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Paper:

Viscosity Control of Magnetorheological Fluid by Power Saving Magnetizing Mechanism Using Movement of Permanent Magnet

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Generally, the magnetic field applied to a magnetorheological fluid (MRF) is generated by electromagnets. Electromagnets consume electric power during MRF magnetization, which is an issue. In this study, we examine two kinds of magnetizing mechanism using a permanent magnet, instead of electromagnets, to save electric power and generate a magnetic field on the MRF. One mechanism linearly moves the permanent magnet into the magnetic circuit composed of yokes. The magnetic field intensity on the MRF is then controlled by changing the overlap between the magnet and the yokes. The other mechanism rotates a permanent magnet in the magnetic circuit. The magnetic field intensity on the MRF is then controlled by changing the relative angular position between the magnet and the yokes. These two mechanisms normally generate force or torque on the magnet toward a magnetically stable position concerning the magnet, and the force or torque causes power consumption to hold and move the magnet. We design herein special magnetic circuits and a cancelation mechanism for the force or torque that drastically reduce the power consumption during the MRF magnetization compared with an electromagnet-type magnetizing device.

Keywords: functional fluid, magnetorheological fluid, permanent magnet, magnetic circuit, motion control

1. Introduction

A magnetorheological fluid (MRF) is a functional fluid that changes its viscosity according to the intensity of the applied external magnetic field. The MRF viscosity can be controlled by the external magnetic field; hence, various applications (e.g., dampers, brakes, and clutches) are put to practical use [1–13]. An electromagnet is generally used as the source of the external magnetic field applied to the MRF. However, an electromagnet keeps consuming electric power and generating the heat at the solenoid during MRF magnetization. The authors have already developed a hybrid magnetizing device for the viscosity control of the MRF using the combination of an electromagnet and a permanent magnet material [14, 15]. The device can perform good power-saving magnetization for the MRF in terms of maintaining a constant magnetic field intensity on the MRF. However, it is not effective for power saving in the case where the magnetic field on the MRF continuously varies. This study proposes a non-electromagnetic and power-saving magnetizing mechanism for the viscosity control of the MRF using only a permanent magnet to save power magnetization in the MRF without using an electromagnet. The MRF magnetization using only a permanent magnet requires moving and holding the magnet against the yoke. We examine two kinds of magnetizing mechanism to control the magnetic field intensity on the MRF using a permanent magnet. One mechanism linearly moves a permanent magnet into the magnetic circuit composed of yokes. The magnetic field intensity on the MRF is then controlled by changing the overlap between the magnet and the yokes. This mechanism is suitable for stationary magnetizing devices and MRF dampers because it can be replaced with an electromagnet. Meanwhile, the other mechanism rotates a permanent magnet in the magnetic circuit. The magnetic field intensity on the MRF is then controlled by changing the relative angular position between the magnet and the yokes. This mechanism is suitable for rotating magnetizing devices, such as disk brakes and clutches using an MRF. These mechanisms normally generate an attractive force or torque on the magnet toward a magnetically stable position concerning the magnet. Consequently, the force or torque causes power consumption in the actuator to move and hold the magnet. Two types of magnetic circuits for MRF magnetization using only a permanent magnet, in which the magnetic attractive force or torque is drastically reduced, have been designed. We apply the electromagnetic field analysis in this magnetic circuit design considering the magnetic non-linearity. We also conduct an experiment to estimate the advantages of the two kinds of mechanisms and further evaluate the performances of the two prototypes.

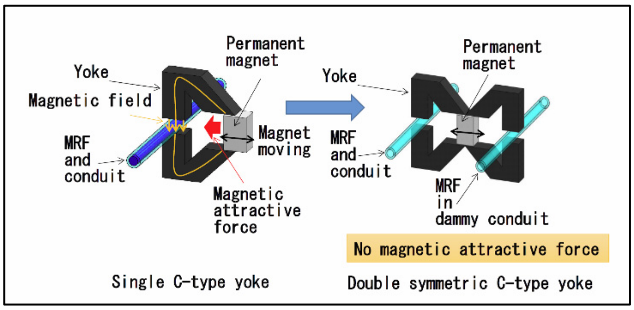

Fig. 1. Power-saving magnetic field intensity control mechanism for the MRF using a permanent magnet and double symmetric C-type yokes.

