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Effects of Diffuser Length of An Open and Ducted Propellers in UAV Applications

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ABSTRACT

This study aimed to determine effects of diffuser length of open and ducted propellers in UAV applications. This study opted for Computational Fluid Dynamics (CFD) as the primary research method. Results have shown that the diffuser length impacts are largely independent results-wise and show no correlation, however, more data would be needed to form a conclusive statement. From this study, miniature models could be fabricated for the purpose of further testing. For instance, future studies could conduct an experimental approach to attain data that is as close to real-world applications as possible. This will be vital for the industrial application.

1. Introduction

Aerodynamics studies have received much attention mainly in reducing fuel consumption [1-5]. One of the improvements in UAV is by varying the diffuser length. This study aimed to determine the effects of diffuser length of open and ducted propellers in UAV applications. The study findings are crucial in overcoming the challenge presented by ducted fan/ shrouded rotor when the ducted fan is tilted at a high angle of attack.

In a UAV context, ducted fans are relevant (electric ducted fans (EDF) in electrically powered UAVs). An EDF unit comprises a duct around the fan(s), and a motor connected to a power source, after which it can produce compressed air moving at higher speeds (hence allowing the unit to generate thrust). Hovey [6] as well as Rutkowski and Krusz [7] determined the advantages of ducting a propeller / rotor. One of the earliest mentions of ducted propellers was of a patent by Taggart [8], in which experimental work was conducted to investigate ducted implementation for marine

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propellers, which offered better thrust in smaller frames. In this configuration, thrust is produced by the duct due to the circulation occurring. Propeller thrust is also reduced as a result of inflow velocity increase and pressure drop. This is typical for accelerating and decelerating nozzles (see Figure 1).

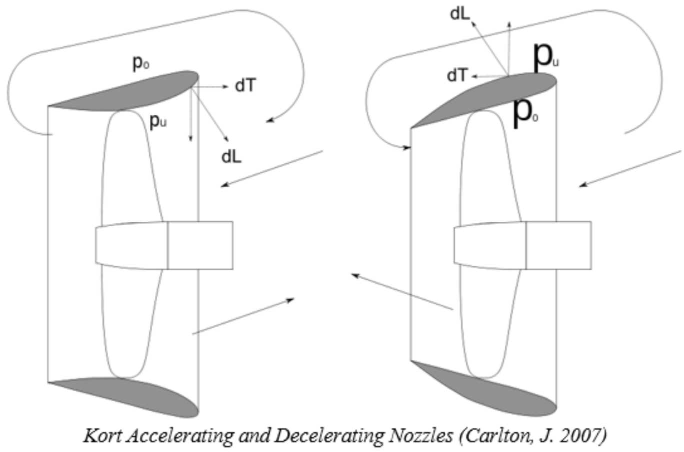
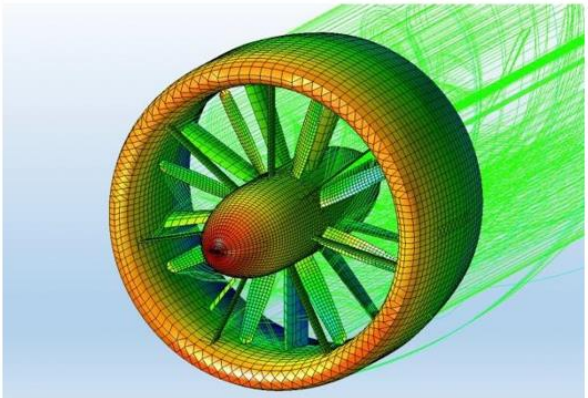


Fig. 1. Kort Accelerating and decelerating nozzles [9]

An EDF unit is comprised of a duct that is around the fan(s), and a motor connected to a power source, and this produces compressed air moving at higher speeds generating thrust.

