. Secondly, these can be sorted into the in-vessel type and external type with the location of the CRMS. Thirdly, these contain the analog type, digital type and digital-analog type by the output signal of the CRMS. Fourthly, according to the measurement mode of the CRMS, it can be divided into the direct measurement type and indirect type. The detailed classifications of the CRMS are as shown in Fig. 1. 1 (Hu et al.,2020a).

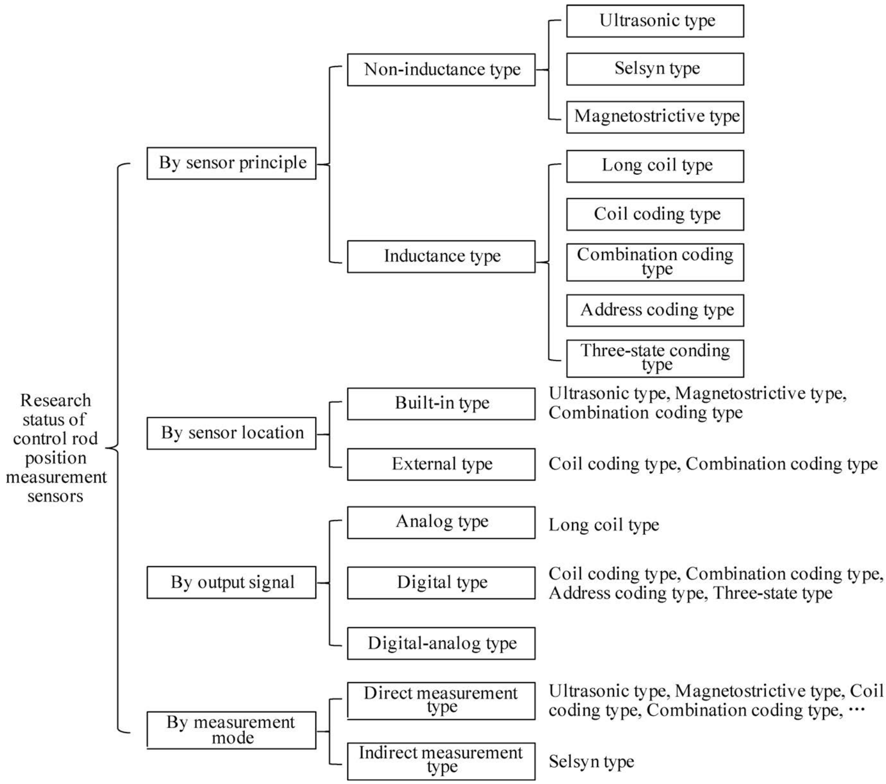

Fig. 1. 1 Detailed classifications of the CRMS

1. 1. 2 CRMS of the inductance type

As for the CMRS of the inductance type, it is widely adopted by the commercial nuclear power plant as shown in Table 1. 1. Hence, it is necessary to be illustrated detailly. And the research profile of the CRMS with the inductance type is described as follows.

Initially, the control rod position is measured along the longitudinal axis of a long induction coil continuously. And it is a CRMS of both the inductance type and analog type. However, the accuracy and reliability are low with this method (Regis, 1978).

Then, the Westinghouse introduced two series connected groups of equal numbers of parallel connected coils (Dirk et al., 1986; James, 1987). It is a digital type while disadvantages still exist.

Afterwards, the CRMS of the inductance type is gradually developed. And this CRMS are adopted by the majority of commercial nuclear power plants (Gregory et al., 2002; Hashemian et al., 2013; Casey et al., 2014; Paul, 2019). For example, the accuracy of the CRMS of the 1000 MWe China Pressurized Reactor (CPR1000) is 127 mm (±4 steps) (Lei, 2009). And it is improved to 95 mm (±3 steps) in the 1000 MWe Advanced Passive Reactor (AP1000) (Peng et al., 2012).

In the 1990s, the CRMS of the combination coding type was introduced. In addition, the CRMS of the combination coding type consists of several grouped transformers and one coding bar which is composed of m lengths of magnetic core and q lengths of non-magnetic portion. And the accuracy of the CRMS of the combination coding type is ±1 step. For the 200 MWe nuclear heating reactor (NHR-200) and 5 MWe nuclear heating reactor (NHR-5), the accuracy are 50 mm, 30 mm respectively (Li et al., 1996a; Wang et al., 1996; Jiang et al., 1996; Jiang et al., 1998a). It should be noted that the CRMS of the digital-analog type has the advantages of both the analog type and digital type (Jiang et al., 1998b). And the accuracy of the CRMS of the digital-analog type is still ±1 step.

