Analysis of sound transmission loss characteristics of aircraft composite panel under variable temperature environment

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Abstract
An improved sound transmission loss (STL) experimental technique based on the sound pressure method (SPM) and acoustic box method is proposed to investigate the temperature influence on the STL of the ribbed carbon fiber reinforced plastics aircraft panel. SPM principle is given. The measurement procedure of the improved STL technique is presented and its reliability is verified. STL variable characteristics of the panel within −40°C–40°C were measured. Results showed that temperature had a significant effect on the panel’s STL. The overall STL varied nonlinearly with temperature, whereas STL exhibited a fluctuation or monotony trend at a single center frequency. Temperature variation caused changes of STL peak/dip frequencies and redistribution of stiffness-controlled, resonance-controlled, coincidence-controlled, and damping-controlled regions. The causes of the aforementioned are given. This study reveals the relationship between temperature, thermomechanical parameters and STL. The findings have applications in the design, measurement, analysis, and theoretical development of composite structure acoustics.

Keywords
Sound transmission loss, composite structure, experiment, temperature effect, aircraft

Introduction
Sound transmission loss (STL), which is usually determined via experiments, is an important design index for aerospace structures. However, due to the temperature dependence of composite structures’ STL and the widespread use of composite materials in aerospace structures,1,2 STL experimental technologies developed at room temperature cannot fully meet measurement requirements under variable temperature environments. Meanwhile, this issue has not been addressed in the reported studies. In this paper, an improved STL experimental technique based on the sound pressure method (SPM) and acoustic box method (ABM) is proposed for demonstrating the vibroacoustic behavior sensitivity of a ribbed carbon fiber reinforced plastics (CFRP) aircraft panel at ambient temperature.

Aircrafts operate within a broad ambient temperature range, typically varying between −50°C and 50°C, for hours. Concerning spacecraft, ambient temperature is worse (typically −100°C to 200°C) within their mission. Studies have shown that composite structures’ properties (elastic modulus, damping loss factor, natural frequency, etc) strongly depend on temperature.3–6 Given that the aforementioned properties are related to STL, the temperature should affect composite structures’ STL. Therefore, researchers conducted some investigations on the acoustic analysis of composite structures. However, the main concerns were sound transmission mechanism,7–9 numerical simulation method,10–13 and composite
The influence of thermomechanical behavior on composite structures’ STL is still a field of sporadic research.

Only a few papers have been reported. In 2013, the temperature-dependent STL was investigated based on statistical energy analysis. Following that, several theoretical models were proposed. Xin created a theoretical model of a simply supported plate and used numerical methods to determine its accuracy and feasibility. Li studied sandwich panels’ STL in a thermal environment using the mode superposition method and presented an analytical method for sandwich panels in thermal environments. Then, Zhou investigated the sound radiation of porous functionally graded material (FGM) plates with a temperature gradient along with the thickness. Recently, Hu proposed a semi-analytical model to analyze FGMs’ STL. Meanwhile, an analytical strategy was proposed to determine the thermal load’s effect on STL via parametric studies. In mentioned studies, attention is paid to theoretical derivation and simulation modeling, experimental methods are rarely adopted.

The reason is that the STL analysis of composite structures at varying temperatures is still preliminary. The experimental theory is not perfect (thermal instability problems), available techniques have not been proposed, and reliable measurement equipment for harsh environments (pull-in instability influence) has been developed inefficiently. Therefore, theoretical modeling and numerical simulation are the most viable options. Moreover, theoretical analyses and simulations are appropriate for studying various composite structures over a wide temperature range and are cost-effective compared to experimentation. Nowadays, in practice, the demand for STL measuring of composite structures has emerged and theoretical/simulation models should be modified via experiments. As a result, developing STL experimental technology under variable temperature environments is critical. Based on SPM and ABM, an improved STL experimental method is proposed in this study to reveal the relationship between temperature, thermomechanical parameters and STL.

**Figure 1.** Experimental system of sound intensity method.

**Figure 2.** Experimental system of sound pressure method.
The paper is organized as follows: In *A Brief Statement of the Improved STL Experiment*, *Determination of Experimental Methods*, *Experiment principle*, *Measurement Objects and Experimental Devices*, *Measurement Process* are introduced. *Verification and Analysis of Experimental Results* includes *Reliability Analysis of Measurement Results*, *The Analysis of STL at Different Temperatures*, *Discussion of STL Variation*. Finally, *Conclusion* discusses the concluding remarks and potential applications of the presented work.

