

Study on macroscopic behavior of silicone oil-based magnetorheological fluids

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In order to reveal the transmitting mechanism of silicone oil-based magnetorheological fluids, experiment equipment was set up and testing experiments were carried out. Firstly, double viscosity model was introduced and magnetism theoretical principles were presented. Secondly, three silicone oil-based magnetorheological fluids with different volume fractions of magnetic particles 10%, 20% and 30% were prepared, and several testing experiments were carried out to describe the rheological properties of MRF. Finally, a macroscopic model for mechanical characteristic of silicone oil-based magnetorheological fluids was proposed.

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1. Introduction

As one of the most promising intelligent materials in the future, magnetorheological fluids (MRF) are a type of suspensions formed by soft magnetic particles under the action of surface activator and dispersed in carrier liquid. The basic characteristic is that MRF can be rapidly varied from the free flow of liquid into semisolid under the action of a strong magnetic field and this change process can be reversible. At present, the applications of MRF in the dampers, brake devices and some other devices show excellent performance. With the deepening of research, magnetorheological fluids transmission technology has great potential in aerospace engineering, mechanical engineering, automobile engineering, precision processing engineering and control engineering, etc [1-2].

As an important factor to evaluate the performance of MRF, shear yield stress is the turning point of liquid form and solid structure, and reflects the curing strength and transmission ability. Thus, accurate testing method of shear yield stress and study on macroscopic behavior of MRF have an important significance on the work of theory research, performance analysis, engineering applications especially the design of MRF devices [3].

At present, many researchers have worked on the problem of MRF shear yield stress testing and proposed different methods such as Bucket MRF testing method, Rotating disk MRF testing method [4], Tube testing method [5] and Flat-pulling method [6], etc. Due to the characteristics of compact structure, uniform magnetic field, easy to test and achieve accurate results, Rotating disk MRF testing method is applied in this paper and different volume fractions of MRF are tested under different magnetic fields, and the macroscopic model for

mechanical characteristic of silicone oil-based magnetorheological fluids is proposed.

The rest of our paper was organized as follows: section 2 outlined several related works on MRF. Section 3 presented the related theory for MRF shear yield stress. Section 4 discussed the experiments equipment and results. Section 5 summarized our conclusions and future work.

2. Literature review

2.1 Rheological property of MRF

The most typical rheological behavior of MRF is the changing rule of shearing force with different shearing strain rate in different magnetic field and Bingham model is the most representative and constitutive model to describe MRF behavior [7]. But the Bingham model cannot explain the shear thinning phenomenon of MRF, so the Bingham model can be improved to be generalized Bingham model as follows [8]:

$$\tau = \tau_0(H) \operatorname{sgn}(\dot{\gamma}) + \eta \dot{\gamma}^n \quad (1)$$

Where index n reflects the degree of shear thinning of

MRF, $\dot{\gamma}$ is the shear rate.

Some experimental results about the onset of a yield stress when a magnetic field was applied either to an aqueous suspension of polystyrene particles which behaved as magnetic holes was reported by G.Bossis and E.Lemaire from France. It was shown that a simple model

based on a calculus of magnetic forces between two spheres well reproduced the yield stress behavior [9]. A model based on the energy approach was built by Yalcintas and some assumptions in this model were shown as: no normal stresses in the MR layer and no shear strains in the elastic layers existed. They used shear module to describe the relationship between shear stress and shear strain [10]. A simulation approach through integration of Monte Carlo method and GPU accelerated technology was proposed and three-dimensional micro-structure of magnetic particles in different strength magnetic fields were simulated by Liu Xinhua and Liu Yongzhi [11]. K. C. Chen focused on the expression of stress tensor and the mechanism of energy dissipation. Comparisons among the vectorial internal variable, the tensorial internal variable and the Cauchy's deformation tensor were made to explicate the connection among the different approaches [12]. A general three-dimensional non-linear constitutive law for such a fluid was given for the case in which the magnetic induction vector was used as the independent magnetic variable [13]. A novel approach based on the two-component Lattice Boltzmann method with double meshes was proposed, and the micro-scale structures of magnetorheological fluids in different strength magnetic fields were simulated by Liu Xinhua and Liu Hao to study the rheological characteristics of magnetorheological fluids [14]. A visco-plastic model of MRF was given by Si Hu which can characterize the mechanical properties of magnetorheological materials in plastic and viscous variation [15]. Compression working mode of MRF was applied and mechanical property of MRF micro-structure under compression working mode was researched by Liu Xinhua and Chen Qingqing to improve the yield stress of magnetorheological fluids [16].