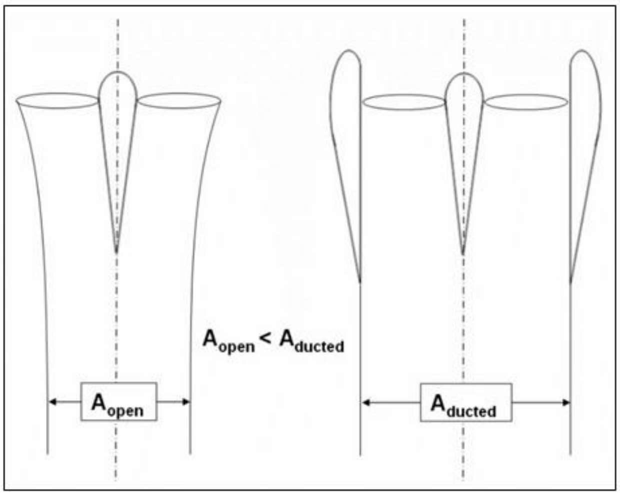
The main advantage of a ducted/ shrouded propeller is that it acts as a shield for the blades [11]. This is useful in urban areas where UAVs are expected to operate in close quarter conditions as it reduces the laceration risks to personnel or damage to objects in the environment. The blades are also protected (meaning that in case of any malfunction, the UAV can be retrieved relatively intact). Thus, ducted analysis is crucial and can be conducted via simulation for cost-effectiveness (see Figure 2). Ducting the propellers reduces the tip losses in free propellers (see Figure 3). The tip losses generate vortices which adds to the noise, hence by shrouding the propellers, the noise level of the UAV is reduced (beneficial for surveillance or night-time operations) [12].

As shown in Figure 3, the slipstream contraction is not as pronounced when a duct is introduced; hence there is more air mass flow compared to the open propeller. Ducted fans operate on a mass flow rate to generate thrust in comparison to the low/high-pressure zones used by propellers. Hence the ducted fan configuration allows for better static thrust performance compared to open rotor, producing the same static thrust at 40-50% the size of an open propeller [14]. This gives it a size advantage, being able to provide similar thrust while being more compact than an open rotor. However, a ducted propeller's disadvantages are the high-power consumption. Open rotors allow for larger propellers; hence a lower RPM / higher torque is needed to produce thrust (thrust/area is smaller), which results in lower power consumption. In comparison, EDFs need a higher RPM for sufficient mass flow due to its smaller propellers; hence power consumption is higher.



Ducted Fan Analysis, DARcorporation (2021)

Fig. 2. Ducted fan analysis [10]



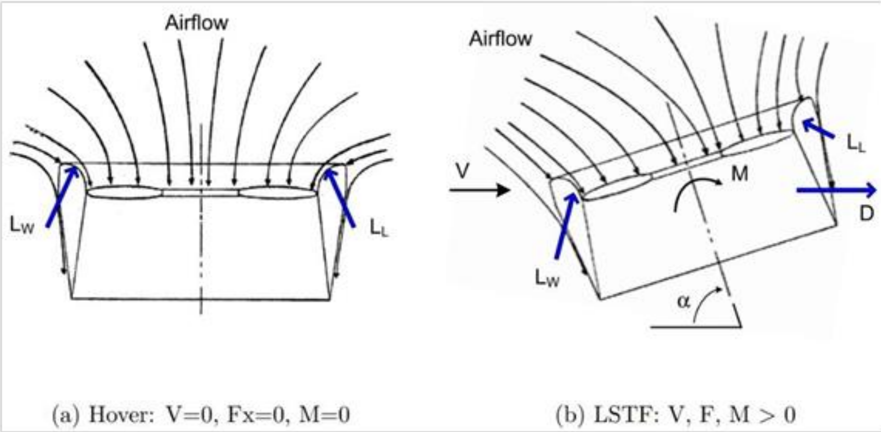
Slipstream contraction comparison between open and ducted propellers; Pereira (2008)

Fig. 3. Slipstream comparison of open and ducted propeller [13]

The main challenge with regards to ducted fan/ shrouded rotor occurs when the ducted fan is tilted at a high angle of attack, α, [13]. In flight, ducted fans have two modes; hovering and low speed tilted flight (LSTF) or forward flight. When the fan is hovering, the airflow into the duct is symmetrical, hence the forces and moments are balanced. The two flight configurations can be seen in Figure 4.

During hover configuration (as shown in Figure 4(a), the lift produced at the leeward (direction of the wind) LW is equivalent to the lift produced at the windward (opposite direction of the wind) Lw. When the duct is tilted at an angle of attack α, as shown in Figure 4(b), the airflow into the duct no longer remains symmetrical, and as a result, more lift is generated at the windward side, creating a pitching moment M, orientating the duct back into a hovering orientation.