### A brief statement of the improved sound transmission loss experiment

#### Determination of experimental methods

As well known, the sound intensity method (SIM), SPM, and ABM are commonly used for experimental measurement of STL in the aviation field.

In SIM, incident/transmitted sound power is measured using the sound intensity probe (Figure 1). To improve measurement efficiency, SPM (Figure 2) is being developed, where sound pressure level (SPL) is used to determine incident/transmitted sound power. However, the experiment cannot be standardized for some cases. Hence, ABM is being developed (Figure 3). Since each method has advantages and disadvantages, it’s difficult to determine which method should be used in this study. So, a comparison of the three methods in Table 1 is given.

Considering the aforementioned comparison, the principle of SPM should be adopted. Based on existing experimental conditions, the design idea of ABM is applied.

#### Experiment principle

To introduce SPM’s principle, whose model has been shown in Figure 2, this section is given. It was assumed that the specimen was the only source-to-receiving sound transmission path. A diffusion sound field was created in the source room, then sound waves were randomly incident on the specimen, forcing the specimen to radiate sound. Sound energy density $D_1$ in the source room is

$$D_1 = \frac{4W}{cr_1}$$

where $W$ is source sound power, $c$ is the sound velocity in air, and $r_1$ is the room constant of the reverberation chamber. Incident sound power is given as

$$W_1 = \frac{1}{4} D_1 c S_1$$

$S_1$ is specimen area; thus, the transmission coefficient $\tau$ is

$$\tau = \frac{W_1}{W_2}$$

Transmitted sound power $W_2$ is

$$W_2 = \tau W_1 = \frac{1}{4} \tau D_1 c S_1$$

Then

$$STL = 10 \log_{10} \left( \frac{1}{\tau} \right)$$

Sound energy density $D_2$ in the receiving room is.

$$D_2 = \frac{W_2}{c} \left( \frac{1}{S_1} + \frac{4}{r_2} \right)$$

$r_2$ is the room constant of the receiving room. Considering the relationship between sound energy density $D$ and effective sound pressure $p_e$ in equation (7), we would find the SPL.
\[ D = \frac{p^2}{\rho c^2} \]  
\[ L = 20 \log_{10} \frac{p}{p_{\text{ref}}} \]  

$L$ is SPL, $p_{\text{ref}}$ is the reference sound pressure, and $p_{\text{ref}} = 2 \times 10^{-5}\text{Pa}$.

By substituting equations (3), (4), (6)–(8) into equation (5), the STL is calculated as

**Figure 3.** Experimental system of acoustic box method.

**Table 1.** Methods comparison.

| Method | Advantage | Disadvantage |
|--------|-----------|--------------|
| SIM    | Standardized, High precision, Mature technology | Limited spectral information, Time-consuming, Potential hearing damage |
| SPM    | Standardized, Mature technology, Engineering application friendly, Spectrum information completeness | Precision lower than SIM, Measurement correction |
| ABM    | Actual application status, Mature technology, Engineering application friendly | Relatively low precision, Not standardized |

SIM: sound intensity method; SPM: sound pressure method; ABM: acoustic box method.

**Figure 4.** Scheme of the experimental system.
\[ STL = L_r - L_t + 10 \log_{10} \left( \frac{1}{4} + \frac{S_1}{r_2} \right) \tag{9} \]

\( L_r \) is the effective sound pressure in the source room and \( L_t \) is the effective sound pressure on the specimen surface in the receiving room. \( r_2 \) is the room constant of the receiving room.

\[ r_2 = \frac{S_2 \alpha_2}{1 - \alpha_2} \tag{10} \]

\( S_2, \alpha_2 \) are the indoor surface area and absorption coefficient of the receiving room, respectively.