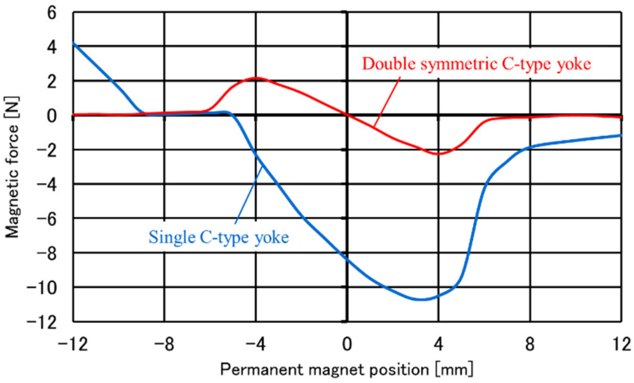

Fig. 2. Measurement result of the magnetic attractive force acting on the permanent magnet in the single and double symmetric C-type yoke models.

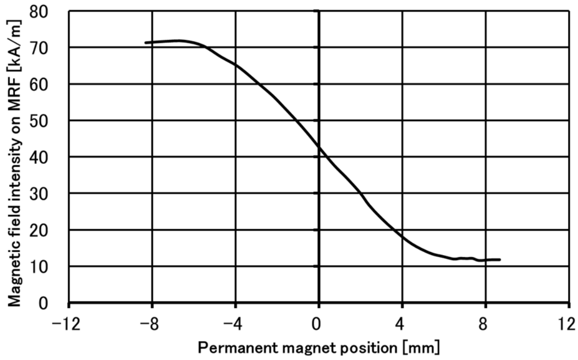

Fig. 3. Measurement result of the magnetic field intensity on the MRF in the double symmetric C-type yoke model.

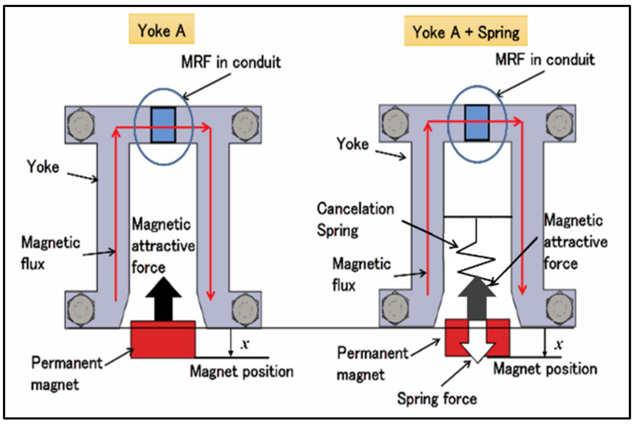

Fig. 4. Magnetizing mechanisms for the MRF using a linear movable permanent magnet.

2. Non-Electromagnetic Magnetizing Device Prototype for MRF Using Only Permanent Magnet

We developed a non-electromagnetic magnetizing device for the MRF using only a permanent magnet and reported its performance in [16]. As shown in **Fig. 1**, the device had a C-type yoke and a linearly movable permanent magnet. In this magnetizing mechanism, the overlap between the yoke pole and the permanent magnet can be controlled by linearly moving the permanent magnet. The magnetic field intensity on the MRF can also be controlled. Although the attractive magnetic force always acted on the permanent magnet moving into the yoke in the single C-type yoke, the symmetric arrangement of the double C-type yokes canceled the force by 80% at the maximum value (**Fig. 2**). Force was not needed to move the magnet; hence, the magnetic field intensity on the MRF can be controlled without power consumption. However, some complication issues were encountered when linearly moving the magnet in the double C-type yokes. The increase of its volume due to the symmetrical arrangement with the yokes was an issue. The shortage of the control range of the magnetic intensity for controlling the MRF was also a problem. The measurement result of the magnetic field intensity on the MRF in the power-saving magnetic field intensity control mechanism with double symmetric C-type yokes is shown in **Fig. 3**. The controllable magnetic intensity range was from 12 to 72 kA/m, which was not sufficient compared with the target controllable range of 0 to 250 kA/m. Accordingly, two kinds of non-electromagnetic magnetizing mechanism of the MRF are proposed herein to avoid drawbacks. One linearly moves a magnet into the yoke poles, in which the magnetic attractive force is canceled by the specially designed compressive coil spring. The other rotates a magnet against the yoke, in which the magnetic torque is reduced by adding a sub-yoke around the magnet.