A significant lack of literature is observed related to the implementation of ducts with regards to consumer and commercial grade drones, hence an insight into ducted fan VTOL drones was needed. From here, the parameters from ducted fan VTOL were interpolated as a starting point to investigate upon. Furthermore, there is limited data on the propeller thrust loss effect as observed by Kort (1933), which occurs due to the higher velocity inflow and the pressure reduction caused [15]. In addition, most of the data obtained in the study are applicable only to practical experimentation, in which it is difficult to determine the breakdown of lift into propeller and duct components. Hence, in this study, the main focus would be on the diffuser length.



(a) Hovering (b) Forward Flight
Fig. 4. Flight configuration of drone [13]

2. Methodology

Due to the limited timeframe, mesh independence study was not feasible as it would need to be conducted across multiple designs. Standard unstructured mesh was also chosen, as it is deemed suitable by Ahmed *et al.,* [16], although modifications in size were made to ensure skewness is kept below 0.8. Furthermore, ANSYS Student License limits number of elements to 512K.

Transient is chosen as sliding mesh motion requires transient to work properly (ANSYS Fluent 2020 Guide). The mesh is set to rotate, and the RPM is set as an input parameter. A study conducted by Sadikin *et al.,* [17] served to determine the best turbulence model for airfoil (between Realizable k-ε, k-ω SST and Spalart-Allmaras), concluding that Realizable k- ε is optimum due to the delay of flow separation occurrences. Hence, Realizable k-ε is chosen with scalable wall function for near wall treatment.

Report files are then created for lift forces acting on the duct, propeller, and the combination of the two, and set as output parameters. As transient is used, 50 timesteps with a timestep size of 0.003s along with 100 iterations/timestep is chosen, although 50 iterations/timestep produced results that converge within 30 timesteps. The solution is set to be exported for CFD-Post at the end of each simulation (see Figure 5 for the setting).

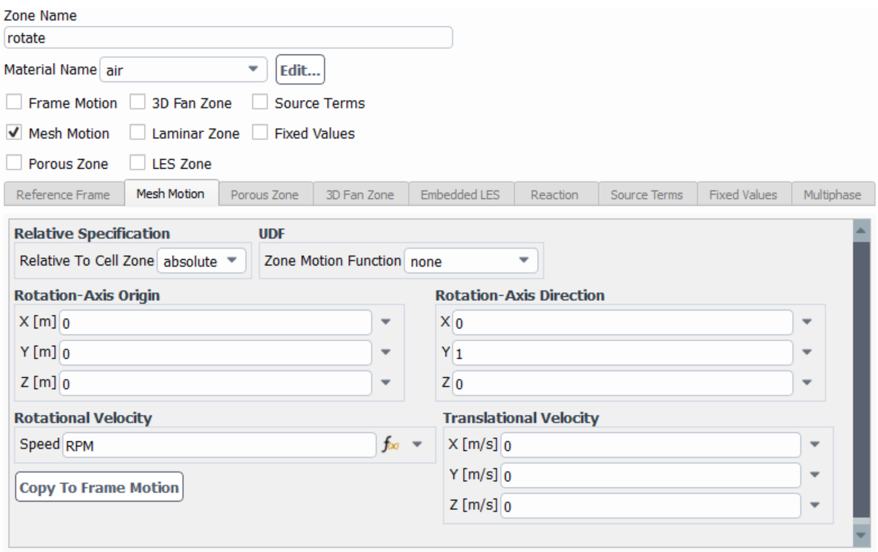


Fig. 5. CFD Setting

3. Result and Discussion

3.1 Effects of Diffuser Length

As 0.25mm blade tip clearance was determined to be the optimum blade tip clearance, the controlled design parameters were set as 0.25mm BTC and 16.5mm inlet lip radius. Table 1 shows the effects of diffuser length of 35 mm while the effects for diffuser length of 45 mm is depicted in Table 2. Table 3 and 4 shows the effect of diffuser length of 55 mm and 65 mm, respectively.

