Research Article

Simulation Analysis of the Sound Transmission Loss of Composite Laminated Cylindrical Shells with Applied Acoustic Coverings

Bin Li,1 Haoyang Ding,1 Zhigang Hu,1 Junya Zhao,2 Menghui Qi,2 and Zhiyong Wang1

1School of Mechanical Engineering, Wuhan Polytechnic University, Wuhan, Hubei 430023, China
2Hubei Key Laboratory of Theory and Application of Advanced Materials Mechanics, Wuhan University of Technology, Wuhan, Hubei 430070, China

Correspondence should be addressed to Bin Li; libin_027@126.com

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The noise reduction problem of composite laminated cylindrical shells at low and medium frequencies from 150 Hz to 1000 Hz is addressed by using the noise control method of laying acoustic coverings and conducting noise reduction experiments in a cylindrical shell cavity by laying melamine foam, sound-absorbing cotton, and multilayer combination materials and obtaining the corresponding transmission loss curves. Additionally, based on the LMS Virtual Lab acoustic simulation software, finite element models corresponding to the noise reduction experiments are established, and the acoustic cavity’s simple positive frequency and acoustic response of the cavity are numerically calculated. Based on this, the influence law for a laid acoustic cover layer on the sound transmission loss of a cylindrical shell is investigated. The results show that the noise reduction of sound-absorbing cotton with the same thickness is about 1.26 times that of melamine foam, and the noise reduction of melamine foam with the same mass is about 1.42 times that of sound-absorbing cotton. For multilayer laying, the noise reduction of adding the same thickness of butyl rubber is about 6.18 times that of melamine foam, and the larger the laying ratio is, the better the noise reduction effect will be.

1. Introduction

Most new launch vehicles use composite fairings, which not only have the advantages of lightweight, high-temperature resistance, and fatigue resistance [1], but also reduce the redundant mass of a spacecraft and improve the payload ratio. With the development of launch vehicle technology toward large thrust and large diameter ratios, the problem of low and medium frequency noise in the cavity has become highly prominent, increasing the risk of payload damage such as precision instruments. An acoustic cover layer, as one of the most effective measures for noise reduction in the fairing cavity, has been a popular area of research and a point of difficulty for noise passive control research. Therefore, the study of the sound transmission loss of composite structures with applied acoustic coverings has attracted extensive attention from scholars around the world [2].

Usually, precision instruments are placed in the cylindrical section of a fairing. A cylindrical shell structure is a basic structural unit in the industries of aerospace, automobiles, shipbuilding, etc. The analysis of the internal sound fields of aircraft fuselages, rocket fairing cylindrical sections, vehicles, and ships can be translated into the study of the noise inside a cylindrical shell cavity. Yao et al. [3] derived the acoustic wave equation within a uniform flow field based on the classical thin shell theory and studied the incident. Sohn et al. [4] used a genetic algorithm to optimize the placement of macroscopic fiber composite (MFC-Macrofiber Composite) material in a cylindrical shell to control the first three orders of shell vibration to reduce acoustic radiation. Based on the former study [5], Kim et al. simultaneously laid three MFC materials to effectively control the sound radiation of a cylindrical shell by a feedback control algorithm. Rebca et al. [6] measured the sound insulation
capacity of a certain fiber-reinforced laminate with an experimental method and compared it with the numerical simulation results. Tsai et al. [7] used the conjugate gradient method combined with the nonlinear stiffness equation to derive the sound transmission capacity of a thick composite laminate and then optimized the relevant parameters of the composite laminate by using the conjugate gradient method combined with the nonlinear stiffness equation to derive the sound transmission loss equation. The above theoretical calculations or numerical simulations were focused on the sound insulation performance of a composite cylindrical shell or laminate structure in the wide frequency domain. Few experimental methods have been used to investigate the low and medium frequency domains. Based on this, Zhao et al. [8] used a combination of experimental tests and numerical simulations for the noise reduction of composite laminated cylindrical shells to obtain the influence law of factors such as the layup angle, thickness, and material parameters on the sound transmission loss of a shell. The sound insulation performance of a composite cylindrical shell structure is very limited, and an acoustic cover layer is needed to further reduce the noise level inside a cylindrical shell cavity. Pirk and Souto et al. [9] used statistical energy analysis software to build a simulation model of the acoustic covering layer of glass fiber laid in the fairing of a Brazilian launch vehicle, but they only discussed the noise reduction effect of acoustic materials for different thicknesses, densities, and laying rates at medium and high frequencies. Lane et al. [2] experimentally investigated the noise reduction effect of a thermal protection system on MF materials in composite fairings at three test bandwidths, but the noise reduction law of the MF materials in low and medium frequency bandings was less involved. Li Bin et al. [10–12] studied the noise reduction of melamine foam-lined cylindrical cavities in the low and medium frequency bands (100–400 Hz), and they analyzed the influence of the acoustic parameters of melamine foam pores and different laying rates on the acoustic resonance response in the low and medium frequency bands of 100–400 Hz. Yan Wenjie et al. [13, 14] used finite element simulation to study the influence of the laying scheme, laying thickness, and Helmholz resonator on the noise response of a cylindrical shell acoustic cover layer. Qi Menghui et al. [15] solve the problem of the harsh midlow frequency noise of rocket fairing. The cylindrical section of the protective precision instrument fairing is simplified as cylindrical shells, and different lining strategies of melamine foam (MF) are studied experimentally and numerically. However, all of the above analyses only studied the effect of a single material on the noise level in a cavity, and there was a lack of comparative studies on the noise reduction characteristics of different types of acoustic coverings.