In equation (9), \( L_r \) and \( L_t \) can be measured directly. Next to solve equation (10). In anechoic chambers, \( \alpha_2 \leq 1, S_1 \ll S_2 \). So, \( S_1/r_2 \approx 0 \), then

\[ 10 \log_{10}(1/4 + S_1/r_2) \approx -6 \]

Thus equation (9) is simplified to

\[ STL = L_r - L_t - 6 \tag{11} \]

In semi-anechoic chambers, \( \alpha_2 \leq 1 \), which should be measured. In practice, to get accurate results, the standard specimen method is often used to modify \( 10 \log_{10}(1/4 + S_1/r_2) \) (as shown in Step 1, Measurement Process). \( L_t - 10 \log_{10}(1/4 + \)

Table 2. Properties of monolayer carbon fiber reinforced plastics material (25°C).

| Property  | \( E_1 \) (GPa) | \( E_2 \) (GPa) | \( E_3 \) (GPa) | \( G_{12} \) (GPa) | \( G_{13} \) (GPa) | \( G_{23} \) (GPa) | \( \nu_{12} \) | \( \nu_{13} \) | \( \nu_{23} \) |
|-----------|----------------|----------------|----------------|------------------|------------------|------------------|-----------|-----------|-----------|
| E1        | 8.91           | 8.91           | 4.16           | 4.16             | 3                | 0.31             | 0.31      | 0.45      |

Note: \( E_1 \) — Longitudinal modulus; \( E_2, E_3 \) — Transverse modulus; \( G_{12}, G_{13}, G_{23} \) — Shear modulus; \( \nu_{12}, \nu_{13}, \nu_{23} \) — Poisson’s ratio.
\( S_1/r_2 \) is represented by the corrected average effective SPL \( \overline{L}_r \); \( L_r \) is represented by the average effective SPL \( \overline{L}_r \). Then equation (9) is simplified as

\[
STL = \frac{L_r}{C_0} \overline{L}_0 t \quad (12)
\]

In equation (12), the near field is ignored and assuming that the correction parameter does not vary with temperature. During measuring, microphones were arranged at \( k \) selected positions in the source room; Microphone Array 1 was placed at the optimal measurement distance \( d_{op} \) in the receiving room. \( \overline{L}_r \) and \( \overline{L}_i \) are calculated by equation (13).

\[
\overline{L} = 10 \log_{10} \left( \frac{1}{k} \sum_{i=1}^{k} 10^{\frac{L_{pi}}{10}} \right) \quad (13)
\]

\( L_{pi} \) is SPL at the \( i \)-th measurement position.

**Measurement objects and experimental devices**

In order to investigate the temperature effect on composite structures’ STL via experiments, the experimental system shown in Figure 4 was proposed based on SPM and ABM. A ribbed reinforced CFRP aircraft panel (Figure 5) and an environmental simulator device (Figure 6) were designed and then manufactured. Table 2 shows the properties of monolayer CFRP.

One of the inner walls of the device was designed with a window to install the specimen, and the others were designed with cylindrical reflectors to ensure the diffusion sound field could be generated. The device performed temperature control and humidity adjustment to meet STL experimental requirements under variable temperatures.

Before measurements, the system shown in Figure 4 was constructed. The device was placed in a semi-anechoic chamber. The panel was installed in the window, and the boundaries were clamped and sealed. The device’s reverberation chamber functioned as a source room, where white noise generated by a loudspeaker was used to excite the diffusion sound field. Figures 7 and 8 show experimental status in the source and receiving rooms. The measurement process is given in Measurement Process.
Measurement process

According to *Determination of Experimental Methods, Experiment Principle and Measurement Objects* and *Experimental Devices*, the measurement process shown in Figure 9 was designed. During experiments, it was assumed that all equipment operate stably. To avoid pull-in instability, electronic instruments were protected and maintained regularly.

**Step 1: Determination of optimal measurement distance** $d_{op}$. First, at room temperature, STL ($STL_0$) was measured via SIM and calculated using equations (13) and (14).

$$ STL_0 = L_r - L_t - 6 \quad (14) $$

$L_t$ is the transmitted sound intensity level.

Then, in the receiving room, the measurement distance $d$ between Microphone Array 1 and the panel was set as $d_1$ (usually $d_1 = 10$ cm), STL ($STL_1$) was measured via SPM and calculated by equations (12) and (13).

Next, setting $d$ to $d_2$ ($d_2 = d_1 + \Delta d$, $\Delta d = 5$ cm), STL ($STL_2$) was measured again using SPM. This measurement was repeated until $d = d_n = 1$ m ($d_n = d_{n-1} + \Delta d$), corresponding result was marked as $STL_n$.