Table 1
Results of effects of diffuser length (35mm length)

RPM	Prop Lift(N)	Duct Lift(N)	Total Lift(N)	Output%
26400	12.2413	4.3890	16.6304	18.125
24000	10.018	3.9073	13.9191	20.640
21600	8.0828	3.2352	11.3180	22.006
19200	6.3191	2.5383	8.8574	26.089
16800	4.8015	1.8826	6.6841	30.108
14400	3.5671	1.2666	4.8337	27.434
12000	2.4581	0.7761	3.2343	22.989
9600	1.5732	0.4451	2.0183	19.100
7200	0.8879	0.2209	1.1087	14.930
4800	0.3758	0.0799	0.4557	10.224
2400	0.0952	0.0162	0.1114	9.095
0	0	0	0	-

Table 2
Results of effects of diffuser length (45mm length)

RPM	Prop Lift(N)	Duct Lift(N)	Total Lift(N)	Output%
26400	11.5806	3.6445	15.2252	8.144
24000	9.4550	3.1892	12.6442	9.591
21600	7.6188	2.6584	10.2772	10.786
19200	5.9303	2.1087	8.0390	14.438
16800	4.4966	1.5567	6.0533	17.829
14400	3.5399	1.1243	4.6642	22.964
12000	2.3388	0.6379	2.9768	13.197
9600	1.5104	0.3611	1.8715	10.437
7200	0.8525	0.1808	1.0333	7.114
4800	0.3611	0.0642	0.4253	2.879
2400	0.0905	0.0124	0.1029	0.776
0	0	0	0	-

Table 3
Results of effects of diffuser length (55mm length)

RPM	Prop Lift(N)	Duct Lift(N)	Total Lift(N)	Output%
26400	12.3473	4.4709	16.8182	19.459
24000	10.0931	3.8142	13.9073	20.538
21600	8.1145	3.2308	11.3453	22.300
19200	6.3047	2.5905	8.8952	26.627
16800	4.7765	1.9637	6.7402	31.200
14400	3.5609	1.3616	4.9224	29.773
12000	2.4850	0.8674	3.3524	27.482
9600	1.6087	0.5225	2.1312	25.759
7200	0.9082	0.2862	1.1944	23.814
4800	0.3856	0.1178	0.5034	21.765
2400	0.0950	0.0297	0.1248	22.223
0	0	0	0	-

Table 4
Results of effects of diffuser length (65mm length)

RPM	Prop Lift(N)	Duct Lift(N)	Total Lift(N)	Output%
26400	12.5637	4.6986	17.2622	22.613
24000	10.3324	3.9504	14.2828	23.792
21600	8.3306	3.3378	11.6684	25.783
19200	6.4472	2.7249	9.1721	30.569
16800	4.8987	2.0659	6.9646	35.568
14400	3.6376	1.4344	5.0720	33.717
12000	2.5301	0.9104	3.4405	30.833
9600	1.6367	0.5413	2.1780	28.525
7200	0.9224	0.2946	1.2171	26.159
4800	0.3893	0.1192	0.5085	23.011
2400	0.0939	0.0300	0.1239	21.355
0	0	0	0	-

3.2 Effect of Lift at Varying RPM

Effects of lift at various speeds are investigated. Table 5 shows effects of combined lift at varying speed up to 26400 RPM. Figure 6 show the effects of propeller lift at different speeds ranging between 0 to 26400 RPM. The effects of duct lift is depicted in Table 7.

Table 5
Results of effects of Combined Lift (N) vs RPM

RPM	Open	35 mm	45 mm	55 mm	65 mm
26400	14.0787	16.6304	15.2252	16.8182	17.2622
24000	11.5377	13.9191	12.6442	13.9073	14.2828
21600	9.2766	11.3180	10.2772	11.3453	11.6684
19200	7.0247	88574	8.0390	8.8952	9.1721
16800	5.1373	6.6841	6.0533	6.7402	6.9646
14400	3.7931	4.8337	4.6642	4.9224	5.0720
12000	2.6297	3.2343	2.9768	3.3524	3.4405
9600	1.6946	2.0183	1.8715	2.1312	2.1780
7200	0.9647	1.1087	1.0333	1.1944	1.2171
4800	0.4134	0.4557	0.4253	0.5034	0.5085
2400	0.1021	0.1114	0.1029	0.1248	0.1239
0	0	0	0	0	0

