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A feasible experimental test setup for vibration analysis on a rotating cylindrical shell

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Abstract

Although numerous theoretical studies have investigated the vibration characteristics of rotating cylindrical shells, most of them do not rely on experimental results for validation. Non-contact vibration sensors provide superior accuracy in modal testing because they have no mass effect on the vibrating structure and do not require attachment to the rotating shell with many wiring complexities. However, the rotation of the shell necessitates the use of multiple non-contact sensors arranged in the circumferential direction of the shell to achieve an adequate data acquisition frequency in the modal testing of rotating cylindrical shells, which increases both cost and complexity. This challenge can be alleviated through careful shell selection and a proper experimental test setup. In the present study, specific dimensions and rotational velocities of the cylindrical shell, along with the components and test setup for modal testing are proposed in a way that enables and facilitates experimental modal testing of a rotating cylindrical shell with simplicity. To this end, the accuracy of a finite element method (FEM) for determining the natural frequencies and mode shapes of rotating cylindrical shells has been validated through a comparative study. Subsequently, based on the proposed components and setups, the modal testing of the cylindrical shell has been simulated and validated. The results of the simulations demonstrate that the proposed method for conducting modal testing not only accurately determines the natural frequencies and mode shapes of the selected rotating cylindrical shell but also offers a simple and practical approach.

Keywords: Rotating cylindrical shells; Signal processing; Test simulation; Finite element method.

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1. Introduction

Because of their symmetrical geometry, simplicity of manufacture, and superior stiffness-to-weight ratio, cylindrical shells are widely used as rotating parts in aviation, aerospace, and other fields. For instance, rotating satellites, centrifugal separators, and rotors for gas turbine engines. Vibration, however, commonly negatively affects the performance and life of these structures because they consist of thin shells of long lengths. As a result, the vibration of rotating cylindrical shells has been extensively studied in the literature.

Cylindrical shells can be theoretically studied by applying several shell theories along with some assumptions [1]. In this regard, Donnell's shell theory is relatively simple, especially when combined with the Rayleigh-Ritz method [2, 3]. The dynamic behavior of cylindrical shells becomes more complex when rotation is introduced [4-6]. In addition to separating forward and backward traveling waves, spinning cylindrical shells also exhibit multiple internal resonances [4].

Nomenclature

R	radius of the cylinder	ω	dimensional natural frequency
h	thickness of the cylinder	Ω	dimensional rotational speed
L	length of the cylinder	ω^*	non-dimensional natural frequency
μ	Poisson's ratio	Ω^*	non-dimensional rotation speed
ρ	density	n	circumferential wave number
E	young modulus	m	longitudinal wave number

The study of vibrations in rotating structures dates back to 1890 when Bryan [7] first investigated the traveling-mode phenomenon resulting from Coriolis forces in rotating rings. Since then, many researchers have contributed novel findings to this field. Ditaranto [8] studied the effects of Coriolis and centrifugal forces on infinite long rotating cylindrical shells, which leads to distinct natural wave speeds for forward and backward-traveling waves, varying with rotational speed. L. Hue [9] employed the generalized differential quadrature (GDQ) method to examine the impact of boundary conditions on the frequency characteristics of thin rotating cylindrical shells. Free vibration analysis of rotating cylinders has been conducted using various techniques, including the harmonic reproducing kernel particle method [10] and the discrete singular convolution technique (DSC) [11]. Concerning different boundary conditions of the shell, Sun [12] extended the Fourier expansion method, first introduced by Chung [13] to analyze the free vibration of stationary cylinders, and to analyze vibration characteristics of thin rotating cylindrical shells under various boundaries. Another study from Sun [14] considered orthogonal polynomial series as admissible functions with more general boundary conditions by simulating elastic constraints using artificial springs. Although elastic boundary conditions could simulate most boundary conditions, it requires many terms of admissible function to obtain accurate results [15].

Compared with the numerous theoretical studies on cylindrical shell vibration, experimental studies are insufficient. Fakkaew [16] studied the vibration of a thin-walled cylindrical rotor with active magnetic bearing support subject to small non-circularity by experiment and compared the results with theoretical predictions. In another study, Fakkaew [17] performed a theoretical and experimental study to establish the vibrational dynamics of a rotating thin-walled cylinder with radial bearing supports. Liu [18] performed an experimental study that showed how to measure the natural frequencies and mode shapes of the spinning cylindrical shell and used the experimental data of the stationary cylindrical shell to adjust the stiffness of the boundary springs in the theoretical model via a genetic algorithm.