3. Non-Electromagnetic Magnetizing Device for MRF Using the Linear Motion of a Permanent Magnet

3.1. Concept of the Non-Electromagnetic Magnetizing Device Using the Linear Motion of a Magnet

In **Fig. 4**, “Yoke A” shows a simple single C-type yoke based on the non-electromagnetic magnetizing device for

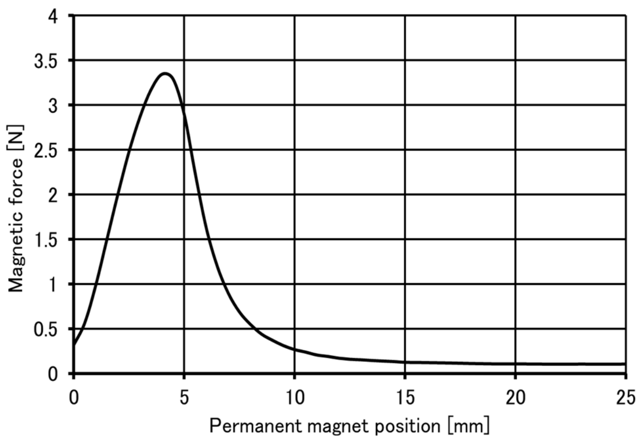

Fig. 5. Characteristic of the magnetic attractive force of Yoke A.

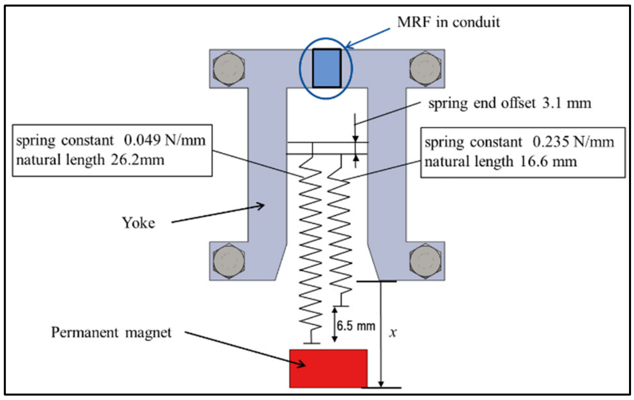

Fig. 7. Specifications of two different springs.

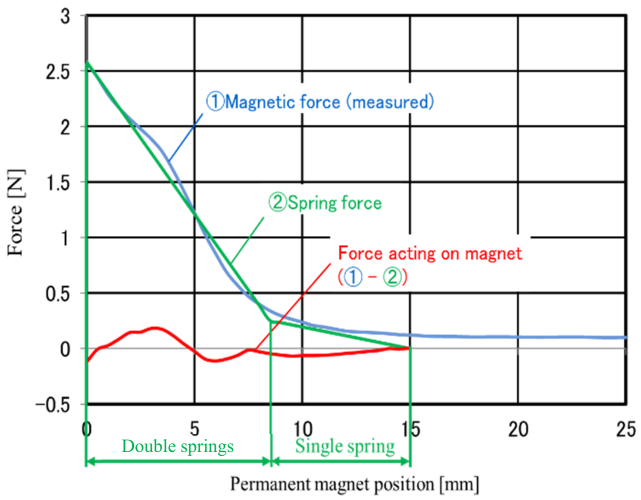

Fig. 6. Measurement result of the magnetic attractive force acting on the permanent magnet in the linear motion model.