Table 6
Results of effects of Propeller Lift (N) vs RPM

RPM	35 mm	45 mm	55 mm	65 mm
26400	12.2413	11.5806	12.3473	12.5673
24000	10.0118	9.4550	10.0931	10.3324
21600	8.0828	7.6188	8.1145	8.3306
19200	6.3191	5.9303	6.3047	6.4472
16800	4.8015	4.4966	4.7765	4.8987
14400	3.5671	3.5399	3.5609	3.6376
12000	2.4581	2.3388	2.4850	2.5301
9600	1.5732	1.5104	1.6087	1.6367
7200	0.8879	0.8525	0.9082	0.9224
4800	0.3758	0.3611	0.3856	0.3893
2400	0.0952	0.0905	0.0950	0.0939
0	0	0	0	0

Table 7
Results of effects of Duct Lift (N) vs RPM

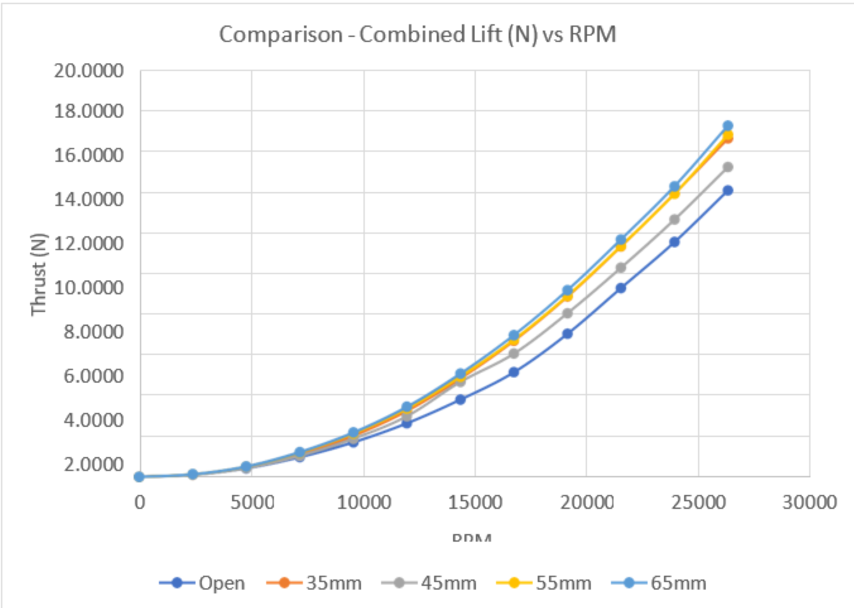
RPM	35 mm	45 mm	55 mm	65 mm
26400	4.3890	3.6445	4.4709	4.6986
24000	3.9073	3.1892	3.8142	3.9504
21600	3.2352	2.6584	3.2308	3.3378
19200	2.5383	2.1087	2.5905	2.7249
16800	1.8826	1.5567	1.9637	2.0659
14400	1.2666	1.1243	1.3616	1.4344
12000	0.7761	0.6379	0.8674	0.9104
9600	0.4451	0.3611	0.5225	0.5413
7200	0.2209	0.1808	0.2862	0.2946
4800	0.0799	0.0642	0.1178	0.1192
2400	0.0162	0.0124	0.0297	0.0300
0	0	0	0	0

As 0.25 mm BTC was determined to be the optimum BTC value, this set of experiments serve to determine the optimum diffuser length, with the inlet lip radius of 16.5 mm kept as constant as well. The following diffuser length values were tested as shown in Table 8.