A substantial body of theoretical research has been conducted on the vibrations of rotating cylindrical shells. Researchers have extensively studied the influence of Coriolis and centrifugal accelerations on natural frequencies [5, 8]. Additionally, investigations have focused on how various parameters, such as shell dimensions and wave numbers, affect natural frequencies [1, 4, 9-11]. Several studies have also explored the analysis of boundary conditions [12, 14, 15]. Consequently, numerous shell theories have been developed and assessed [1], alongside a diverse array of solution methods [9, 11, 12, 14]. However, it is important to note that these studies predominantly lack experimental validation. Furthermore, experimental research in this field is relatively scarce [16-18], and none of the existing experimental studies have attempted to determine the vibration characteristics of rotating cylindrical shells using non-contact vibration sensors.

Non-contact vibration sensors are more accurate than contact sensors due to their lack of mass effect on the free vibration of the structure. For modal testing of rotating cylindrical shells, they are highly convenient to implement because they do not require wiring under rotating conditions. However, due to the rotation of the shell, multiple non-contact sensors must be used in the circumferential direction to achieve an adequate data acquisition frequency in modal testing of rotating cylindrical shells, which makes the process costly and complex. To address the stated problem effectively, in the present study, the appropriate dimensions and rotational velocity of a rotating cylindrical shell, along with components and test setup of experimental modal testing will be presented and evaluated to enable this kind of novel modal testing with simplicity and practicability. Additionally, the results of modal testing based on the proposed method will be generated by the simulation of modal testing.

2. Components and test setup of vibration analysis

The cylindrical shell selected for vibration analysis has dimensions, rotational velocity, and material properties as presented in Table 1. This shell has a free-clamped boundary condition. It is important to note that the frequency of data acquisition for a presumed point on the shell by only one non-contact sensor is limited to the rotational velocity of the shell and to achieve higher data acquisition frequencies, multiple circumferential non-contact sensors are necessary. Taking this limitation into account, the shell parameters, including dimensions and rotational velocity, have been carefully chosen to minimize the required number of non-contact circumferential sensors, thereby reducing the cost and complexity of the modal testing procedure and enabling this kind of novel modal testing on a rotating cylindrical shell by non-contact sensors.

Table 1 Dimensions and material properties of the selected cylindrical shell.

h/R	0.01
L/R	2
R (m)	0.5
Ω (Hz)	50
μ	0.3
ρ (Kg/m^2)	7850
E (GPa)	200

The mass of contact vibration sensors in rotating conditions induces imbalance forces, which introduce errors in data acquisition for modal testing. Additionally, implementing wiring for contact sensors under rotating conditions is challenging. In contrast, non-contact sensors do not exert mass effects on the vibrating structure, making them more accurate for modal testing of rotating cylindrical shells. This increased accuracy is the primary reason for selecting non-contact sensors in this study.

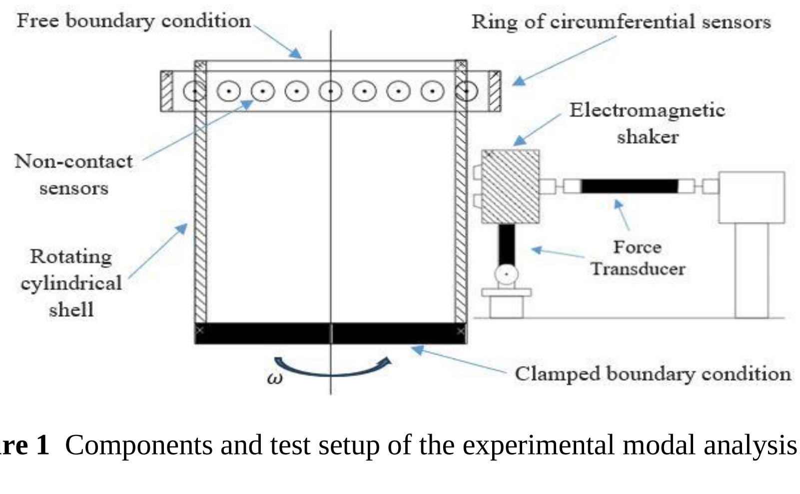


Figure 1 Components and test setup of the experimental modal analysis.

