Transmission loss analysis of acoustic metamaterial using finite element models

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Abstract. FE models used for measurement of transmission loss (size 300mm×300mm) and impedance tube were created by using an acoustic metamaterial in which films were laminated on top and bottom of polypropylene processed into a honeycomb structure. Numerical calculation of sound transmission loss, comparison with experimental results, and various parameter studies were conducted. In the calculation of the transmission loss of the FE model of the impedance tube, it was possible to obtain a value close to the experimental result by changing the value of the spring stiffness which is the boundary condition. The attenuation of the boundary spring has no effect on the transmission loss of FE model. The hardness of the spring affects the low frequency stiffness line and the first dip (about 100Hz). The first dip is the effect of the vibration mode in which the entire honeycomb deforms out of plane.

1. Introduction

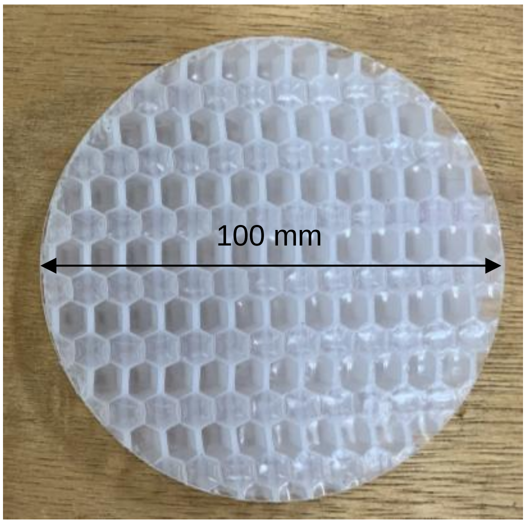
In recent years, the comfort of automobiles has been emphasized, and the noise inside the automobile has been reduced from the design concept stage. In addition, as the number of electric vehicles and hybrid vehicles increases and engine noise decreases, wind noise and tire noise become noticeable, and countermeasures are required. There is a limit to the sound source measures for wind noise such as door mirrors, pillar shapes, and vehicle appearance, and noise measures for tires alone, so it is important to take measures on the vehicle body side in consideration of cost and weight. Nakayama et al. conducted research to improve sound insulation performance using resonant acoustic metamaterials using silicon rubber and metal [1]. In this study, we considered using a material with a new structure for the trim of automobiles to reduce the noise inside the car. Specifically, one PP (polypropylene) sheet is folded to create a repeating structure (metamaterial) of a hexagonal cross-sectional honeycomb. By adhering a thin film made of PP (polypropylene) or PE (polyester) to it, sound energy is absorbed and blocked by out-of-plane resonance of the film. Regarding the test piece of this structure, the authors found that two sound absorption peaks occur due to membrane vibration and Helmholtz resonance, and that the membrane material (Young's modulus, density, thickness), hole diameter, and honeycomb cell size Published research on the correlation of sound absorption performance [2]. This time, we created a model of acoustic metamaterial using the measurement result of transmission loss by the acoustic tube and reverberation room method, and the finite element method, and changed the sound insulation characteristics when the structure and material data were changed by numerical calculation [3]. The result of the analysis is reported.

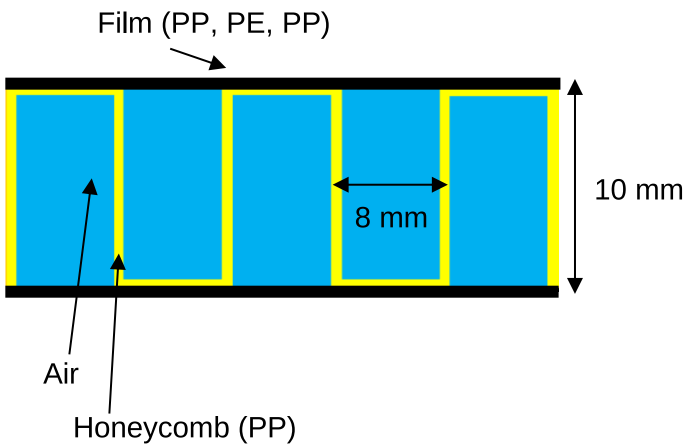
2. Test piece measurement result

Figure 1 shows the test piece of the metamaterial used in the acoustic tube measurement this time. A 100 mm diameter tube was prepared to match the sound tube (thick tube). The core size of the honeycomb is about 8 mm and the height is about 10mm. The top and bottom of the PP honeycomb were bonded with a three-layer film of PP, PE, and PP.

