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Analysis of the Effect of Optimised Slot Shape on Electromagnetic Characteristics of Radial Magnetic Levitation Bearings

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***Abstract* – On the basis of practical engineering experience, different stator slot structure optimisation solutions are designed for the problem of excessive magnetic induction intensity and stress concentration at the stator slot distortion point under the basic structure form of radial magnetic levitation bearing. The electromagnetic field analysis of the radial magnetic levitation bearing is completed with the aid of Ansoft Maxwell electromagnetic finite element analysis software, and the magnetic induction intensity distribution clouds are obtained. The simulation results show that a smooth transition fillet can effectively reduce the magnetic line concentration phenomenon at the stator slot inflection point.**

***Keywords* – Magnetic Bearing, Electromagnetic Characteristics, Finite Element Analysis.**

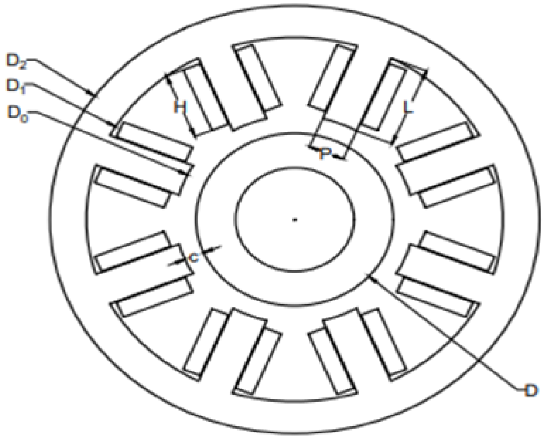
I. INTRODUCTION

The Magnetic Bearing (MB) is a new type of non-contact bearing that uses electromagnetic force to achieve stable suspension of the rotor. AMB) and Hybrid Magnetic Bearing (HMB) [1, 2]. Compared with traditional rolling bearings and sliding bearings and other contact mechanical bearings, they have low noise, no wear and controlled stiffness and damping, avoiding the problems of wear and energy loss due to mechanical contact, and are particularly suitable for use in high speed, vacuum and ultra-clean scenarios [3, 4, 5]. They are now widely used in industrial production, transportation and medical equipment, as well as in flywheel energy storage UPS, magnetic levitation high-speed motors, magnetic levitation centrifugal blowers, magnetic levitation air compressors, high-speed CNC machine tools and other rotating machinery [1, 2, 3]. Radial magnetic levitation bearings mainly include stator, rotor and coil windings, and their structure is directly related to the electromagnetic characteristics of magnetic levitation bearings [4, 6]. The basic structure of the radial magnetic levitation bearing stator slot has a tip inflection point, in the actual use process there is the phenomenon of magnetic force line gathering, easy to lead to local magnetic saturation, beyond the linear working range of ferromagnetic materials, aggravate the leakage, loss and temperature rise [7, 8].

In this paper, on the basis of the basic structural form of radial magnetic levitation bearings, an optimisation scheme is proposed for the stator slot structure, and the magnetic field distribution is simulated and calculated with the help of electromagnetic finite element analysis software, and the influence of different optimisation schemes on the electromagnetic characteristics of radial magnetic levitation bearings is analysed to provide reference for the design of radial magnetic levitation bearings.

II. RADIAL MAGNETIC LEVITATION BEARING STRUCTURE DESIGN

The basic structural form of the 8-pole radial magnetic levitation bearing is shown in Figure 1.



D - rotor outer diameter; D1 - stator inner diameter; P - pole width; D2- stator middle diameter; D3 - stator outer diameter; L - stator window depth; H -coil winding length; c - one-sided air gap value. In addition, there are parameters such as the magnetic bearing width B; the number of turns of the coil winding N, etc. to be considered.

Fig. 1. The structure of radial magnetic bearing.

According to the design basis of radial magnetic levitation bearing [5, 9, 10, 11], the design of radial magnetic levitation bearing under the basic structure form, its theoretical bearing capacity is 150N, the maximum air gap magnetic induction strength is 1.2T, the static working current is 2A, the coil winding wire diameter is 0.96mm. Its main structural parameters are shown in Table 1.

Table 1. Main structural parameters of radial magnetic bearing.