Table 1.1 Research status of the CRMS of the inductance type

Type of the CMRS	Reference	Accuracy
Inductance type/Analog type	Regis, 1978	Low
Inductance type/Digital type	Dirk et al., 1986; James, 1987	Low
Inductance type/Digital type	Gregory et al., 2002; Lei, 2009; Peng et al., 2012	127 mm (±4 steps) in CPR1000
Inductance type/Digital type	Hashemian et al., 2013; Casey et al., 2014; Paul, 2019	95 mm (±3 steps) in AP1000

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Type of the CMRS	Reference	Accuracy
Inductance type/Digital type	Li et al.,1996a; Wang et al.,1996; Jiang et al.,1996; Jiang et al.,1998a	50 mm (±1 step) in NHR-200 30 mm (±1 step) in NHR-5
Inductance type/Digital-analog type	Jiang et al.,1998b	50 mm (±1 step) in NHR-200

1.1.3 CRMS of the non-inductance type

For the CMRS of the non-inductance type as shown in Table 1.2, there are mainly the ultrasonic type, magnetostrictive type, fixed in-core neutron detector type, reed switch type, selsyn type, capacitance type, and so on. These CRMSs are explained as follows.

Firstly, the CRMS of the ultrasonic type was introduced in 1990. A receiver is configured to receive the reflected sonar signal and communicate the reflected sonar signal to a processing unit. Then the control rod position is determined. Additionally, it is a CRMS of the in-vessel type (Wang et al., 1990; Pramod et al., 1994; Anandaraj et al., 2009; Carvajal et al., 2017).

Secondly, the CRMS of the magnetostrictive type works in the high temperature and high pressure water. So it is also a CRMS of the in-vessel type. The accuracy of the CRMS of the magnetostrictive type is proved to be 1.2 mm (Ishida et al., 2001; Ichikawa et al., 2001; Zhang et al., 2010; Lee et al., 2016a).

Thirdly, the CRMS of the fixed in-core neutron detector type was developed in 1993 (Impink et al., 1993; Garis et al., 1998). And the accuracy of the CRMS of the fixed in-core neutron detector type is less than 2 steps (±1 step) in the 100 MWe Advanced China Pressurized Reactor (ACP100) when the detector signals are contaminated by 1% random noise (Peng et al., 2015; Peng et al., 2017).

Fourthly, the CRMS of the reed switch type was applied in the field of the nuclear reactor in 1970s. And it is a CRMS of the digital type (Foxworthy et al.,1977; Yu et al.,2009; Nakamura et al.,2013).

Fifth, the CRMS of the selsyn type contains a stepping motor, a magnetic damper, a gearbox, a sprocket wheel device. And the control rod position is obtained by a synchro transforming the rotary angle to a tri-phase alternating current signal. And the accuracy of the CRMS of the selsyn type is ±4 mm in the 10 MWe High Temperature Gas-cooled Reactor (HTR-10) (Ramaswami et al.,2001; Wu Y. Q. ,et al.,2002; Wu Z. X. et al.,2002).

Sixth, the CRMS of the capacitance type is a in-vessel type (Hu et al. ,2018). And the control rod position is measured by a helix-electrode capacitance sensor system. The accuracy of the CRMS of the capacitance type is within 1 step up NHR-200 (Hu et al.,2019a; Hu et al.,2019b; Hu et al.,2019c; Hu et al.,2020a).

Table 1.2 Research status of the CRMS of the non-inductance type

Type of the CMRS	Reference	Accuracy
Ultrasonic type/In-vessel type	Wang et al.,1990; Pramod et al.,1994; Anandaraj et al.,2009; Carvajal et al.,2017	1 mm
Magnetostrictive type/In-vessel type	Ishida et al.,2001; Ichikawa et al.,2001; Zhang et al.,2010; Lee et al.,2016a	1.2 mm
Fixed in-core neutron detector type	Impink et al.,1993; Garis et al.,1998; Peng et al.,2015; Peng et al.,2017	±1 step in ACP100
Reed switch type/Digital type	Foxworthy et al.,1977; Yu et al.,2009; Nakamura et al.,2013	-
Selsyn type/Digital type	Ramaswami et al.,2001; Wu et al.,2002; Wu Y. Q. et al.,2002	±4 mm in HTR-10

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Type of the CMRS	Reference	Accuracy
Capacitance type/In-vessel type	Hu and Bo,2018; Hu et al.,2019a; Hu et al.,2019b; Hu et al.,2019c; Hu et al.,2020a	1 step in NHR-200
Hall effect type/Digital type	James,1975	-
Magneto-sonic Type	Bettencourt et al. ,1978	±1%
Thermocouple type	Heibel et al.,1990	±1.7-±12 steps
Electromagnetic transducer type	Pesic et al.,1992	< 6%