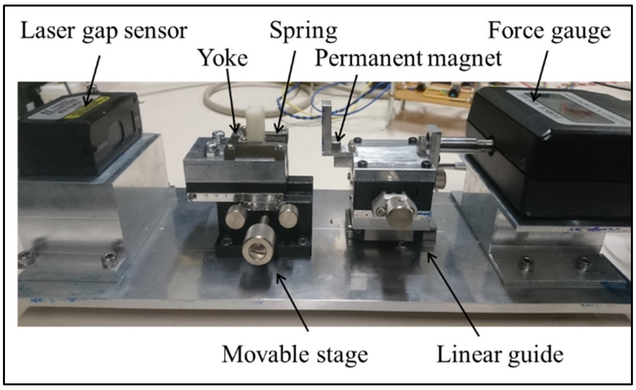

Fig. 8. Experimental equipment for measuring the magnetic attractive force in the non-electromagnetic magnetizing device using the linear motion of a magnet.

the MRF using the linear motion of a permanent magnet. Its magnetic circuit consisted of the conduit in the MRF inside, yokes, and permanent magnet. The magnetic field intensity can be controlled by the overlap between the yoke pole and the linearly movable magnet. The attractive magnetic force always acts on the magnet moving into the yoke, and the force intensity depends on the magnet's position. In "Yoke A + Spring," the special designed yokes and a compressive coil spring were installed into the device to cancel the attractive magnetic force. The corners of the yokes were cut away properly to enhance the characteristic of the magnetic attractive force. The characteristic of the magnetic attractive force of Yoke A in a graph that is convex upward is shown in **Fig. 5**. Canceling this characteristic by a single spring is not ideal because the spring force linearly changes. Thus, we introduce Yoke B. As shown in **Fig. 6**, the corner cut of Yoke B realizes the ideal characteristic of the magnetic attractive force for spring cancelation. In **Fig. 7**, the double springs are composed of two different stiffnesses and natural length springs. One spring was designed with a relatively low spring constant and a long stroke to cancel the magnetic force in the middle range with a spring constant of 0.049 N/mm and a natural length of 26.2 mm. The other spring was designed with a relatively high spring constant and a short stroke to cancel the magnetic force in the short range with a spring constant of 0.235 N/mm and a natural length of 16.6 mm. The magnetic force in the middle range is not that strong and gradually changes. However, the closer the distance between the yokes and the magnet, the stronger the magnetic attractive force. To follow the characteristic by the spring, in the case where the permanent magnet gets closer to the yokes, only the soft spring comes into contact with the magnet at first from a distance of 15 mm. Thereafter, at a distance of 8.5 mm, the hard spring starts contact, and two springs start generating force together. These designs realize a drastic reduction of the magnetic attractive force (**Fig. 6**).

3.2. Cancelation of the Magnetic Attractive Force Acting on the Linearly Movable Magnet

We measured the magnetic attractive force using the experimental equipment shown in **Fig. 8**. The measurement results of the magnetic attractive force acting on the

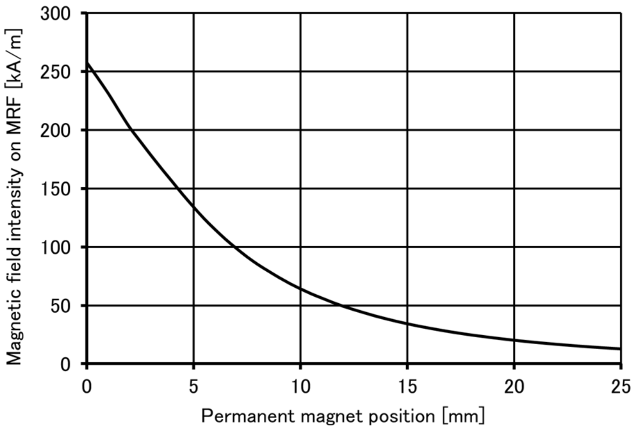

Fig. 9. Simulation result of the magnetic field intensity on the MRF in the linear motion model with "Yoke B."