Finally, all results were plotted in one graph to find out the STL curve which was consistent with $STL_0$’s, the calculation method is given as equations (15) and (16).

$$ \chi_n^2 = \frac{1}{N} \sum_{i=1}^{N} [STL_0(f_i) - STL_n(f_i)]^2 \quad (15) $$

$\chi_n^2$ is the mean square deviation, $f_i$ is the center frequency, and $N$ indicates center frequency number.

$$ d_{op} = \text{Min} \{ \chi_1^2, \chi_2^2, \chi_3^2, \ldots, \chi_n^2 \} \quad (16) $$

$\chi_n^2$ was determined by $\chi_{op}^2$.

**Step 2: Control of target temperature.** Before controlling the temperature, the panel and source room were sealed with adiabatic devices. Then, the temperature control-monitoring system was turned on to heat or cool the reverberation field until the target temperature $T$ was achieved. To mitigate the effects of temperature shock and instability, temperature sensors were arranged on both surfaces of the panel. After temperatures ($T_i, T_o$) on both surfaces were consistent with $T$ ($T_i \approx T, T_o \approx T$), keep the temperature for a while (>0.5 h) to meet the experiment state. The judgment criterion was $\Delta T_i \leq 0.5^\circ C, \Delta T_o \leq 0.5^\circ C$.

**Step 3: The measurement of sound pressure level.** In the source room, the loudspeaker was turned on to excite the diffusion sound field, which was monitored via Microphone Array 2 (comprising $k$ microphones, the position sequence is $s_0, s_1, \ldots, s_{k-1}, s_k$). To determine whether the sound pressure was stable, the stability analysis was performed, which is similar to step 1.
For each microphone, mark the time series as $t_0$, $t_1$, $\ldots$, $t_{m-1}$, $t_m$ ($t_{m-1} < t_m$), the SPL measured at $t_m$ was denoted as $SPL_m$. Judgment criterion was

$$\chi^2_m = \chi^2_m - \chi^2_{m-1}, \quad \chi^2_m = \frac{1}{N} \sum_{i=1}^{N} [SPL_{m-1}(f_i) - SPL_m(f_i)]^2$$

(17)

$\chi^2_m$ is the mean square deviation between $SPL_m$ and $SPL_{m-1}$. Once $\chi^2_m \approx 0$, the sound field is considered to be stable. Then, the incident SPL was measured, and the radiated SPL was tested at $d_{op}$.

Figure 9. Measurement process.
Step 4: Analysis of measurement data. Above all, uniformity analysis and repeatability analysis were performed to ensure the reliability of the measured data. The uniformity analysis was used to determine whether the sound field was uniform and it was performed after the sound field was stabilized. The procedure was the same as for the stability analysis. Just convert the time series, $\text{SPL}_m / C_0$ and $m$ to the position series, $\text{SPL}_0$ (SPL measured at $s_0$) and $k$. The repeatability analysis determined whether the experimental results were valid. The procedure was the same as for the stability analysis. Set the sequences of multiple independent STL measurement results as $a_0$, $a_1$, $\ldots$, $a_{p-1}$, $a_p$, and mark the $a_p$-th measurement result as $\text{STL}_{ap}$.

Figure 10. Reverberation chamber sound pressure level at six uniformly distributed spatial measuring points (25°C).

Figure 11. Repeated experiments at $-40^\circ\text{C}$ on June 10, 12, and 13, 2018.

Figure 12. Repeated experiments at $40^\circ\text{C}$ on June 11, 12, and 13, 2018.
Next, repeatability analysis could be done by equation (17). In practice, measured results are usually drawn in one figure and compared directly.

Then, the error analysis was performed to verify the effectiveness of the improved STL experimental method. First, STL was calculated by equation (12). Second, the overall STL $L_T$ was obtained by equation (18). Third, equation (19) was employed to solve the STL range $Range(f_r)$ at $f_r$ (See Reliability Analysis of Measurement Results for detailed examples).

\[
L_T = 10 \log_{10} \sum_{r=1}^{N} 10^{0.1L_{pr}}
\]  

$L_{pr}$ is STL at $r$-th 1/3 octave band.

\[
Range(f_r) = \max\{STL(f_r)\} - \min\{STL(f_r)\}
\]

Max$\{STL(f_r)\}$, Min$\{STL(f_r)\}$ represent the maximum and minimum STL at $f_r$.