Parameter	**Unit**	**Value**	**Parameter**	**Unit**	**Value**
D	mm	40	D_1	mm	40.8
c	mm	0.4	D_2	mm	91.2
P	mm	8	D_3	mm	107.2
H	mm	21.2	L/	mm	25.2
N	Number of turns	191	B	mm	15.6

Based on the data in Table 1, a radial magnetic levitation bearing model was established and its magnetic induction intensity distribution was observed, and the results are shown in Figure 2.

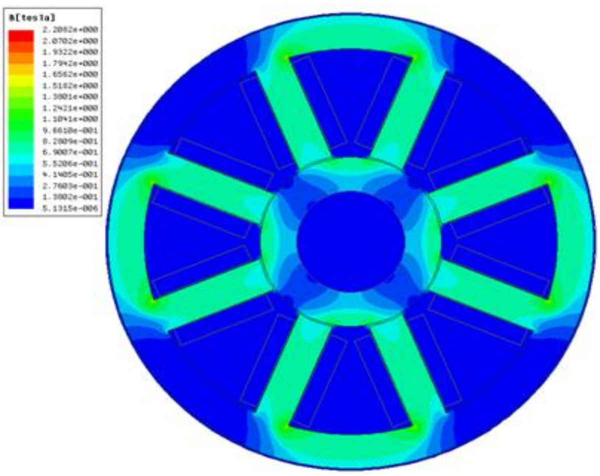


Fig. 2. The magnetic induction distribution of radial magnetic bearing.

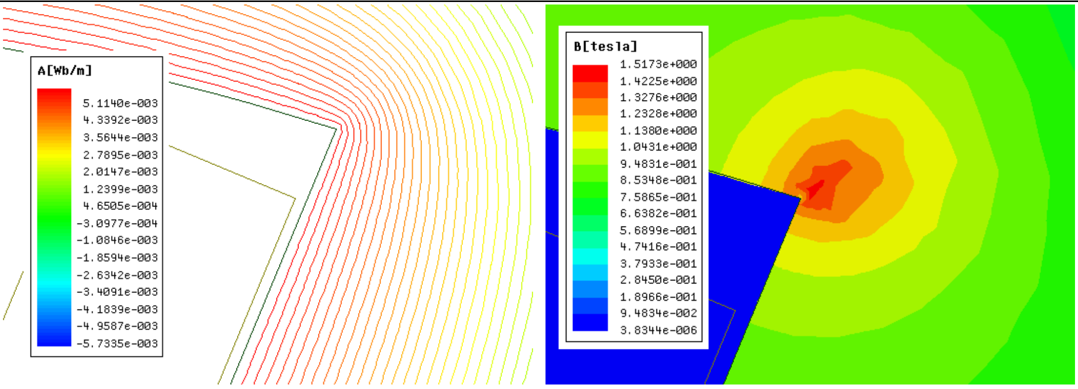


Fig. 3. Magnetic field lines and magnetic induction distribution of stator slots.

As can be seen from Figure 2 and Figure 3, the magnetic field distribution in the magnetic flux circuit inside the magnetic levitation bearing is not uniform, and there are distortion points at the corners of the stator slots in the radial magnetic levitation bearing in the basic structure form, where the magnetic lines of force are concentrated and the magnetic induction intensity is significantly higher compared to other locations, which is prone to magnetic saturation and beyond the linear working range of the magnetic pole material, resulting in increased leakage, loss and temperature rise, which is not conducive to the use and control of the magnetic levitation bearing.

The slot structure of the radial magnetic levitation bearing needs to be improved and optimized in order to achieve the phenomenon of magnetic line clustering at the stator slot inflection point.

On the premise of keeping the basic structural parameters of the radial magnetic levitation bearing unchanged, three optimisation solutions are proposed for the slot structure, namely the straight chamfer solution, the circular transition angle solution and the elliptical transition angle solution.