The components of the test setup that are considered for vibration analysis of a rotating cylindrical shell are presented in Fig 1. In addition to a non-contact method of vibration measurement, the excitation force of the modal testing is also assumed to be non-contact, based on magnetic forces on a magnetic shell. In this setup, there are multiple circumferential non-contact sensors on a ring at the free boundary condition of the shell. Note that in this setup vibration of the shell would be measured in a single circumferential direction.

The goal of this vibration analysis is to determine the first five natural frequency and mode shapes of the shell. Note that these natural frequencies are presented in the future part in Table 3. Considering the maximum of these natural frequencies and the rotational velocity of the shell, and to achieve the goal of the vibration analysis, a suitable number of circumferential non-contact vibration sensors was considered equal to 25. Additionally, the frequency of data acquisition for all sensors is considered equal to 2.5 KHz. As a result, Given the shell's rotational velocity of 50 Hz, 50 vibration signals of 50 different circumferential points will be measured per each revolution of the shell. By assembling the resulting vibration signals from each circumferential sensor, the vibration signals of 50 circumferential points on the shell can be measured with an effective data acquisition frequency of 1.25 kHz.

In standard modal testing, it is generally accepted that the minimum required frequency of data acquisition should exceed five times the maximum natural frequency of the structure under investigation [19], and considering the first five natural frequencies of the considered cylindrical shell which is presented in Table 3, the frequency of data acquisition equal to 1.25 KHz is a suitable one. This sampling rate ensures that the Nyquist criterion is satisfied and provides sufficient temporal resolution to accurately capture the dynamic behavior of the shell.

The other point of data acquisition by non-contact sensors is the fact that the frequency of data acquisition should be the multiple of rotational velocity so that the same points on the shell are placed in front of each sensor after each revolution of the shell. Note that this condition has been satisfied on the proposed setup for modal testing with rotational frequency and data acquisition frequency of sensors respectively equal to 50 Hz and 2.5 KHz.

The proposed data acquisition method establishes a systematic pattern for capturing vibration signals. For each sensor, the 1st, 51st, 101st, and subsequent vibration signals at 50-signal intervals correspond to the same point on the shell. Similarly, for all sensors, the 2nd, 52nd, 102nd, and subsequent signals at 50-signal intervals represent measurements from another consistent point. With different such sequences, this pattern extends to all 50 distinct points where sensors measure vibration signals. Furthermore, there is a spatial relationship between adjacent sensors; the point corresponding to the second vibration signal of a given sensor is the same as the point of the first vibration signal of the neighboring sensor which is in the direction opposite to the shell's surface movement relative to the sensors. Note that this spatial relationship could be generalized for all vibration signals of sensors and all points. By using these systematic relationships, it becomes possible to assemble the vibration signals from all sensors, resulting in an effective data acquisition frequency of 1.25 kHz for all 50 circumferential points on the cylindrical shell where sensors measure vibration signals.

The clamped boundary condition of the shell in this paper is assumed to be rigid and its vibration neglected, although in reality boundary condition would have some vibration and this vibration should be measured and used in signal processing.

3. Validation of FEM method for natural frequencies

To establish an appropriate test setup for modal testing of a structure, the theoretical natural frequencies of the structure must be determined. The finite element method (FEM) is commonly employed for this purpose; however, the accuracy of the FEM results must be validated. To assess the accuracy of the FEM method utilized in this paper, a comparative study was conducted.

In this comparative study, a rotating cylindrical shell with clamped boundary conditions has been investigated. Table 2 indicates that the FEM modal analysis determines forward and backward wave frequencies with good accuracy. Note that the reference vibration characteristics of the rotating cylindrical shell [12] for the comparative study in Table 2 are presented by the use of the Fourier series expansion method based on Sanders' shell equations. The accuracy of the results in [12] was validated by comparing its results with the results of other theoretical references. The maximum error is not greater than 1.24% in Table 2, suggesting that the FEM modal analysis is accurate; The formulation of non-dimension parameters is based on [12, 20].