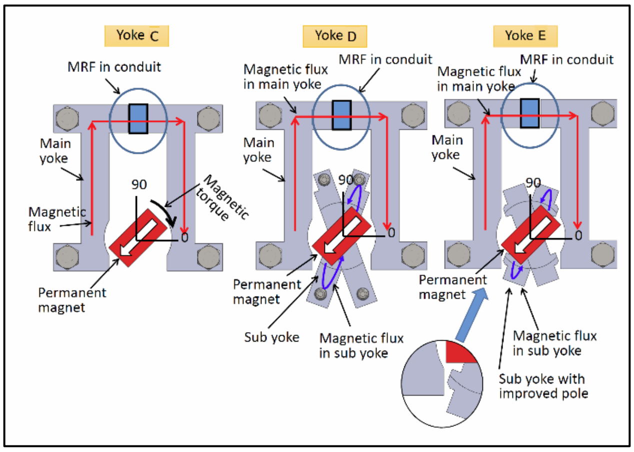

Fig. 10. Magnetizing mechanisms for the MRF using the rotary movable permanent magnet.

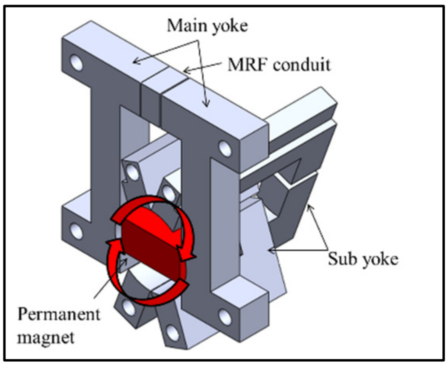

Fig. 11. Magnetizing mechanism using the rotary movable permanent magnet with "Yoke E."

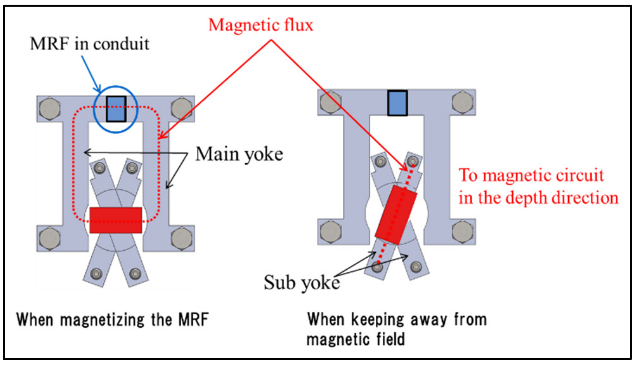

Fig. 12. Method of controlling the magnetic field intensity and canceling the magnetic torque acting on the permanent magnet in the magnetizing mechanism using the rotary movable permanent magnet.

magnet are shown in **Fig. 6**. The result of the simulated magnetic field intensity at the MRF conduit in the linear motion model with "Yoke B" obtained using electromagnetic field analysis software is depicted in **Fig. 9**.

The yoke material was SS400 steel. The permanent magnet block measuring 5 mm × 5 mm × 10 mm was a commercially available neodymium magnet. The relative position of the magnet to the yoke was controlled from 0 to 25 mm by a linearly movable stage operation. The target controllable range of the magnetic field intensity at the MRF was designed to be from 0 to 250 kA/m to obtain the natural viscosity of the MRF and the maximum viscosity of the magnetized MRF.

In the case of "Yoke B," the maximum magnetic attractive force acting on the magnet was 2.6 N. The magnetic field intensity at the MRF was changed from 13 to 250 kA/m by the simulation.

By contrast, in the case of "Yoke B + Spring," the maximum force acting on the magnet was reduced to 0.18 N in the measurement by keeping the controllable range of the magnetic field intensity. Compared with "Yoke B," which had no spring, the cancelation of the force acting on the magnet in this case showed a 93% reduction at maximum value.