2.2 MRF shear yield stress testing methods

Bucket MRF testing method is more and more used in the research of MRF yield stress by foreigner researcher. Bucket testing devices were improved on the basis of viscometer measuring equipments such as MR-100-450 testing devices produced in German which have been commercialized. A kind of concentric cylinder devices was adopted by W. H. Li and Weng Jiansheng [17] from Nanjing University of Aeronautics and Astronautics to research mechanical properties of MRF.

Two parallel disks are used as the coupled devices for testing in Rotating disk MRF testing method. A rotary test system was designed by Jin Yun, Zhou Gangyi from China Science and Technology University [18] using this principle and excellent performance of this system was obtained in actual application. The parallel-plate type commercial rheometer was used by Wollny from German to examine the rheological properties of monodisperse magnetorheological suspensions of magnetic composite particles [19]. A kind of Parallel disk rheology instrument was produced by TA Instruments Company and this device

was used to research the rheological properties of MRF by Park [20]. The rheology instrument produced in Bohlin Company in British was a typical kind of disk rotary test system. In this system the nether disk can be rotated by the driving of motor and the upper disk was connected with torque sensor to test the value of torque of the suspension liquid between two disks. The magnetic field strength was measured by Gauss measurement. Takata used Rotating disk method to examine the dependences of an output torque of the clutch on the applied magnetic field were examined by Shinzo Takata using Rotating disk method under a fixed input torque for different densities of particles, surfactant or smectite in the MRF [21].

A kind of Tube testing method was designed by Anh Dang from the USA [22] and a testing device of MRF yield stress similar to Tube testing device was designed by Jin Yun, Tang Xinlu [23] from China Science and Technology University. With the magnetic field turned on, the measured MRF flowed through the capillary or slender slit under the push of external force. The flow volume in a time unit and the pressure difference between two open ends of the capillary or slender slit were measured. Then the MRF yield stress and other parameters were calculated according to the relative formulas.

Flat-pulling method was used by Pan Sheng [24] and Hu Yuan [25] to design testing devices to test MRF yield stress. The MRF was put in sample room and a panel made of flat plate was put in MRF vertically. Then a stepper motor was used to lift the panel slowly with uniform speed. The tensile force was tested by transducer which was used to calculate the shear yield stress of MRF. But this testing method has a problem in the way of load addition which will lead to a large error because of the variable output torque of stepper motor.

2.3 Discussion

Although many theoretical researches and many shear stress models of MRF have been proposed elaborated in section 2.1, there are some shortage needed to solve summarized as follows: Firstly, the interaction effects between magnetic dipoles and saturation magnetization phenomenon are not taken into consideration in most shear stress models. Once the saturation magnetization appears, the shear stress model cannot describe the yield process accurately. Secondly, most researches just reveal the variation tendency of MRF which cannot describe the saturation process of MRF and cannot reflect the fluid characteristics of MRF in the pre-saturation area. Finally, most of researchers put more emphasis on theoretical study without experimental verification, so the research results cannot be used in practical engineering because of losing sight of influencing factors.

In our paper, double viscosity model and magnetism theoretical principles are analyzed and three silicone oil-based magnetorheological fluids which have different volume fractions of magnetic particles 10%, 20% and 30%

are prepared and tested to research the shear yield stress of MRF and a kind of constitutive model is proposed to describe the MRF behavior.

3. Theories

3.1 Double viscosity model

Although the generalized Bingham model is simple and convenient, it cannot reflect the fluid characteristics of MRF in the pre-yield and post-yield area. Thus, the double viscosity model is proposed to develop Bingham model as follows:

$$\tau = \begin{cases} \eta_B \cdot \dot{\gamma} & |\tau| < \tau_B \\ \tau_s + \eta \cdot \dot{\gamma} & |\tau| \geq \tau_B \end{cases} \quad (2)$$

Where $\dot{\gamma}$ is the shear rate, η_B is the apparent viscosity of MRF under the action of additional magnetic field, η is the viscosity of carrier liquid [26], τ_s is the static shear yield stress when double viscosity model degenerate to Bingham model and τ_B is the dynamic shear yield stress which is function of magnetic field strength as follows:

$$\tau_B = aB^b \quad (3)$$

Where a and b are two constants which depend on the material of MRF and their accurate values can be determined by experiment.