From the current situation of international research, it can be seen that there are more studies on the noise reduction characteristics of acoustic dressing materials, and fewer studies involving multiple and multilayer combined acoustic coverings for the low and medium frequency bands based on the acoustic characteristics of composite materials in a cavity. In this research, the finite element model and noise experimental setup of a scaled-down cylindrical section are established with reference to the structure of the cylindrical section of a launch vehicle fairing, and the typical porous acoustic materials of melamine foam, sound-absorbing cotton, and multilayer combination materials (butyl rubber/melamine foam) are selected as the acoustic cover layer to be laid on the inner wall of the cylindrical shell. The noise reduction law in the cavity of the cylindrical shell is studied in the range of 150–1000 Hz according to the objective conditions of the experiment and the applicable range of the simulation software, which provides a useful reference for a more in-depth study of the application law and characteristics of the acoustic cover layer in the passive noise control method.

2. Experimental Study

The composite laminated cylindrical shell used in the experiment is shown in Figure 1, and the shell material and auxiliary layer method are adopted from the research results of the Zhao subject group [8]. The material is uniaxial glass fiber cloth reinforced with epoxy resin, and the layering method is (90/0/90/0/90). The shell is 1125 mm in height, 1050 mm in diameter, and 4.50 mm in thickness, and the upper and lower covers are 1180 mm in diameter and 25 mm in thickness, with a 1050 mm diameter column inlet in the middle that is 12.50 mm thick and supported by four 50 mm-thick vibration-damping rubber pads at the bottom to simulate the free state. The sound source arrangement, white noise playback, acoustic sensor arrangement inside and outside the cylindrical shell, and experimental data processing in the laboratory are consistent with Li’s published literature [10].

3. Finite Element Simulation Analysis

3.1. Establishment of the Simulation Model. Based on Hypermesh finite element software, a finite element model consistent with the structure of the cylindrical shell used in the experiment is established, as shown in Figure 2. As can be seen from the figure, the finite element model consists of four parts, the cylindrical shell, the upper and lower covers, the inner acoustic cavity, and the outer acoustic cavity. The inner and outer acoustic cavities are used to simulate the air inside and outside the cylindrical shell, respectively. Since the thickness of the cylindrical shell is much smaller than the radius and the shell structure is relatively simple, the cylindrical shell is built by midsurface and simulating quadrilateral shell cells with a mesh size of 28 mm and a total of 4,920 cells. The upper and lower covers are simulated by tetrahedral mesh with a size of 30 mm and a total of 18,150 cells. The inner and outer sound field models are simulated by hexahedral mesh with a mesh size of 30 mm, for a total of 210,064 cells.