4. Non-Electromagnetic Magnetizing Device for MRF Using the Rotational Motion of a Permanent Magnet

4.1. Concept of the Non-Electromagnetic Magnetizing Device Using the Rotational Motion of a Magnet

The non-electromagnetic magnetizing devices for the MRF using the rotational motion of the permanent magnet are shown in **Figs. 10–12**. The magnet can rotate to the main yoke in an angular position from 0° to 90°. Compared with the abovementioned magnetizing device using the linear motion of the magnet, the magnet in this device can be supported by a simple rotary shaft and mechanical bearings and is suitable for rotational machine applications (e.g., brakes and clutches).

Meanwhile, "Yoke C" is only a single C-type main yoke with a rotational magnet. The magnetic torque acts on the magnet to align the axis of the magnet to the yoke pole (0° direction). The magnetic torque never acts on the

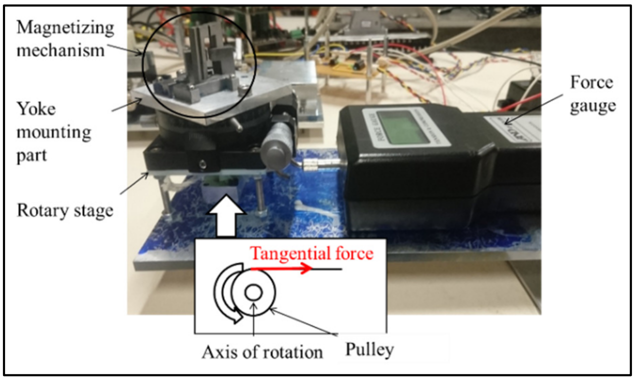

Fig. 13. Experimental equipment for measuring the magnetic torque acting on the permanent magnet in the nonelectromagnetic magnetizing device using the rotational motion of the magnet.

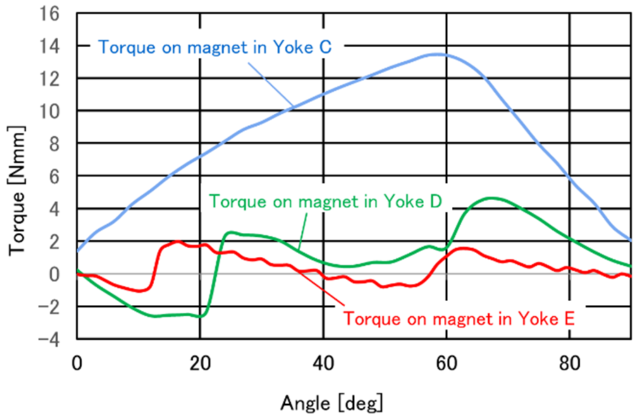

Fig. 14. Measurement result of the magnetic torque acting on the permanent magnet in the rotary motion model.

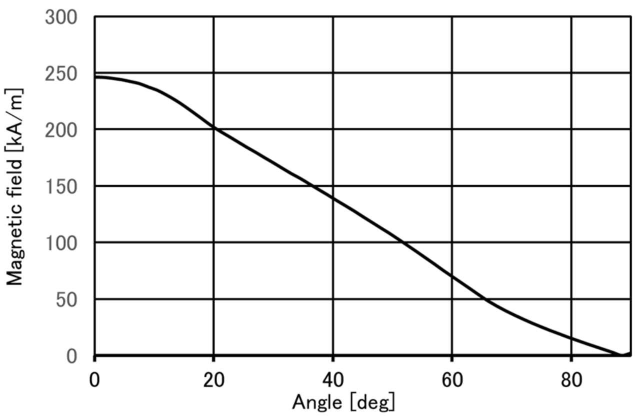

Fig. 15. Simulation result of the magnetic field intensity at the MRF in the rotary motion model, "Yoke E."

magnet if the reluctance between the yoke and the magnet does not change, irrespective of the magnet's angular position.

"Yoke D" comprises a main yoke conducting magnetic flux to the MRF and a sub-yoke not connected to the MRF. The sub-yoke reluctance was designed to be similar to that of the main yoke regarding the magnet.