The double viscosity model shows that magnetic particle is magnetized to form chain structure when the absolute value of shear stress τ_B is larger than $|\tau|$ under the effect of magnetic field and MRF flow slowly with high viscosity at this time. When the absolute value of shear stress $|\tau|$ is larger than τ_B , MRF flow with the viscosity η . The value of viscosity has great difference between post-yield and pre-yield and the interface is called yield surface. The coefficient of viscosity k of double viscosity model can be presented as follows:

$$k = \eta / \eta_B \quad (4)$$

The relationship between τ_s and τ_B is shown as follows:

$$\tau_s = \tau_B(1 - k) \quad (5)$$

3.2 Magnetism theoretical principles

The magnetic dipole model is usually used to calculate the magnetic force of MRF between magnetic particles. Because the interaction effects between magnetic dipoles and saturation magnetization phenomenon are not taken into consideration in this model, the model can be used to calculate the shear stress accurately only in relatively weak magnetic field.

According to Frohlich-Kennelly formula, the magnetization intensity can be expressed as follows:

$$M = \frac{\chi^0 H_m}{1 + \chi^0 H_m / M_s} \quad (6)$$

Where M is the magnetization intensity, χ^0 is the initial magnetic susceptibility of magnetic particles, H_m is the inner magnetic field intensity of magnetic particles and M_s is saturation magnetization intensity.

According to Ohm law in magnetic circuit, the equations of magnetic field intensity can be shown as follows:

$$\begin{aligned} Hl &= H_m(l - l_p) + H_p l_p \\ M + H_m &= H_p \end{aligned} \quad (7)$$

So the relationship between magnetization intensity and magnetic field intensity can be obtained as follows:

$$\left[k + \frac{M_s}{\chi^0(M_s - M)} \right] M = H \quad (8)$$

The magnetization process can be divided into two stages: linear process and saturation process. In the saturation process, the magnetization intensity of particles reaches saturation magnetization M_s under the magnetic field intensity H_c which is called critical magnetic field intensity and can be expressed as follows:

$$H_c = \frac{1 + \chi^0 k}{\chi^0} M_s \quad (9)$$

Two stages of the magnetization process can be expressed as follows:

$$M = \begin{cases} \frac{\chi^0}{1 + \chi^0 k} H, & H \leq H_c \\ M_s & H > H_c \end{cases} \quad (10)$$

Based on the principle of magnetism, a particle unit model has been proposed for analyzing the local magnetic field of MRF to deduce the expression of magnetization intensity and the smallest magnetic field intensity needed to reach saturation magnetization described as follows:

$$H_{smin} = M \left(\frac{1}{\chi^0} + \frac{k_s}{1 + k_s} \right). \quad (11)$$

The magnetic particles occur local saturation magnetization when $H_z \geq H_{smin}$.

4. Experiments

4.1 Experiment equipment

In our lab, three kinds of silicone oil-based magnetorheological fluids which have different volume fractions of magnetic particles 10%, 20% and 30% have been prepared. The average diameter of carbonyl iron is ranging from 0.5-3.5 μ m granules. Dimethyl silicone oil with viscosity of 100 $\text{mm}^2 \cdot \text{s}$ and density of 965 kg/m^3 is applied in our experiments as carrier liquid. The comparison of uncoated and coated magnetic particles is shown in Fig. 1. Obviously, the fibrils that should be additive agent are wrapped on the surface of carbonyl iron powders and the two adjacent particles seem to be connected together by the fibrils. The dispersion stability and zero field viscosity of MRF are promoted observably after coated.