Table 2 Non-dimensional natural frequencies of the rotating cylindrical shell with clamped boundary conditions.

$$(\omega^* = \omega * R * \sqrt{\frac{(1-\mu^2)*\rho}{E}}, \Omega^* = \Omega * R * \sqrt{\frac{(1-\mu^2)*\rho}{E}}, h/R = 0.05, L/R = 2)$$

Ω^*	n	San et all [12]		FEM modal analysis		Error%	
		ω_b^*	ω_f^*	ω_b^*	ω_f^*	ω_b^*	ω_f^*
0.0025	2	0.05996	0.05596	0.06002	0.05603	0.10	0.12
	3	0.11457	0.11156	0.11454	0.11152	0.02	0.03
	4	0.21316	0.21079	0.21246	0.21011	0.32	0.32
	5	0.34227	0.34032	0.33962	0.33771	0.77	0.76
0.0050	2	0.06228	0.05428	0.06266	0.05467	0.61	0.71
	3	0.11662	0.11060	0.11798	0.11198	1.16	1.24
	4	0.21493	0.21019	0.21579	0.21110	0.40	0.43
	5	0.34385	0.33996	0.34289	0.33908	0.27	0.25

4. Results and discussions

4.1 The results of natural frequencies and validation

Having established the validity and accuracy of the FEM modal analysis, the next step is to ensure that the results obtained based on the simulated experimental modal testing converge with those derived from the FEM modal analysis. This convergence serves as a key validation criterion for the simulation method of experimental modal testing and authenticates the test setup presented in this study.

The simulation of modal testing was conducted using the transient analysis of ANSYS, incorporating all relevant components of the modal testing setup. The dimensions and material properties of the cylindrical shell under investigation correspond to those specified in Table 1. To generate the excitation force for the shaker, the "chirp" method is employed in MATLAB, producing a suitable Power Spectral Density (PSD) of force that effectively excites all target natural frequencies within the scope of the modal testing. A fixed boundary condition was applied to one end of the shell. The frequency and time duration of the simulation are respectively equal to 5 KHz and 20 s. after the simulation of experimental modal testing, the measured vibration signals of all circumferential sensors at the free end of the cylindrical shell were obtained; Subsequently, signal processing of the measured data was performed using ARTeMIS Modal software.

Table 3 Natural frequency of the shell based on both FEM modal analysis and simulation of modal testing.

Circumferential and longitudinal wave number (n,m)	Simulation of modal testing (Hz)	FEM Modal Analysis (Hz)	Error (%)
(4,1)	115.35	116.14	0.68
(4,1)	117.65	117.87	0.18
(3,1)	135.65	135.8	0.11
(3,1)	…..	136.02	…..
(5,1)	153.01	153.5	0.32
(5,1)	157.42	157.95	0.33

The resultant natural frequencies from the simulation of modal testing for the cylindrical shell are presented in Table 3 and compared with the results from the FEM modal analysis. The maximum error observed in this table is no greater than 0.68%, indicating that the simulation and signal processing of the modal testing are accurate. It is important to note that the third and fourth natural frequencies in the simulation results are identified as a single natural frequency. This is due to their very close values, making it challenging to differentiate between them in the simulation and signal processing of the modal testing.

4.2 Results of mode shapes

Based on the components and setup presented in this paper, as illustrated in Fig 1, the results of the modal testing simulations and signal processing are discussed in this section. Fig 2 displays the frequency response functions (FRF) for all circumferential points at the free end of the shell. This figure indicates that the excitation force considered in the proposed components and setup for modal testing effectively generates a suitable power spectral density (PSD) of force, which successfully excites all target natural frequencies within the scope of the modal testing because the FRF curves exhibit minimal noise within the frequency range where the target natural frequencies lie.

By further processing of the FRF results, the mode shapes and natural frequencies can be determined. The results for the first five mode shapes, characterized by different circumferential wave numbers, along with their corresponding natural frequencies, are presented in Fig 3. These results are compared with the mode shapes obtained through finite element method (FEM) modal analysis. As illustrated in this figure, the mode shapes and natural frequencies derived from the simulation of modal testing correspond closely with those obtained from the FEM method.