The magnetic flux was divided into the main and sub-yokes according to the magnet's angular position. Therefore, the magnetic field intensity at the MRF can be controlled by the overlap between the main yoke pole and the tip of the rotational magnet. However, a slight toque fluctuation occurred at the boundary between the main and sub-yokes because of the discontinuity of the magnetic flux path. No torque fluctuation occurred when no airgap existed at the boundary between the yokes. However, regarding the magnet's angular position, the magnetic field intensity at the MRF never changed because the magnetic flux cannot be divided at the boundary between the main and sub-yokes. By contrast, when the boundary has a large airgap, the magnetic field intensity at the MRF was controllable, but a large torque fluctuation occurred when the magnet tip passed through the boundary. Hence, an adequate airgap should be designed to reduce the torque fluctuation ("Yoke E," **Fig. 10**).

4.2. Reduction of Torque Acting on a Permanent Magnet in the Non-Electromagnetic Magnetizing Device Using the Rotational Motion of Magnet

We measured the magnetic torque acting on the permanent magnet using the experimental equipment shown in **Fig. 13**. During the torque measurement, the yokes and the MRF conduit were arranged on the rotary table. Furthermore, the magnet was independently supported by a shaft to the rotary table connected to the torque meter. The rotary table rotates the yoke relative to the magnet. The experiment result of the relation between the torque acting on the magnet and the magnet's angular position is shown in **Fig. 14**. The relation between the simulated magnetic field intensity at the MRF and the magnet's angular position is depicted in **Fig. 15**. The yoke and magnet material were similar to those of the abovementioned magnetizing device using the linear motion of the magnet.

The maximum magnetic torque acting on the magnet in "Yoke C" with only the main yoke was 13.4 Nmm.

The maximum magnetic torque in "Yoke D," which consisted of the main and sub-yokes, was 4.6 Nmm. The controllable range of the magnetic field intensity at the MRF was obtained from 2.2 to 253 kA/m, which almost satisfied the target controllable range from 0 to 250 kA/m. Compared with "Yoke C," which had no sub-yoke, "Yoke D" achieved a magnetic torque reduction of approximately 65%. One torque peak was observed when only the main yoke was used; however, the number of peaks increased to three when the sub-yoke was added in "Yoke D" and "Yoke E." Such change occurred because the magnet was attracted to the main yoke at the beginning of the rotation. As the rotation progressed, it was attracted to the two sub-yokes in order.

Compared with "Yoke C," which had no sub-yoke, "Yoke E," in which the airgap at the boundary between the main and sub-yokes was optimized to reduce the magnetic torque and to maintain the controllable range of the magnetic field intensity at the MRF, had a maximum magnetic torque of 2 Nmm and 85% torque reduction. The controllable range of the magnetic field intensity at the MRF was maintained from 2.3 to 246 kA/m, which is almost the same as that in "Yoke D" with a sub-yoke.

5. Conclusion

In this study, two types of non-electromagnetic magnetizing device for the MRF were developed using the motion of a permanent magnet to save the power magnetization of the MRF. The permanent magnet needed no power consumption to move because the magnetic force or torque acting on the magnet was drastically reduced by the special-shape magnetic circuit design. The magnetizing devices can control the magnetic field intensity at the MRF with no power consumption by positioning the magnet in the yoke through a manual operation, a small power actuator actuation, and a wire operation. These devices are expected to be applied to the viscosity control of the MRF in industry applications, such as dampers, brakes, and clutches, by using their power-saving performance.

The proposed magnetizing mechanisms have the advantage of power saving by the continuous application of the controlled magnetic field to the MRF. By contrast, compared with a conventional magnetizing device using electromagnets, the two prototype devices still have disadvantages, such as heavy weight, large volume, and response time. We plan to overcome these disadvantages by optimizing their magnetic circuits and actuator designs and enhancing the control method in the future work.

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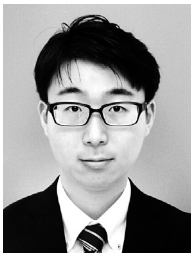

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