The model is imported into the finite element analysis module of LMS Virtual. Lab Acoustic software and MPC line welding constraints are used to connect the cylindrical shell to the upper and lower cover structures. The corresponding mesh properties and material properties are assigned to different meshes, and the material parameters used for the simulation are shown in Table 1. The plane where the lower surface of the cylindrical shell is located is defined as the reflective surface to simulate the ground in order to make the
To allow the acoustic waves to enter and exit freely and transmit completely, the rest of the outer surface is defined as the automatic matching layer (AML).

In order to simulate the reverberant sound field outside the shell in the experiment, the reverberant sound source (manifested as 24 columns of plane waves) is loaded in the simulation, and the simulation load data are input with the experimental test external load power spectrum. The finite element graphs of the applied boundary conditions are shown in Figure 3. The field points in the inner sound field are established at the same location as the experimental acoustic transducer test, and the direct acoustic-vibration coupling analysis is performed to output the sound pressure response values of the corresponding field points and compare them with the theoretical and experimental data to verify the correctness of the finite element modeling.

3.2. Simulation Results and Comparative Analysis. Based on the established simulation model, the correctness of the finite element modeling and simulation calculations are verified on three aspects: the acoustic cavity’s simple positive frequency, the acoustic response of the cavity, and the acoustic response of the cavity when the acoustic cover layer is applied.

3.2.1. Acoustic Cavity Simple Positive Frequency Theory Verification. In order to compare and analyze the simulation calculation results of the cylindrical acoustic cavity with the theoretical values, a finite element model of the cylindrical acoustic cavity consistent with the experiment has been established, in which the radius of the cylindrical shell is 521 mm, the height is 1125 mm, the speed of sound in the air parameters is 343 m/s, and the density is 1.23 kg/m$^3$, and the simulated analysis of the cylindrical acoustic cavity’s simple positive frequency is performed. Based on previous work [11], the cylindrical shell’s simple positive frequency was calculated and compared with the simulation calculation value. The results are shown in Table 2. In the table, $l$, $m$, $n$ are the axial, radial, and circumferential simple positive frequency order. Then $(l, m, n)$ can indicate the order of the cavity’s internal simple positive mode. From the comparison, it can be seen that the maximum error between the simulated and theoretical values of the simple positive frequency of different orders of the acoustic cavity is 0.60%, which proves the correctness of the finite element modeling.
3.2.2. Experimental Verification of the Acoustic Response of the Cavity. Simulation analysis is performed for the established finite element model, and the sound pressure response values of the field points corresponding to the experiment are output and compared with the experimental test results. The results are shown in Figure 4.

From the figure, it can be seen that, in the frequency range of 150–1000 Hz, the simulation curve and the experimental curve basically match. There are several peaks, and the comparison with the sound cavity’s simple positive frequency shows that these peaks appear in the resonance frequency of the sound cavity, caused by the resonance inside the sound cavity. From the perspective of the total sound pressure level (SPL), the experiment and simulation in the frequency band of 150–1000 Hz are 97.24 dB and 97.79 dB, respectively, with an error of 0.56%, which verifies the correctness of the finite element modeling and finite element simulation methods in this frequency band. In the frequency band of 0–150 Hz, which is the stiffness control region [16], the acoustic cavity response is mainly controlled by the stiffness of the structure. Due to the limitations of the finite element method, the simulation results deviate from the experimental results. It is more difficult to obtain accurate results, but this frequency band is verified by the previous theoretical calculations in terms of the correctness of the finite element modeling. From the above comparison results, it can be seen that the simulation calculation can effectively reflect the actual situation in the frequency band of 150–1000 Hz, so this study only focuses on the noise reduction characteristics of the composite laminated cylindrical shell in the frequency band of 150–1000 Hz.

3.2.3. Comparison of the Simulated and Experimental Results of the Response of Laminated Cylindrical Shells with the Applied Coverings. The simulation analysis of the cylindrical shell with different acoustic coverings is carried out, and the acoustic pressure response values of the corresponding field points are output with the experiment. The acoustic pressure response values of all the field points are numerically averaged, and the simulation analysis results are compared with the experimental test results to verify the correctness of the finite element modeling. The parameters of the porous material used in the simulation are shown in Table 3. The density of butyl rubber is 1660.90 kg/m³, the Young’s modulus is 80 MPa, and Poisson’s ratio is 0.43.