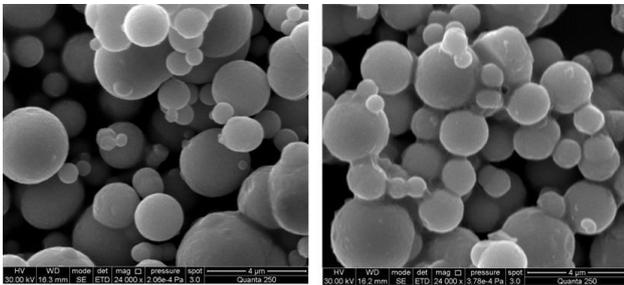


Fig. 1. SEM image: comparison of uncoated and coated magnetic particles.

Shear yield stress of MRF is tested by our self-designed instrument (Rotating disk type magnetic rheology liquid yield stress tester) to research the shear yield performance under the action of magnetic field, as

shown in Fig. 2, in which two parallel disks are used as coupling material [27-28] and digital Tesla is used to measure the magnetic field intensity. The MRF samples are injected into the liquid storage and the electric current is adjusted to achieve different magnetic circuit. The diameter and spacing of the two disks respectively are d and h . The nether disk is fixed and the upper disk can be rotated, so torque is applied in the upper disk. The upper disk cannot rotate until the torque exceeds a large enough value, so the shear yield stress can be calculated by the value M at the beginning rotation moment:

$$\tau_s = \frac{12M}{\pi d^3} \quad (12)$$

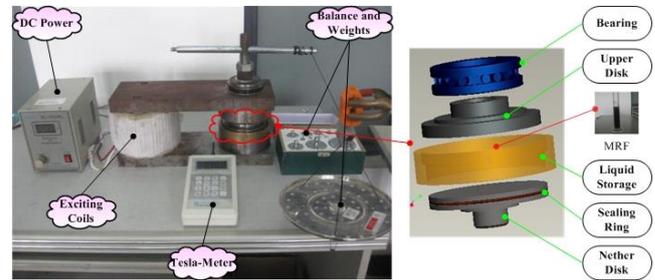


Fig. 2. Experiment equipment.

4.2 Experiment results

(1) Magnetic field distribution between two disks

Fig. 3 shows that the magnetic field intensity is changing with the field current and magnetic field distribution in different regions of the disk. Magnetic field intensity linearly is increasing with the rising of current and the magnetic field distribution is nearly uniform between two disks.

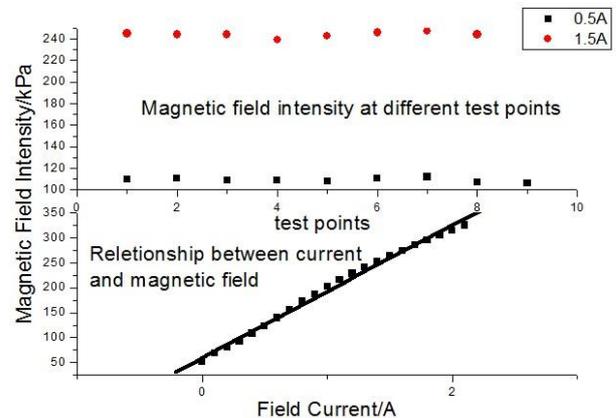


Fig. 3. Magnetic field distribution.

(2) Volume fractions of magnetic particles on shear yield stress

The change trend of MRF shear yield stress with different volume fractions under the different field current 0.5A, 1.0A, 1.5A, 2.0A is shown as Fig. 4. It shows that volume fractions of magnetic particles has great effects on the property of MRF and the shear yield stress increases with the rising of particles volume fractions in linear.

The more magnetic linkages can be produced and the relative magnetic susceptibility of the system will be better because of the rising of particles volume fractions, so the magnetorheological effects become stronger. As Fig. 4 shown, the shear yield stress increases as the rising of particles volume fractions in linear, but the linear increase phenomenon can appear only in low volume fractions. With the increase of particles volume fractions, the interaction between magnetic chains due to the transformation of structure changed from chain to columnar, so much as reticulate structure with obviously improved shear yield stress.