Seventh, the CRMS of the hall effect type employs a plurality of hall effect transducers longitudinally spaced along the control rod motion range (James,1975). In addition, the CRMS of the magneto-sonic type combines the magnetic and sonics techniques to measure the control rod position with an accuracy of 1% (Bettencourt et al.,1978). Meanwhile, the CRMS of the thermocouple type obtains the enthalpy rise deviations by thermocouples to determine the control rod position with an accuracy of ±1.7-±12 steps. And the accuracy changes with the resolution of thermocouples (Heibel et al., 1990). Furthermore, the CRMS of the electromagnetic transducer type utilizes a fast electromagnetic transducer to measure the control rod position with a relative accuracy of less than 6% (Pesic et al.,1992).

1.1.4 Scope of this introduction

In above, the measurement of the control rod position is accomplished by the CRMS, which concerns the start-up, power regulation and shut-down of the nuclear reactor. However, to the best of our knowledge, there still lacks research on comprehensive reviewing the state of art progress on the CRMS of the nuclear reactor. Therefore, this review focuses on the elaborating the classifications of the CRMS and presents the accuracy of the CRMS of several types. In Section 1.2, principles of the CRMS of 7 types would be discussed, including the inductance type, ultrasonic type, magnetostrictive type, fixed in-core neutron detector type, reed switch type, selsyn type, capacitance type, and so on. This review would emphasize the physical model of the inductance type as it is mainly adopted commercially. Section 1.3 will show the experimental and numerical validation details in the field of the CRMS. Section 1.4 comes to the conclusions and future challenges on the field of the CRMS.

1.2 Principles of the CRMS

In this section, principles of the CRMS of 7 types will be illustrated. As the CRMS of the inductance type is mainly adopted commercially, our first task is to describe the principles of CRMS of the inductance type.

1.2.1 Principles of the CRMS of the inductance type

The initial CRMS of the inductance type is an analog type with low accuracy and reliability (Regis, 1978). Hence, commercial nuclear power plants, like the CPR1000 and AP1000 adapt the CRMS of both the inductance type and digital type (Dirk et al. 1986; James et al., 1987; Gregory et al., 2002; Hashemian et al., 2013; Casey et al., 2014; Paul, 2019; Lei, 2009; Peng et al. 2012). And principles of the CRMS of this type are quite similar.

1) CRMS of the inductance type

The CRMS of the inductance type is mounted along the longitudinal axis of the discrete coils. For example, the CRMS in AP1000 consists of 24 coils for group A and group B as shown in Fig. 1.2. In Fig. 1.2, coils of both group A and group B are connected independently and eventually lead out (Lei, 2009). Additionally, coils of the same group in the CRMS are connected in parallel with the input terminal 1 and output terminal 2. Meanwhile, grouped coils are spaced 95 mm apart on the CRMS, corresponding to ± 3 steps mechanically. And the CRMS displays the position of the control rod measured rod with a digital type from 0 to 267 steps.

Fig. 1. 3 shows principles of the CRMS of the inductance type with a local view (marked dashed line in Fig. 1. 2) when the control rod measured rod step in coils A2, B2. Additionally, the control rod measured rod has two modes: the step-in mode, step-out mode. The process in the step-out mode are opposite with the step-in mode.

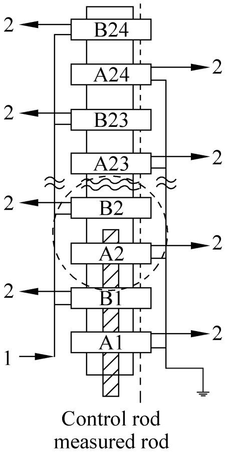

Fig. 1. 2 Diagram of the CRMS in AP1000

1-input; 2-output.

Fig. 1. 3(a) illustrates the schematic diagram of the CRMS. And there are primary coils and secondary coils in the CRMS. It should be noted that primary coils provide the electromagnetic environment and original energy sources for the CRMS. And secondary coils are placed with a distance of $2P$ equally. In Fig. 1. 3(b), the induced voltages V_A, V_B change respectively when the control rod measured rod enters secondary coils in order. Hence, functions between induced voltages V_A, V_B and the position of the control rod measured rod x are $f_A(x)$, $f_B(x)$ respectively. In Fig. 1. 3(c), the voltage difference V is obtained. Then, this value is transformed into a logical signal as shown in Fig. 1. 3(d).