### Verification and analysis of experimental results

After the preparations were all completed, STL measurements of the panel under variable temperatures were performed according to Measurement Process. Considering the potential ambient temperature of the panel being in $-25^\circ$C–$30^\circ$C and the temperature simulation capacity of the device, the temperature range of measurement was determined as $-40^\circ$C–$40^\circ$C. The temperature interval was set to $5^\circ$C, the sampling frequency band was 50 Hz–10,000 Hz, and the recording time was 30 s. The maximum background SPL was 44.6 dB.

Table 3. Measurement results of sound transmission loss.

| 1/3 octave (Hz) | STL interval (dB) | Range (dB) | 1/3 octave (Hz) | STL interval (dB) | Range (dB) |
|----------------|------------------|------------|----------------|------------------|------------|
| 50             | [1.636, 13.867]  | 12.23      | 800            | [25.436, 27.586] | 2.15       |
| 63             | [13.617, 22.184] | 8.57       | 1000           | [27.666, 29.810] | 2.14       |
| 80             | [13.418, 20.215] | 6.80       | 1250           | [28.758, 30.001] | 1.24       |
| 100            | [16.562, 20.977] | 4.41       | 2000           | [28.890, 30.407] | 1.52       |
| 125            | [20.716, 23.343] | 2.63       | 2500           | [29.456, 32.283] | 2.83       |
| 160            | [19.013, 20.801] | 1.79       | 3150           | [29.114, 32.517] | 3.40       |
| 200            | [17.847, 24.576] | 6.73       | 4000           | [29.701, 32.251] | 2.55       |
| 250            | [23.408, 26.172] | 2.76       | 5000           | [29.631, 30.819] | 1.19       |
| 315            | [20.356, 25.642] | 5.29       | 6300           | [30.144, 32.446] | 2.30       |
| 400            | [14.381, 19.918] | 5.54       | 8000           | [32.776, 35.953] | 3.18       |
| 500            | [18.804, 20.217] | 1.41       | 1000           | [34.913, 38.139] | 3.23       |
| 630            | [23.110, 24.038] | 0.93       |                |                  |            |

STL: sound transmission loss.
Reliability analysis of measurement results

The reliability of the improved STL experimental technique is discussed first. Figure 10 depicts the results of the uniformity analysis; Figures 11 and 12 show the results of the repeatability analysis, while Figure 13 illustrates the difference between the proposed and standard laboratory methods.

Figure 10 shows that all SPL spectra were consistent with each other, indicating that the diffusion sound field was uniform. SPL $\geq 60$ dB within 50 Hz–100 Hz and SPL $\geq 90$ dB within 100 Hz–10,000 Hz, proving that the SPL met the measurement standard. As shown in Figures 11 and 12, STL results were similar, indicating good repeatability of experiments at $-40^\circ\text{C}$ and $40^\circ\text{C}$. The same conclusion could be obtained at other temperatures within $-40^\circ\text{C}$–$40^\circ\text{C}$, meaning that the repeatability of the experiment was good. The method can also be used to validate the assumption in Measurement Process. When there is a significant deviation in data, devices must be overhauled.

Figure 13 shows that the error between the standard and improved STL experiments was within 50 Hz–100 Hz, which was caused by the environmental simulator device. The reverberation chamber of the device was too small to reach the ideal state in low frequency. The results should be corrected before use. The deviation was small in 125 Hz–10,000 Hz, demonstrating that the results measured via the improved STL technique were accurate and reliable within these bands. To obtain accurate results, equation (20) was given.

$$\varepsilon = STL_{\text{standard}} - STL_{\text{present}}$$

$\varepsilon$ is corrected value, $STL_{\text{present}}$ is STL measured via the improved method, and $STL_{\text{standard}}$ is STL obtained by the standard laboratory measurement. Introducing equation (20) into equation (12), accurate STL expression equation (21) was obtained.
The mentioned methods can be used in the development of acoustic experiments. The analysis of STL at different temperatures

After making sure the measurements are reliable and accurate, the existence of temperature influence on the panel’s STL is confirmed. The range of STL at each center frequency was solved by equation (19) and listed in Table 3.