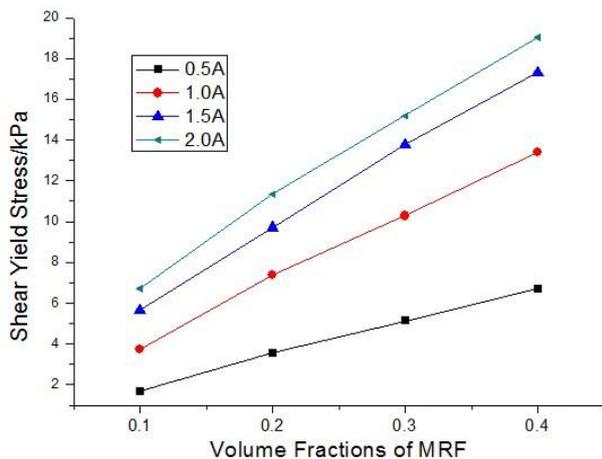


Fig. 4. Shear yield stress for different volume fractions of MRF.

(3) Magnetic field intensity on shear yield stress

The relation between shear yield stress of MRF and magnetic field intensity can be illustrated as Fig. 5. It shows that the shear yield stress linearly increase when the magnetic field intensity is low and when the magnetic field intensity goes up the shear yield stress approaches saturation, the growth of shear yield stress becomes slow. Obviously, the shear yield stress is rising with the increase of magnetic inductive intensity constantly and the shear yield stress tends to stable when the magnetic field intensity reaches a certain value.

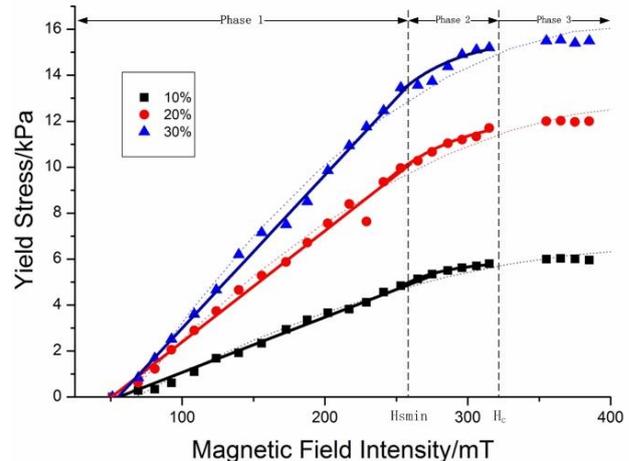


Fig. 5. Magnetic field intensity on shear yield stress.

4.3 Discussion

By using Microcal Origin to match the data, functional curves can be achieved to describe the constitutive relation between shear yield stress and magnetic field intensity as shown in Fig. 5. The process can be divided into three phases: in phase 1, the shear yield stress linearly increases with the rising of magnetic intensity, in phase 2, the saturation magnetization phenomenon appears (when the magnetic field intensity reaches H_{smin}) and the increasing speed of shear yield stress slows down obviously, in phase 3, the yield stress tends to a certain value at last. When the magnetic field intensity goes up to some extent (nearby H_{smin}), the shear yield stress approaches saturation and the curves approximate first order exponential decay. The relationship between the magnetic field intensity B and the shear yield stress τ_s can be expressed as:

$$\left\{ \begin{array}{ll} \tau_s = aB + b & B / \mu_0 \leq H_{smin} \\ \tau_s = \tau_0 + A_1 e^{-(B-B_0)/t_1} & B / \mu_0 > H_{smin} \end{array} \right\} \quad (13)$$

Some researchers used flat-pulling method to test the shear yield stress of MRF and considered that the curves approximated characteristic polynomial equations (dotted line in Fig. 5):

$$\tau_B = \tau_0 + b_1 B + b_2 B^2 + b_3 B^3 + \dots + b_n B^n \quad (14)$$

The precision of the fitting results of these two equations is compared by correlation coefficients R^2 . The numerical value of R^2 are 0.942, 0.935, 0.936 when we use the quadratic equations. The numerical value of R^2 of linear part are all larger than 0.98 and the value of R^2 of first order exponential decay are 0.995, 0.989, 0.977. By contrast we find that the model we proposed can describe

the change rules of MRF shear yield stress better and its fitted value corresponds well to the experimental results.

5. Conclusions and future work

In this paper, macroscopic behavior of silicone oil-based magnetorheological fluids was analyzed based on the theory of double viscosity model and magnetism theoretical principles, and several testing experiments were carried out to describe the rheological properties of MRF. Through theoretical analysis and experiment research, a macroscopic model for mechanical characteristic was proposed to describe the macroscopic behavior of silicone oil-based magnetorheological fluids.