Fig 4 presents the Modal Assurance Criterion (MAC) matrix and bar diagram of the mode shapes resulting from the simulation of modal testing based on the proposed test setup described in this paper. As illustrated in this figure, the orthogonality of the mode shapes exhibits a maximum error of 16.7 percent.

Overall, the results presented in this section indicate that the proposed modal testing components and setup for a rotating cylindrical shell can accurately determine the mode shapes and natural frequencies. Furthermore, it is important to note that, in addition to achieving appropriate accuracy, the proposed modal testing setup employs an optimal number of sensors while maintaining simplicity in its implementation. This enables and facilitates a novel approach to modal testing that has not yet been accomplished in previous studies for rotating cylindrical shells by non-contact sensors.

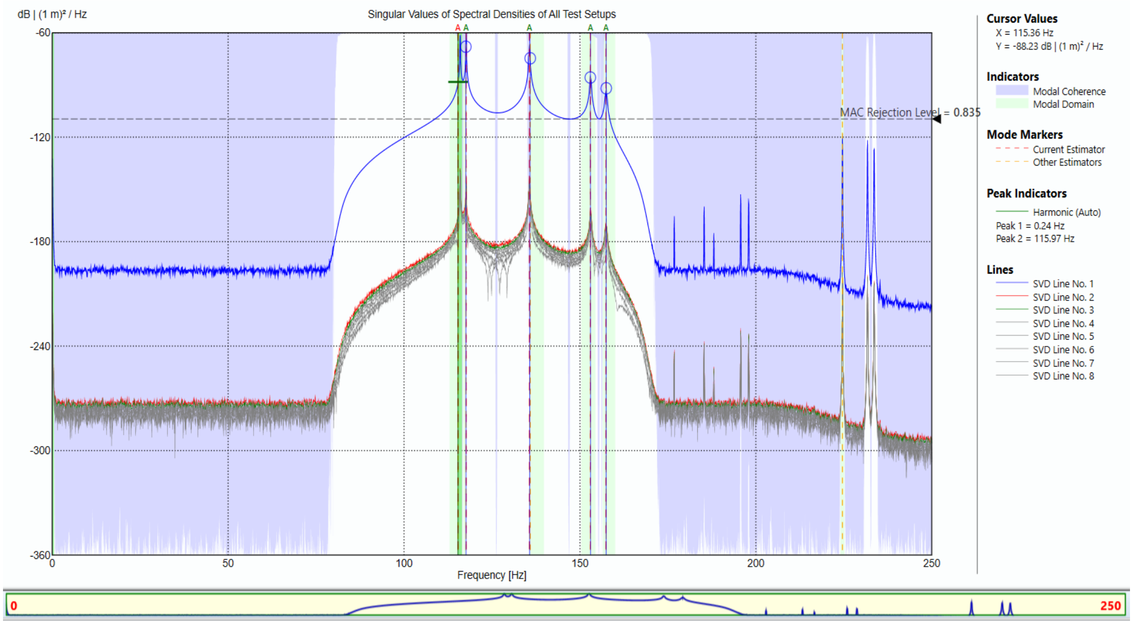


Figure 2 Frequency response (FRF) results of different circumferential points on the cylindrical shell based on the simulation of modal testing for the proposed test setup.