Table 8
Diffuser parameters assessed

35 mm	45 mm	55 mm	65 mm

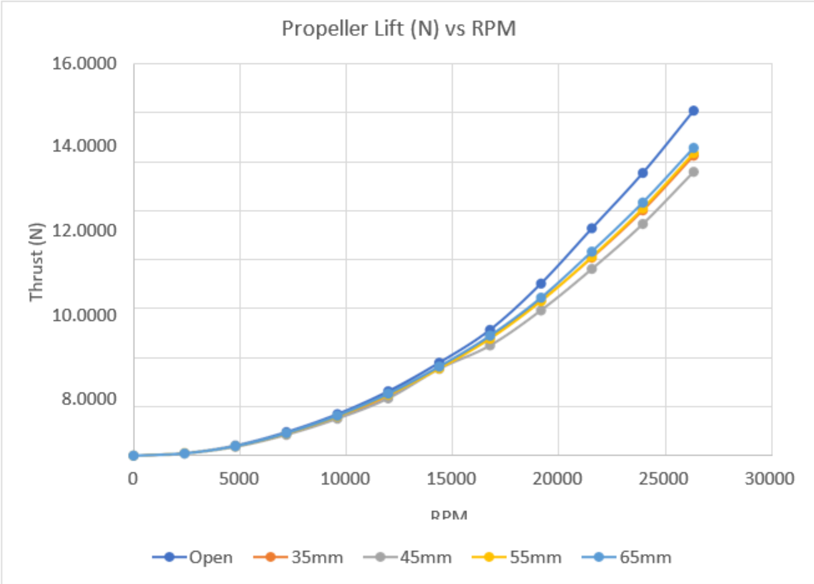
From the data obtained, the optimum diffuser length with respect to thrust remains as 65mm (see Figure 6). Similar to previous results, the data obtained is not conclusive enough to determine any correlation or patterns. For instance, the max thrust output increase for 55 mm is 31.2%, this is then decreased to 22.96% for 45mm, and increased yet again to 30.108% for 35 mm. Overall, the least lift was produced by the 45mm diffuser length.



Diffuser Length, Combined Lift (N) vs RPM

Fig. 6. Comparison results of combined Lift (N) vs RPM

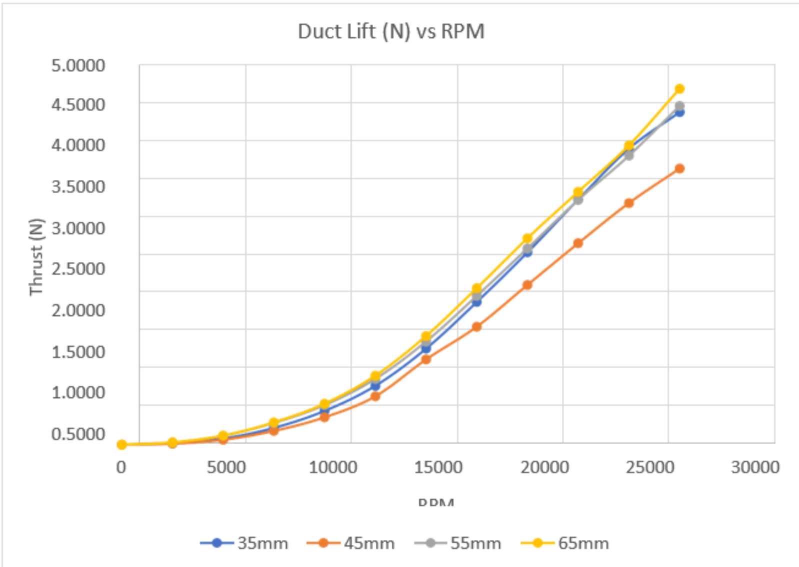
The data obtained consistently placed the 45 mm diffuser length as the lowest thrust outputs as opposed to other diffuser lengths (see Figure 7), yet as discussed previously in BTC effects on propeller lift, a clear pattern or trend cannot be discerned from the data produced.



Diffuser Length, Propeller Lift (N) vs RPM

Fig. 7. Comparison results of Propeller Lift (N) vs RPM

With respect to duct lift, similarly, there are no discernible differences between the different diffuser lengths, with the 45 mm diffuser length being an obvious outlier (see Figure 8). A possible explanation of lower thrust may be attributed to flow separation in the inner surface of the duct, however, the same effects were not seen in the 35 mm.



Diffuser Length; Duct Lift (N) vs RPM

Fig. 8. Comparison results of Duct Lift (N) vs RPM

4. Conclusion

Conclusively, it was found from this study that diffuser length impacts are largely independent results-wise and show no correlation, however, more data will be needed to form a conclusive statement. Besides that, it was mentioned by Pereira (2008) that overall performance is dependent on other parameters, and it is difficult to pinpoint the most prominent effect on thrust based on parameter adjustments. This was true in the context of the study, though based on the conclusions, the most consistent impact was through changing blade tip clearances.

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