Future work will focus on the effects of some factors on MRF such as the size of magnetic particles, temperature field, etc. Furthermore, the improvement of experiment equipment is also an important research for the authors.

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References

- [1] G. Bossis, O. Volkova, S. Lacis, A. Meunier, Springer-verlag Berlin Heidelberg, **594**, 202 (2003).
- [2] S. Kang, Y. K. Suh, Journal of Fluids and Structures, **27**(2), 266 (2011).
- [3] Xing Zhi, LV Jian-gang, Li Meng, Magnetic Materials and Devices, **36**(3), 21 (2005).
- [4] Lv Weiran, Zhang Boming, Wang Dianfu, Journal of Experimental Mechanics, **16**(2), 232 (2001).
- [5] Jin Yun, Zhou Gangyi, Zhang Peiqiang, Li Weihua, Journal of Experimental Mechanics, **14**(3), 288 (1999).
- [6] Pan Sheng, Wu Jianyue, Hu Lin, Shen Feng, Sun Meng, Zhou Luwei, Functional Materials. **28**(2), 264 (1997).
- [7] J. M. Ginder, L. C. Davis, American Institute of Physics, **65**(26), 3410 (1994).
- [8] Li Haitao, Peng Xianghe, He Guotian, Materials Science, **24**(2), 121 (2010).
- [9] E. Lemaire, C. Paparoditis, G. Bossis, Progress in Colloid & Polymer Science, **84**, 425 (1991).
- [10] Melek Yalcintas, Heming Dai, Smart Mater Struct. **8**, 560 (1999).
- [11] Xinhua Liu, Yongzhi Liu, Hao Liu, Computer Modeling in Engineering & Sciences, **91**(1), 65 (2013).
- [12] K. C. Chen, C. S. Yeh, International Journal of Engineering Science, **40**, 461 (2002).
- [13] A. Dorfmann, R. W. Ogden, A. S. Wineman, International Journal of Non-Linear Mechanics, **42**, 381 (2007).
- [14] Xinhua Liu, Hao Liu, Yongzhi Liu, Journal of Applied Mathematics, **2012**, 16 (2012).
- [15] Si Hu, Peng Xiang-he. Journal of Chongqing University (Natural Science Edition). **24**(3), 45 (2001).
- [16] Xinhua Liu, Qingqing Chen, He Lu, Optoelectron. Adv. Mater.-Rapid Comm. **7**(3), 231 (2013).
- [17] Weng Jiansheng, Hu Haiyan, Zhang Miaokang, Chinese Journal of applied mechanics, **17**(3), 1 (2000).
- [18] Zhou Gang-yi, Jin Yun, Xiang Yong, Journal of Experimental Mechanics. **15**(2), 233 (2000).
- [19] Jung-Bae Jun, Seong-Yong Uhm, Jee-Hyun Ryu, Kyung-Do Suh, Colloids and surfaces A: Physicochem. Eng. **260**, 157 (2005).
- [20] Seval Genc, Pradeep P Phule, Institute of Physics Publishing, **11**, 140 (2002).
- [21] Shinzo Takata, Kenjiro Hosoo, Yoshimasa Inoue, International Society for Optical Engineering, **6423**, (2007).
- [22] B. F. Spencer Jr, S. J. Dyke, M. K. Sain, Journal of Engineering Mechanics, **23**(3), 230 (1997).
- [23] Jin Yun, Tang Xinlu, Wang Xiaojie, Zhang Peiqiang, Chen Zuyao, Journal of Engineering Mechanics, **13**(2), 168 (1998).
- [24] Yang Yan, Zou Jiwen, Huang Jin, Modern Manufacturing Engineering, **2**, 9 (2003).
- [25] Jin Yun, Zhang Pei-qiang, Wang Xiao-hua, Wu Sajian, China Science and Technology University, **31**(2), 168 (2001).
- [26] M. Lokander, B. Stenberg, Polymer Testing, **22**, 245 (2003).
- [27] E. Lemaire, G. Bossis, Journal of Physics D: Applied Physics, **24**, 1473 (1991).
- [28] Xinhua Liu, He Lu, Qingqing Chen, Dongdong Wang, Xiaojiao Zhen, Materials and Manufacturing Processes, **28**(6), 631 (2013).

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