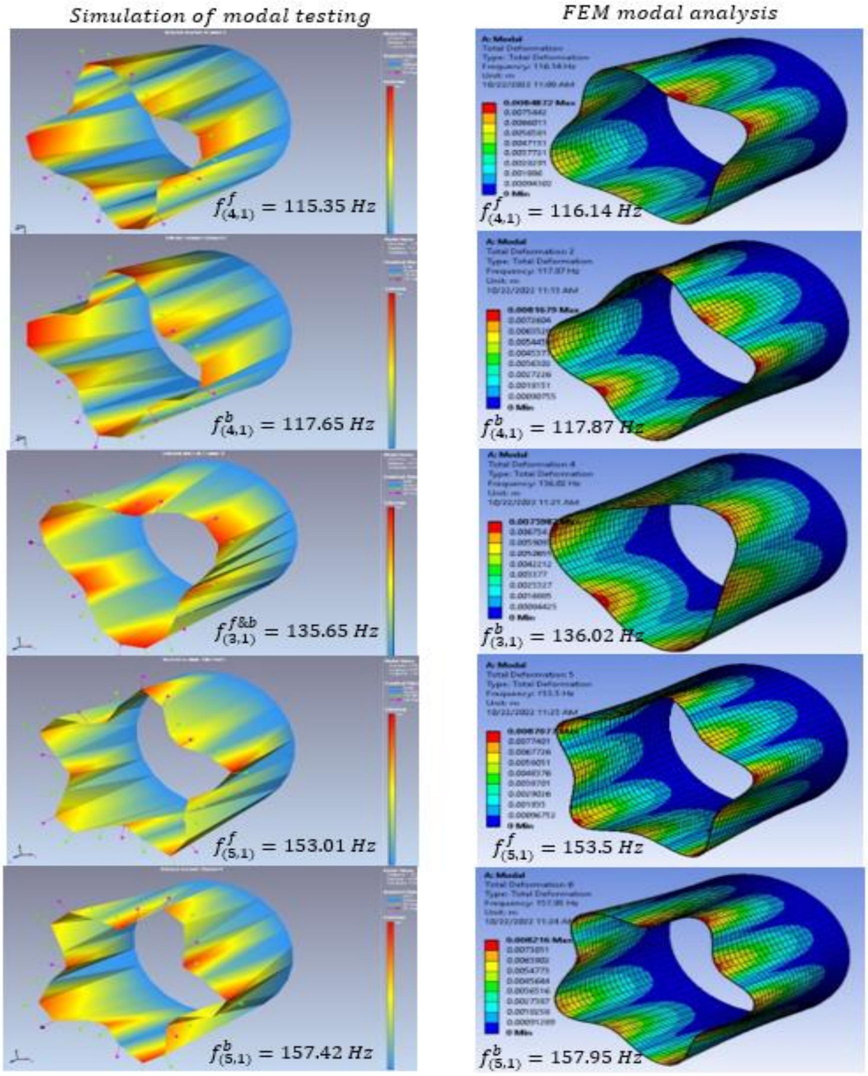
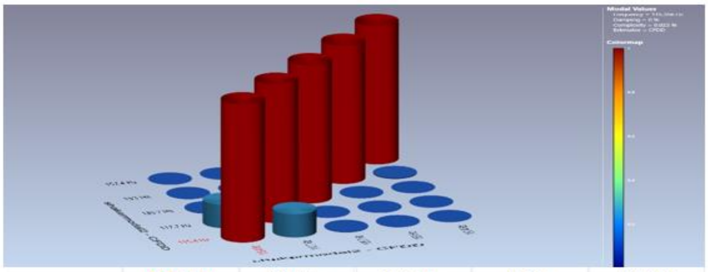


Figure 3 Mode shapes resulted from the simulated modal testing based on the proposed test setup.



	115.4 Hz	117.7 Hz	135.7 Hz	153 Hz	157.4 Hz
115.4 Hz	1	0.1679	0.001963	0.0002101	0.000294
117.7 Hz	0.1679	1	0.00002907	0.00003277	0.0000672
135.7 Hz	0.001963	0.00002907	1	0.0002174	0.0001505
153 Hz	0.0002101	0.00003277	0.0002174	1	0.004999
157.4 Hz	0.000294	0.0000672	0.0001505	0.004999	1

Figure 4 MAC bar diagram and matrix based on the simulated modal testing.

5. Conclusion and summary

Modal testing of rotating cylindrical shells, despite a significant number of theoretical studies, has not been investigated using non-contact sensors until now. Non-contact sensors do not exert a mass effect on vibrations and are more accurate than contact sensors in modal testing. However, in the modal testing of rotating cylindrical shells, a multiple number of these sensors is needed in the circumferential direction to achieve an adequate frequency of data acquisition, which makes this type of vibration analysis complex and costly. This issue can be mitigated through careful shell selection and an appropriate test setup to enable this novel approach to modal testing. In the present study, specific dimensions and rotational velocities for a cylindrical shell, along with the components and test setup for modal testing were proposed, which facilitate the implementation of non-contact sensors with simplicity and applicability. Subsequently, the proposed method of modal testing on rotating cylindrical shells has been simulated and validated. The results of the simulated modal testing indicated that the proposed method effectively determines the natural frequencies and mode shapes of a rotating cylindrical shell.

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