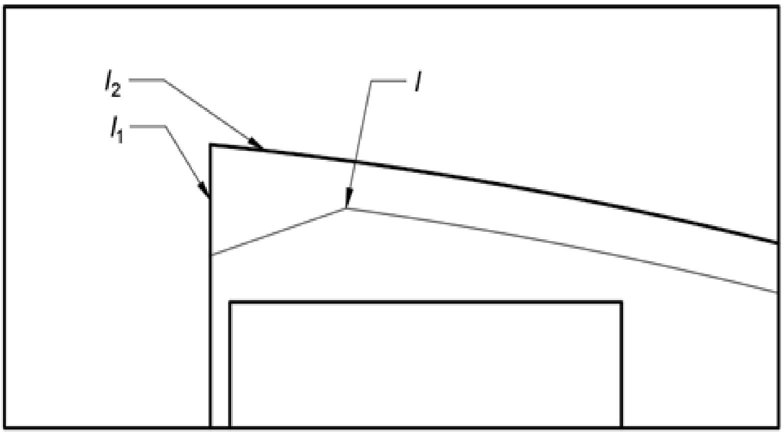


Fig. 4. Straight chamfering scheme.

The straight chamfering improvement scheme is shown in Figure 4. The chamfering distances d1 and d2 are set separately for the radial magnetic levitation bearing stator pole l1 and the inner side of the yoke l2. According to actual engineering experience, the coil winding end needs to be left at a certain distance from the stator mid-diameter end. Therefore, in the straight chamfering scheme, d1 is set to 0.5mm and d2 to 0.5mm, 1.0mm and 1.5mm. The inner curve of the stator slot yoke is l. It can be seen that in the improved scheme, the stator yoke width is increased and the stator slot still retains the tip inflection point.

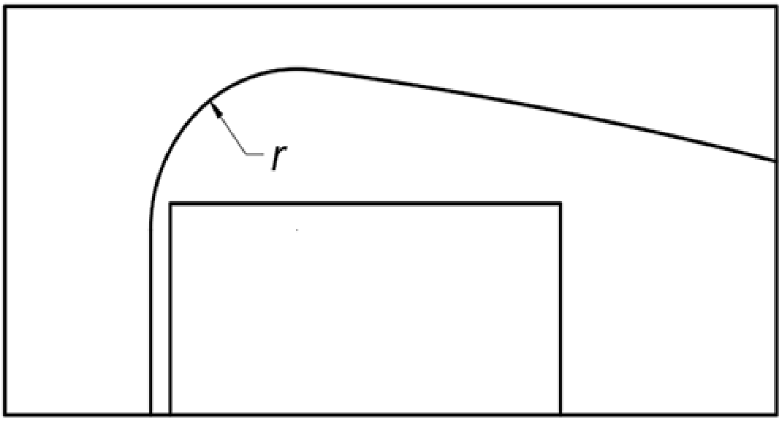


Fig. 5. Circular transition angle scheme.

The round transition angle improvement scheme is shown in Figure 5. In the circular transition angle scheme, the radii r of the transition angle are set to 0.5 mm, 1.0 mm and 1.5 mm respectively, taking into account the space allowance between the coil winding and the stator. It can be seen that in the improved scheme, the stator slot transition is smooth and the tip inflection point is eliminated.

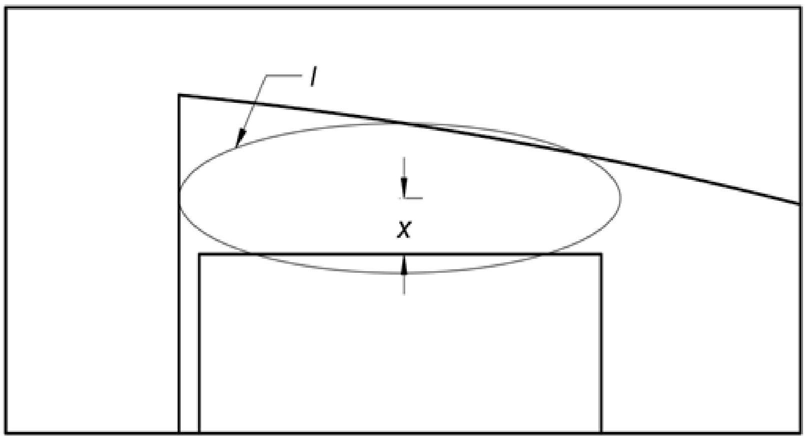


Fig. 6. Elliptical transition angle scheme.