The experimental and simulated noise response spectra of the composite laminated cylindrical shell with 40-mm melamine foam, 10-mm sound-absorbing cotton, and 8-mm multilayer combination material (2-mm butyl rubber + 6-mm melamine foam) are shown in Figures 5–7. It can be seen from the plots that the simulated and experimental curves have good agreement in the frequency band of 150–1000 Hz, and the curve trends are basically the same. As shown in Table 4, the errors are no more than 0.85% from the SPL perspective, and the experimental and simulation results are in good agreement, which verifies the correctness of the finite element model and finite element modeling in this frequency band.

4. Influence Law of Laying a Cover Layer on the Sound Transmission Loss of the Laminated Cylindrical Shell

In order to further discuss the application rules and characteristics of acoustic coverings in the passive noise control methods, the influence laws of covering types and multilayer layup schemes on the sound transmission loss of composite cylindrical shells are studied separately. To facilitate the observation of the effect of laying acoustic materials on the noise reduction performance of the structure, the sound transmission loss (STL) value of the external load minus the acoustic cavity response is used in the following analysis, represented by “STL” in the figure below.

4.1. Effect of Laying Different Acoustic Materials on the Sound Transmission Loss of the Laminated Cylindrical Shell Structure. Finite element simulation is used to analyze the effect of a lining with the same mass and thickness of melamine foam and sound-absorbing cotton on the sound transmission loss of the cylindrical shell.

4.1.1. Laying the Same Thickness of Porous Sound-Absorbing Materials. The results for the composite laminated cylindrical shell lined with 20-mm-thick melamine foam and sound-absorbing cotton material simulated by acoustic simulation software are shown in Figure 8.

It can be seen from the figure that the curve of sound-absorbing cotton is higher than that of melamine foam in the whole frequency range, so the noise reduction effect of sound-absorbing cotton is better than that of melamine foam. From the perspective of overall noise reduction, the total sound transmission loss value of the empty drum of composite material is 10.21 dB, and the total sound transmission loss value after laying 20-mm melamine foam is 17.69 dB, which is 7.48 dB more than that of the empty drum. The total sound transmission loss value after laying 20-mm acoustic cotton is 19.67 dB, which is 9.46 dB more than that of the empty drum and 1.98 dB more than that of the melamine foam. The total sound loss value is 19.67 dB, which is 9.46 dB more than the empty drum, and 1.98 dB more than that of the melamine foam. Therefore, laying

| Table 2: Comparison of natural frequencies achieved with analytical method and simulation computation. |
|---------------------------------------------------------------|
| **Mode** | **Analytical value /Hz** | **Simulation value /Hz** | **Error /%** |
| l, m, n | (1,0,0) | (0,0,1) | (1,0,1) | (2,0,0) | (0,0,2) | (1,0,2) | (2,0,1) | (0,1,0) |
| Analytical value | 152.44 | 192.93 | 246.68 | 304.66 | 319.80 | 355.11 | 361.34 | 401.51 |
| Simulation value | 152.44 | 192.97 | 245.19 | 304.89 | 319.97 | 354.43 | 360.82 | 401.62 |
| Error | 0.00 | 0.02 | 0.60 | 0.08 | 0.05 | 0.19 | 0.14 | 0.03 |
acoustic materials can effectively increase the sound transmission loss of the structure, and 450 g/m² sound-absorbing cotton of the same thickness has a better noise reduction effect than that of the melamine foam.

### 4.1.2. Porous Sound-Absorbing Materials of the Same Mass

Melamine foam (thickness of 32.70 mm) and 450 g/m² sound-absorbing cotton material (6.30 mm) with a mass of 1 kg are laid inside the composite laminated cylindrical shell and simulated by acoustic simulation software. The results are shown in Figure 9.

As can be seen from the figure, the curve of melamine foam is basically higher than that of sound-absorbing cotton in the whole frequency range, so the noise reduction effect of melamine foam of the same quality is better than that of sound-absorbing cotton. From the perspective of overall noise reduction, the total sound transmission loss

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#### Table 3: Fluid bulk properties of porous material.

| Fluid bulk properties | Melamine foam | 450 g/m² sound-absorbing cotton |
|-----------------------|---------------|---------------------------------|
| Flow resistivity/Pa·s/m² | 13000         | 15023                           |
| Porosity (%)         | 97.30         | 82.31                           |
| Tortuosity           | 1.05          | 1                               |
| Viscous characteristic length (mm) | 0.064 | 0.034 |
| Thermal characteristic length (mm)  | 0.21         | 0.091                           |

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Figure 4: Comparison of internal response spectrum achieved from experiment and simulation before the laying of the material.