Three conclusions can be drawn from Table 3: I) Temperature significantly affected the STL of the panel. Once the panel was immersed in different temperature environments, the STL changed. II) STL temperature sensitivity was different at each center frequency. The range at 50 Hz, 63 Hz, 80 Hz, 100 Hz, 200 Hz, 315 Hz, 400 Hz, 3150 Hz, 8000 Hz, and

\[ STL = L_r - L_f + \varepsilon \]  

The mentioned methods can be used in the development of acoustic experiments.
Figure 18. $L_T$ with temperature.

Figure 19. Sound transmission loss measured at $-40^\circ C$, $40^\circ C$, and $0^\circ C$.

Figure 20. Measurement of elastic modulus. (a) $-55^\circ C$ (b) $23^\circ C$ and (c) $71^\circ C$.

Figure 21. Elastic modulus $E_1$. 
10,000 Hz was $>3$ dB, and it was 1–2 dB at others. III) Overall, the panel’s STL was most affected by temperature at low/high frequencies and less in middle frequency. Conclusions I–III) show that STL measurement at room temperature is insufficient for composite structures and it is necessary to study STL at various temperatures. The proposed STL experimental technique is a good choice.

Since Table 3 cannot visually reveal the variation of the panel’s STL with temperature, Figures 14–17 and Appendix A are given. These figures exhibit that temperature had a severe impact on the STL variation trend of the panel, mainly
Figure 26. Sound transmission loss variation with η (η₁ < η₂ < η₃).

Figure 27. Relationship between sound transmission loss and temperature at 3150 Hz.

Figure 28. Relationship between sound transmission loss and temperature at 4000 Hz.

Figure 29. Critical frequency variation with temperature.

Figure 30. Poisson’s ratio variation with temperature.
including monotonicity and fluctuation. The monotonically increasing trend appeared at 2500 Hz (Figure 16), 3150 Hz (Figure 27), and 4000 Hz (Figure 28); the monotonically decreasing trend appeared at 6300 Hz (Figure 17), 8000 Hz (Figure 31), and 10,000 Hz (Figure 32); fluctuation trend appeared at other center frequencies. These trends suggest that the acoustic design of CFRP structures at room temperature may fail. A solution is: I) Finding out the temperature $T_{\text{min}}$ where the minimum STL is; II) Noise reduction scheme design at $T_{\text{min}}$.

Due to STL variation trends being different at different center frequencies, the overall STL ($L_T$) was applied to describe the temperature effect on the panel’s STL (Figure 18).

Figure 18 shows that $L_T$ fluctuated with temperature, temperatures of $-15^\circ\text{C}$ and $15^\circ\text{C}$ were the extreme points of change. $L_T$ increased within $-40^\circ\text{C}–15^\circ\text{C}$ and $15^\circ\text{C}–40^\circ\text{C}$ and decreased within $-15^\circ\text{C}–15^\circ\text{C}$. The smallest $L_T$ appeared at $-40^\circ\text{C}$ and $15^\circ\text{C}$. The results have application in the noise reduction design of composite structures. Noise reduction schemes, for example, should be designed at $-40^\circ\text{C}$, $15^\circ\text{C}$ and redesigned when the temperature rises above $40^\circ\text{C}$ or falls below $-40^\circ\text{C}$. Given the laboratory’s limited temperature simulation capability ($-55^\circ\text{C}–90^\circ\text{C}$), theoretical modeling or simulation analysis should be used if the temperature simulation capability is insufficient.
Discussion of sound transmission loss variation

STL variation in *The Analysis of STL at Different Temperatures* was essentially caused by the change of damping loss factor and elastic modulus, with temperature. To illustrate the mechanism, measurement results at 40°C, 0°C, and −40°C were employed, as shown in Figure 19 and Table 4.

Figure 19 and Table 4 show that temperature change led to the redistribution of controlled regions. When the temperature dropped from 40°C to −40°C, the resonance-controlled region expanded to the high frequency, while the coincidence-controlled and damping-controlled regions had an opposite change. The phenomenon was directly caused by the change of STL peak/dip frequencies with temperature. The basic reason is discussed later.