The elliptical transition angle improvement scheme is shown in Figure 6. In the elliptical transition scheme, the long axis of the ellipse is designed to be parallel to the top of the coil winding and at a distance x. The shape of the ellipse and the modified inner curve of the yoke l are determined according to the vertical points of the ellipse to the sides of the stator slot. x is set to 0.5mm, 1.0mm and 1.5mm respectively, taking into account the space allowance between the coil winding and the stator. It can be seen that in the modified scheme, the stator slot eliminates the tip inflection point.

III. Radial Magnetic Levitation Bearing Finite Element Analysis

The radial magnetic levitation bearing finite element model is based on the data in Table 1. The magnetic levitation bearing model includes the stator, rotor, coil winding and main shaft [5, 10, 11]. At the same time, considering the possible magnetic leakage of the outer yoke of the magnetic levitation bearing, a certain thickness of air layer is set outside the stator and a Balloon boundary condition is set at the outer edge of the air layer, i.e., the magnetic field strength is considered to be 0 at infinity, in order to investigate the magnetic leakage of the model [12]. The material properties of each part of the radial magnetic levitation bearing finite element model were set: the stator and rotor material was set as silicon steel sheet of type DW465_50, the coil winding material was set as copper, the spindle material was set as steel and the air layer material was set as air. Then, the current excitation is loaded and the mesh dissection is completed, and finally the relevant solution settings are set and the simulation is performed [13, 14, 15, 16].

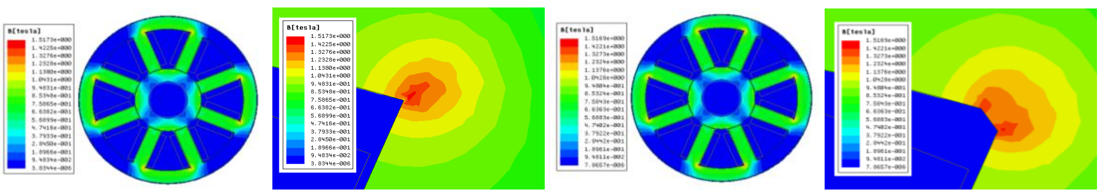
For the radial maglev bearing under each improvement scheme, the magnetic induction intensity distribution clouds are shown in Figure 7-9, focusing on the magnetic induction intensity near the stator slot distortion point, whose simulation calculation results are shown in Table 2.

Table 2. The magnetic field calculation results of radial magnetic bearing.

Straight Chamfering Scheme	**d_2/mm**	**d_2 : L**	**B/T**	**$B : B_1$**	**$B : B_0$**
1	0	0	1.4332	1.0000	1.1943
2	0.5	0.0198	1.4456	1.0087	1.2047
3	1.0	0.0397	1.4545	1.0149	1.2121
4	1.5	0.0794	1.3811	0.9636	1.1509
Circular transition angle scheme	r/mm	r : L	B/T	$B : B_1$	$B : B_0$
1	0	0	1.4332	1.0000	1.1943
2	0.5	0.0198	1.4086	0.9828	1.1738
3	1.0	0.0397	1.3407	0.9355	1.1173
4	1.5	0.0794	1.2755	0.8900	1.0629
Elliptical transition angle scheme	x/mm	x : L	B/T	$B : B_1$	$B : B_0$
1	/	/	1.4332	1.0000	1.1943
2	0	0.0198	1.3133	0.9163	1.0944
3	0.5	0.0397	1.4199	0.9907	1.1832
4	1.0	0.0794	1.5885	1.1084	1.3237

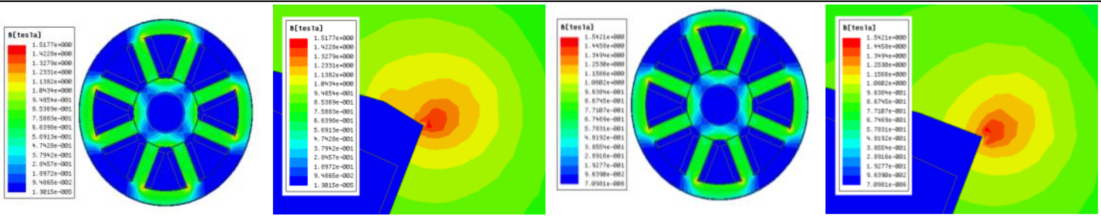
Note: 1 in each scheme group is the calculated data in the basic structural form; B is the maximum magnetic induction near the stator slot distortion point; B1 is the maximum magnetic induction near the stator slot distortion point in the basic structural form; B0 is the design magnetic induction.