Figure 5: Comparison of internal response spectrum achieved from the experiment and simulation with the laying of melamine foam.

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value of the empty drum of composite material is 10.21 dB, and the total sound transmission loss value after laying 6.30 mm sound-absorbing cotton is 16.85 dB, which is 6.64 dB more than that of the empty drum. The total sound transmission loss value after laying 32.70 mm melamine foam is 19.98 dB, which is 9.77 dB more than that of the empty drum, and at the same time, the value is 9.77 dB more than that of the empty drum. At the same time, this increases the noise reduction by 3.13 dB compared with the same quality of sound-absorbing cotton. Therefore, melamine foam of the same mass has a better noise reduction effect than 450 g/m² sound-absorbing cotton.

4.2 Influence of Multilayer Combination Materials on the Sound Transmission Loss of Laminated Cylindrical Shell Structure. By keeping the thickness of one material in the multilayer combination material constant and changing the thickness of the other material, the influence of the thickness of each layer of the multilayer combination material on the sound transmission loss of the structure is investigated, for
which three groups of multilayer combination materials with different thicknesses are set.

1. 2 mm butyl rubber + 6 mm melamine foam
2. 2 mm butyl rubber + 10 mm melamine foam
3. 6 mm butyl rubber + 6 mm melamine foam

The simulation analysis is carried out in the acoustic simulation software. The results are shown in Figure 10.

From the figure, it can be seen that different thicknesses of multilayer combination materials have different effects on the sound transmission loss of the structure. Compared with changing the thickness of melamine foam, when only the thickness of butyl rubber is changed, the values of the peak point and trough point of the sound transmission loss curve increase significantly with the increase of the butyl rubber thickness in the whole frequency range, which indicates that butyl rubber effectively suppresses the vibration of the structure and reduces the noise in the cavity. From the perspective of overall noise reduction, the total sound transmission loss values of the three curves of 2 mm butyl rubber + 6 mm melamine foam, 2 mm butyl rubber + 10 mm melamine foam, and 6 mm butyl rubber + 6 mm melamine foam are 14.39 dB, 15.51 dB, and 21.31 dB, respectively. That is, increasing the melamine foam by 4 mm alone can increase the noise reduction by 1.12 dB. Adding 4 mm of butyl rubber can increase the noise reduction by 6.92 dB. Thus, it can be seen that adding the same thickness of butyl rubber results in
6.18 times the noise reduction rate of adding the same thickness of melamine foam.

4.3. Effect of Multilayer Laying on the Sound Transmission Loss of Laminated Cylindrical Shell Structure. From the results of the previous study, it can be seen that melamine foam has better sound absorption and noise reduction effect than acoustic cotton in the studied frequency band of 150–1000 Hz, and is lighter and easier to cut. Although the noise reduction effect of butyl rubber of the same thickness is better than that of melamine foam, the true density of butyl rubber is 1.77 g/cm³ (no porosity), and the true density of melamine foam is 2.23 g/cm³ (99.28% porosity), so the same thickness of butyl rubber mass increase is more obvious. Generally, there is an upper limit to the quality of the cavity material laying requirements, so the butyl rubber and melamine foam multilayer combination of materials is taken as the object of study, combined with the characteristics of the noise control for the combination, to explore the impact of multilayer laying on the cylindrical shell sound loss law.

4.3.1. Effect of Multilayer Laying of the Same Thickness on the Sound Transmission Loss of a Laminated Cylindrical Shell Structure. The total thickness of the material is set at 10 mm when multilayer laying is used. The influence of the different laying ratios of each layer on the sound transmission loss of the structure is investigated, and three different laying ratio schemes are set.

(1) 1 mm butyl rubber + 9 mm melamine foam
(2) 3 mm butyl rubber + 7 mm melamine foam
(3) 5 mm butyl rubber + 5 mm melamine foam

Simulation analysis is carried out in the acoustic simulation software, and the graphs of the influence of different laying ratios of multilayer materials on the sound transmission loss of the cylindrical shell are obtained, as shown in Figure 11.