Figure 19 exhibits, in the resonance-controlled region, the maximum STL dip frequency decreased with temperature. Therefore, when the temperature dropped, the resonance-controlled region expanded to a high frequency. The problem was caused by the change in composite stiffness. In Refs. 20, 21 and 37, it has been proved that the increased temperature results in decreased composite stiffness, the decreased stiffness produces reduced resonance frequencies, and the reduced resonance frequencies induce the decreasing of STL peak/dip frequencies. Hereby, the reason is verified via experiments shown in Figure 20.

Considering that elastic modulus is the microscopic reflection of stiffness, the problem is to verify that the elastic modulus of composites would change with temperature. Thus, the mechanical properties of the panel’s skin used in this study were measured at −55°C, 23°C, and 71°C. Results are plotted in Figures 21 and 22. Obviously, the elastic modulus decreased with temperature, indicating the correctness of the above analysis. Changes in elastic modulus are detrimental to composite acoustic design and may fail noise reduction schemes. An adiabatic design of composite structures should be developed to overcome the failure, bionics35 is a potential option.

But it seems different from the conclusions obtained in Refs. 18, 19 and 22 that peak/dip frequencies of the panel’s STL did not present a simple decline with temperature. As shown in Figure 19 and Table 5, there were two peak frequencies and two dip frequencies within 100 Hz–630 Hz. The first peak frequency appeared at 125 Hz, which did not change with temperature; the first dip frequency was 200 Hz at 40°C, 0°C, and became 160 Hz at −40°C. These phenomena appear to be distinct from those described in Refs. 18, 19 and 22. The data processing method is to blame for these phenomena. Measured data is difficult to analyze because the STL spectra of the panel are not smooth curves. To make the analysis easier, data is filtered by 1/3 octave. Thus, the results in Figure 19 and Table 5 represent the STL within each 1/3 octave band rather than the STL at each frequency point. As a result, the illusion is formed. According to the findings, structural-acoustic design should be done for the frequency band rather than the frequency points, thereby improving the noise reduction effect.

It can also be found that, when STL peak/dip frequencies did not change with temperature, temperature increase caused a decrease in STL peak value and an increase in STL dip value, in Figure 19 and Table 5. To clearly describe this phenomenon, Figure 23 was given. At 125 Hz (a peak frequency), STL value declined with temperature; conversely, STL value rose at 160 Hz (a dip frequency). The phenomenon was caused by η, the damping loss factor.

The panel was made from CFRP, so its glass transition temperature $T_g$ was ≤90°C, which was documented in Ref. 37 (Figure 24). And η increased with temperature when the temperature is below $T_g$, which had been verified (Figure 25). Meanwhile, considering that η increased make STL peak values decrease and STL dip values rise (Figure 26), the phenomenon in Figure 23 appeared. Further, it explains why the STL of the panel decreased with temperature (Figure 14) within −40°C–−15°C.

In Figure 14, when the temperature continued to increase, the stiffness reduced, then STL peak/dip frequency changed. While η increased with temperature. As a result of the common change of both η and STL peak/dip frequency, STL fluctuation was produced. Changes in Appendix A can also be explained. The fluctuation indicates that the best noise reduction measures should be designed at the temperature where the STL is the lowest.

With further measurements in the coincidence-controlled region, Figures 27 and 28 were plotted. They show that the panel’s STL increased with temperature at 3150 Hz, 4000 Hz, which was caused by η too. Because STL increased with η in the coincidence-controlled region and the panel’s η increased with temperature37. The finding suggests that in the coincidence region, the STL of CFRP panels could be improved by increasing the temperature.

After that, adding data in Figure 19 formed Figure 29. It can be seen that critical frequency $f_c$ increased with temperature, which was caused by elastic modulus reduction as the temperature rose (Figures 21 and 22). $f_c$ is exhibited in equation (22).

$$f_c = \frac{c^2}{2\pi h} \sqrt{\frac{12\rho_m(1 - \nu^2)}{E}}$$  \hspace{1cm} (22)$$

where $h$ represents the thickness, $\rho_m$ describes the surface density, and $E$ is elastic modulus.
Considering \( v \) was less affected by the temperature (Figure 30), \( \rho_m \) is constant, \( h \) is constant when the effect of thermal expansion and contraction is ignored, and \( f_c \) would be proportional to \( c^2 \sqrt{1/E} \). As \( c \) and \( \sqrt{1/E} \) increase with temperature, so does \( f_c \). Due to \( f_c \) increases, the whole damping-controlled region of the panel moves towards the high-frequency band, resulting in decreased STL at each center frequency in the damping-controlled region (Figures 31 and 32). This indicates that temperature rise in the damping-controlled region is detrimental to the acoustic performance of CFRP structures and should be avoided.