Using the straight chamfering scheme, the magnetic induction intensity distribution of each group of radial maglev bearings is shown in Figure 7.



(a) d1 = 0.0mm; d2 = 0.0mm

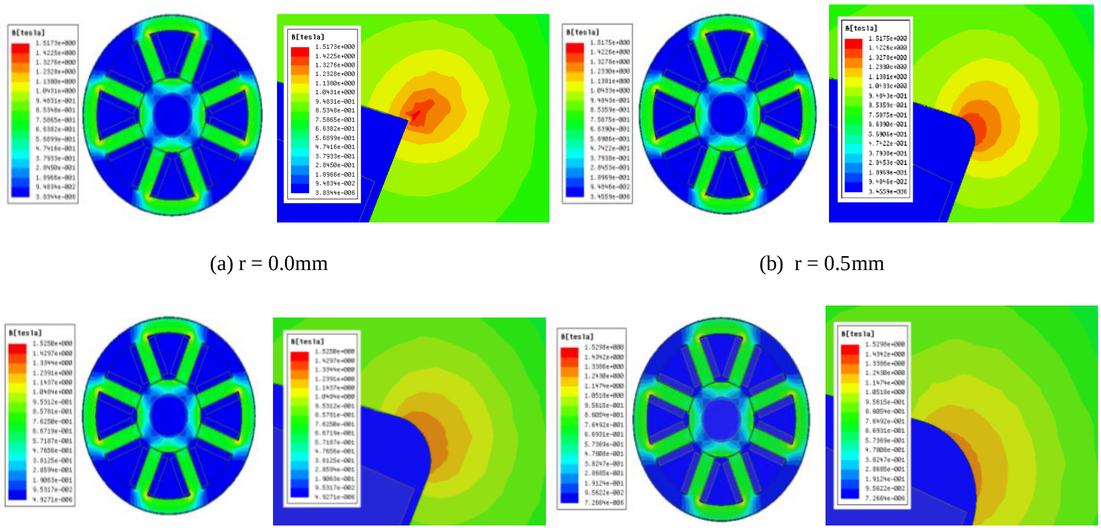
(b) d1 = 0.5mm; d2 = 0.5mm



(c) $d_1 = 0.5$mm; $d_2 = 1.0$mm (d) $d_1 = 0.5$mm; $d_2 = 1.5$mm

Fig. 7. Straight chamfering scheme.

Using the circular transition angle scheme, the magnetic induction intensity distribution of each group of radial maglev bearings is shown in Figure 8.

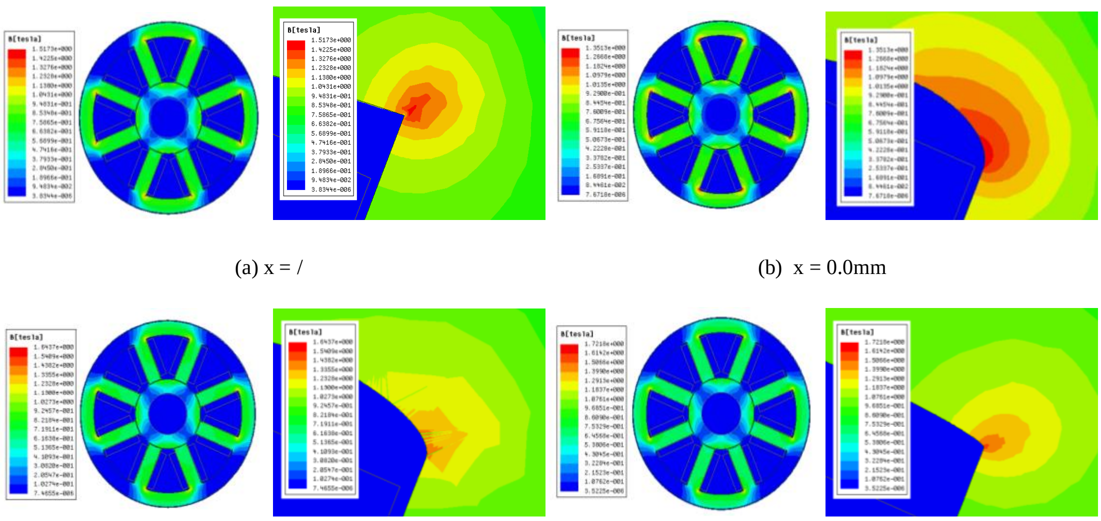


(a) r = 0.0mm (b) r = 0.5mm

(c) r = 1.0mm (d) r = 1.5mm

Fig. 8. Circular transition angle scheme.