From the graph, it can be seen that in most of the frequency bands, the sound transmission loss curve gradually increases with the increase of the proportion of butyl rubber laying, which is especially obvious in the frequency band of 150–400 Hz, and the peak point value of the sound transmission loss curve increases to a greater extent for the larger proportion of butyl rubber laying. From the perspective of overall noise reduction, the total sound transmission loss values of 1 mm butyl rubber + 9 mm melamine foam, 3 mm butyl rubber + 7 mm melamine foam, and 5 mm butyl rubber + 5 mm melamine foam are 14.28 dB, 17.53 dB, and 19.89 dB, respectively. The total sound transmission loss value of the composite cylindrical shell without laying material is 10.21 dB. Therefore, the total sound pressure levels are reduced by 4.07 dB, 7.32 dB, and 9.68 dB for the three multilayer layups; i.e., the noise reduction increases by 3.25 dB and 2.36 dB, and it is found that the increase in noise reduction decreases with the increase in the proportion of butyl rubber in the layup.

4.3.2. Influence of Different Thicknesses of Multilayer Laying on the Sound Transmission Loss of the Laminated Cylindrical Shell Structure. By gradually increasing the thickness of each layer of the laid acoustical material, the effects of different total thicknesses of multilayers laying on the sound transmission loss of the cylindrical shell are studied, and three groups of laying schemes with different thicknesses are set.

(1) 2 mm butyl rubber + 2 mm melamine foam
(2) 5 mm butyl rubber + 5 mm melamine foam
(3) 8 mm butyl rubber + 8 mm melamine foam

Simulation analysis was carried out in the acoustic simulation software to obtain the graph of the effects of different material thicknesses on the sound transmission loss of the cylindrical shell, as shown in Figure 12.

As can be seen from the figure, the values of the peak point and trough point of the sound transmission loss curve increase to a larger extent with the increase of the thickness
of each layer of the layered material in the whole frequency range. From the perspective of overall noise reduction, the total sound transmission loss values of 2 mm butyl rubber+2 mm melamine foam, 5 mm butyl rubber+5 mm melamine foam, and 8 mm butyl rubber+8 mm melamine foam are 13.20 dB, 19.89 dB, and 24.02 dB, respectively. The total sound transmission loss value of the composite cylindrical shell without dressing material is 10.21 dB. Therefore, the total sound pressure levels are reduced by 2.99 dB, 9.68 dB, and 13.81 dB for the three kinds of multilayer laying. In other words, the noise reduction increases by 6.69 dB and 4.13 dB for each 6-mm increase in the total thickness of multilayer laying, but the magnitude of the increase in the noise reduction is reduced.

5. Conclusions

In this research, the finite element modeling of a cylindrical shell and an acoustic cover is established by comparison with experimental data to verify the correctness of the finite element modeling in the frequency range of 150–1000 Hz. For the noise reduction of the composite laminated cylindrical shell at the low and medium frequencies of 150–1000 Hz, the effect of the acoustic cover type and multilayer laying on the sound transmission loss of the composite laminated cylindrical shell is simulated and analyzed, and the following conclusions are obtained:

(1) When the same thickness of melamine foam and sound-absorbing cotton is laid, the noise reduction of sound-absorbing cotton is about 1.26 times that of melamine foam. When the same mass of melamine foam and sound-absorbing cotton is laid, the noise reduction of melamine foam is about 1.42 times that of sound-absorbing cotton.

(2) By increasing the material thickness in the multilayer combination material, respectively, the noise
reduction of butyl rubber is about 6.18 times that of melamine foam for the same thickness.

(3) For multilayer laying with the same total thickness, the larger the proportion of butyl rubber laying is, the better the noise reduction effect will be. When using multilayer laying with gradually increasing laying thickness, the total thickness increases from 4mm to 10mm and 16mm, and the noise reduction increases by 6.69dB and 4.13dB successively, and the increase of noise reduction decreases.

Data Availability

All data were obtained in the work at Wuhan University of Technology and Wuhan Polytechnic University and are detailed in the paper. No additional data need to be listed.

Conflicts of Interest

The author declares that there are no conflicts of interest regarding the publication of this article.

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