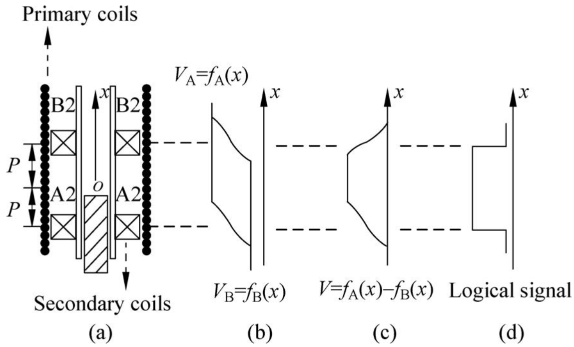

Fig. 1. 3 Principles of the CRMS of the inductance type

Therefore, a logical signal equals 0 when the position of the control rod measured rod x is larger than P or smaller than $-P$ ($x>P$ or $x<-P$). And it becomes 1 when x is greater than $-P$ and smaller than P ($-P<x<P$). It should be noted that the relationship between the control rod position x and binary code will be explained in the following part.

2) CRMS of the combination coding type

The CRMS of the combination coding type consists of a primary coil, N secondary coils, a compensation coil and a coding bar. And the coding bar is composed of m lengths of magnetic core and q lengths of non-magnetic portion alternately. As the control rod measured rod steps up or steps down, the coding bar passes secondary coils.

Hence, outputs of coils which introduced by the primary coil will change. By receiving and processing those outputs, the control rod position is obtained (Li et al., 1996a; Wang et al., 1996; Jiang et al., 1996; Jiang et al., 1998a). Furthermore, the CRMS of the digital-analog type has the advantages of both the analog type and digital type (Jiang et al., 1998b). and the relationship between the number of secondary coils N, lengths of magnetic core m, lengths of non-magnetic portion q and positions of control rod measured rod x are given in Eq. (1.1)-Eq. (1.3).

$$q = m - 1 \tag{1.1}$$

For N is an odd number, we have

$$m = \frac{N-1}{2} \tag{1.2a}$$

$$x = (N-1)(N-2) + 3 \tag{1.2b}$$

For N is an even number, we have

$$m = \frac{N-2}{2} \tag{1.3a}$$

$$x = (N-2)^2 + 3 \tag{1.3b}$$

From Eq. (1.1)-Eq. (1.3), the relationship between the number of secondary coils N, lengths of magnetic core m, lengths of non-magnetic portion q and positions of control rod measured rod x are obtained with 6 cases as shown in Table 1.3. And lengths of magnetic core m are $3P$, $7P$, $\cdots$, $3P+(m-1)P$, respectively. Meanwhile, lengths of non-magnetic portion q are $[2(N-2)-3]P$, $[2(N-2)-7]P$, and so on.

Table 1.3 Relationship between the number of secondary coils N, lengths of magnetic core m, lengths of non-magnetic portion q and positions of control rod measured rod x

Variables	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
N	5	6	7	8	9	10
m	2	2	3	3	4	4
q	1	1	2	2	3	3
x	15	19	33	39	59	67

Fig. 1.4 is the schematic diagram of the CRMS of the combination coding type with the number of secondary coils $N=8$. The CRMS is mainly composed of 1 primary coil, 8 secondary coils, 1 coding bar and 1 compensation coil. And lengths of magnetic core m, lengths of non-magnetic portion q are also given in Fig. 1.4 according to Eq. (1.1)-Eq. (1.3).

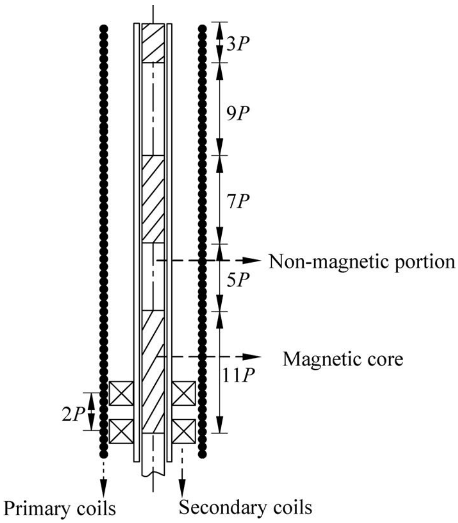

Fig. 1.4 Schematic diagram of the CRMS of the combination coding type with the number of secondary coils $N=8$

1.2.2 Principles of the CRMS of the ultrasonic type

The CRMS of the ultrasonic type emits the ultrasonic wave at a certain speed v in water. And it will be reflected and subject to the law of