Using the elliptical transition angle scheme, the magnetic induction intensity distribution of each group of radial maglev bearings is shown in Figure 9.

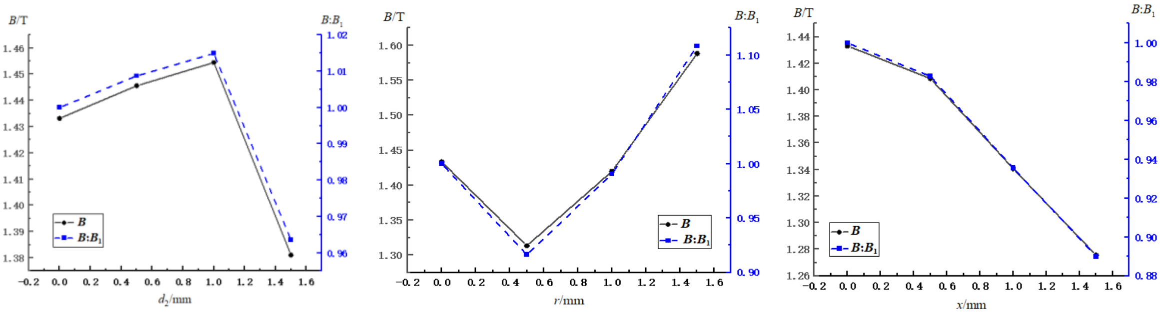


(a) x = / (b) x = 0.0mm

(c) x = 0.5mm (d) x = 1.0mm

Fig. 9. Elliptical transition angle scheme.

Analysis of the effect of optimised slot type on the load carrying capacity of radial magnetic levitation bearings. Based on Table 2, the trend of the effect of each scenario on the maximum magnetic induction near the stator slot distortion point of the radial maglev bearing is plotted, as shown in Figure 10.



(a) Straight chamfering scheme (b) Circular transition angle scheme (c) Elliptical transition angle scheme

Fig. 10. Ellipse shape chamfer scheme.

Figures 7-10 show that the straight chamfering solution does not eliminate the tip corner of the stator slot and is not effective in improving the magnetic induction near the stator slot inflection point with little change in size. Moreover, the presence of straight chamfers creates additional distortion points, which are not conducive to the improvement of the linearity of the magnetic line of force gathering. The elliptical transition angle solution is effective in achieving a smooth transition at the stator slot inflection point to improve the flux density distribution and reduce the maximum magnetic induction intensity by 8.37%, however its elliptical centre near the inner stator yoke does not allow for a smoother stator slot tip inflection point, resulting in limited improvement or even an increase in the maximum magnetic induction intensity. The circular transition angle solution is the relatively optimal solution, which effectively improves the magnetic induction near the stator slot inflection point, and the improvement is related to the radius of the transition angle. The larger the radius of the transition corner, the greater the reduction in maximum magnetic induction, and a suitably selected transition corner can reduce the maximum magnetic induction by more than 10%.

IV. CONCLUSION

In this paper, based on practical engineering experience, different optimisation schemes for the stator slot are designed on the basis of the basic structural form of the radial magnetic levitation bearing. Simulations of the radial magnetic levitation bearing models under each stator slot optimisation scheme are carried out using the method of electromagnetic field finite element analysis, and the magnetic induction strengths under the different schemes are analysed, and the following conclusions are obtained.

- The smooth stator slot tip inflection point can effectively alleviate the magnet line clustering phenomenon and enable the stator ferromagnetic material to work in the linear operating range as far as possible.
- The circular transition angle solution has a significant improvement on the magnetic induction intensity near the stator slot. A larger transition angle can bring better improvement under the design requirement of radial magnetic levitation bearing.
- The chamfered angle scheme and the elliptical transition angle scheme are difficult to produce good improvement because they cannot make the stator slot inflection point smoother.

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