So far, the STL variation mechanism of CFRP structures with temperature has been explained. Unfortunately, STL variable characteristics of the panel with temperature in the stiffness-controlled region were not observed. This was caused by the panel’s first-order frequency. To validate the reason, an assumption was made, that the first-order frequency was less than 50 Hz, exceeding the lower frequency bound of STL measurements. Then, a modal test was performed. Figure 33 and Table 6 show the current status of the test and result. The result supports the assumption. We can infer that the panel’s STL in the stiffness-controlled region was decreased with temperature. Because in the stiffness-controlled region, STL increased with stiffness\(^{26}\) and the panel’s stiffness decreased with temperature according to Figures 21 and 22.

Considering the discussion above, the thermal characteristics of \( E \) and \( \eta \) in the acoustic design of composite structures should be focused upon. The relationship between temperature, thermomechanical parameters \((E, \eta)\), and STL can be used in composite structures’ noise control. By temperature control to change \( E \) to redistribute controlled regions, the structural sound insulation capacity can be enhanced in some local frequency bands. By temperature control to change \( \eta \) to improve structural STL in resonance, coincidence, and damping-controlled regions. The relationship can also be used for acoustic metamaterial design.

**Conclusion**

Herein, a novel STL experimental technique was demonstrated. The effect of temperature on the vibroacoustic performance of composite structures was revealed, and the relationship between temperature, thermomechanical parameters, and STL was elucidated. Accordingly, the following conclusions were obtained:

1. The improved STL experimental technique provided a new way for composite structures’ acoustic analysis and was complementary to theoretical modeling and simulation analysis.
2. Temperature had a significant impact on composite structures’ acoustic behavior. The influence was realized by changing temperature-dependent parameters \((E, \eta)\). It can be inferred that this phenomenon is common in composite structures.
3. Findings in this paper can be used to guide the acoustic design of composite structures in vehicle manufacturing, shipping industry, environmental protection, etc.

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**Data availability**

The data used to support the findings of this study are included in the article.

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**Appendix A**

STL variations of the panel with the temperature at the other center frequencies are presented as follows:

(a) Relationship between STL and temperature at 50 Hz. (b) Relationship between STL and temperature at 63 Hz. (c) Relationship between STL and temperature at 80 Hz. (d) Relationship between STL and temperature at 100 Hz. (e) Relationship between STL and temperature at 160 Hz. (f) Relationship between STL and temperature at 200 Hz. (g) Relationship between STL and temperature at 250 Hz. (h) Relationship between STL and temperature at 400 Hz. (i) Relationship between STL and temperature at 500 Hz. (j) Relationship between STL and temperature at 600 Hz. (k) Relationship between STL and temperature at 800 Hz. (l) Relationship between STL and temperature at 1000 Hz. (m) Relationship between STL and temperature at 1250 Hz. (n) Relationship between STL and temperature at 1600 Hz. (o) Relationship between STL and temperature at 2000 Hz. (p) Relationship between STL and temperature at 5000 Hz.
(a) Relationship between STL and temperature at 50 Hz

(b) Relationship between STL and temperature at 63 Hz

(c) Relationship between STL and temperature at 80 Hz

(d) Relationship between STL and temperature at 100 Hz

(e) Relationship between STL and temperature at 160 Hz

(f) Relationship between STL and temperature at 200 Hz

(g) Relationship between STL and temperature at 250 Hz

(h) Relationship between STL and temperature at 400 Hz
(i) Relationship between STL and temperature at 500 Hz

(ii) Relationship between STL and temperature at 630 Hz

(iii) Relationship between STL and temperature at 800 Hz

(iv) Relationship between STL and temperature at 1000 Hz

(v) Relationship between STL and temperature at 1250 Hz

(vi) Relationship between STL and temperature at 1600 Hz

(vii) Relationship between STL and temperature at 2000 Hz

(viii) Relationship between STL and temperature at 5000 Hz