Since the diameter of the honeycomb is a structure in which one PP is folded, the surfaces of the PP are alternately bonded to the film (see the cross-sectional view in Figure 1). Figure 2 shows the transmission loss measuring device consisting of the reverberation room and the anechoic room used in this measurement. Sound was output from the reverberation room side, and 9 points were measured with the probe on the anechoic room side to obtain the sound transmission loss. The size of the sample is 300mm × 300mm. Figure 3 shows a comparison of the measurement results of the transmission loss of the acoustic tube (diameter 100mm) and the sample of 300 mm × 300 mm.

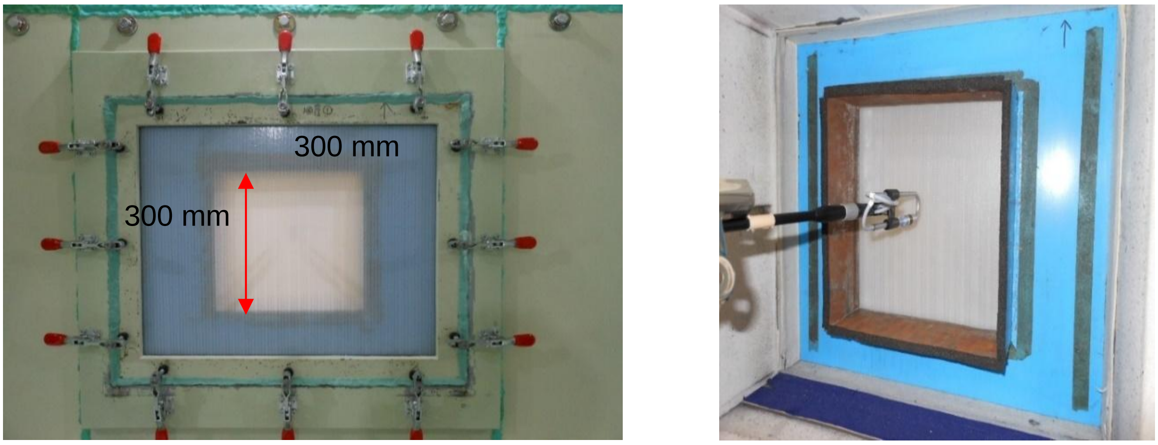
In the measurement result of 300 mm × 300 mm (red line in Fig. 3), there was an initial drop at about 100 Hz (black circle in Fig. 3). By the experimental mode analysis conducted separately, it was confirmed that the entire honeycomb plate is in a vibration mode that deforms out of the plane. The transmission loss measurement result by the acoustic tube (blue line in the figure) shows that there is an initial dip at about 1000 Hz (red circle in the figure), and it was confirmed that the value of the transmission loss until the first dip differs greatly depending on the size of the sample.





(a) Test piece for measurement (b) Cross section of acoustic metamaterial

Fig. 1. Test piece (Acoustic meta-material). A PP sheet is folded to create a honeycomb repeating structure (metamaterial) with a hexagonal cross-section. A thin film made of PP or PE was glued there.



(a) Sound source side (reverberation chamber) (b) Microphone side (anechoic chamber)

Fig. 2. Experimental setup of transmission loss. A transmission loss measurement device consisting of a reverberation chamber and an anechoic chamber is shown. Sound was emitted from the reverberant chamber side, and measurements were taken at 9 points with a probe on the anechoic chamber side to determine the sound transmission loss. The sample size is 300 mm × 300 mm.

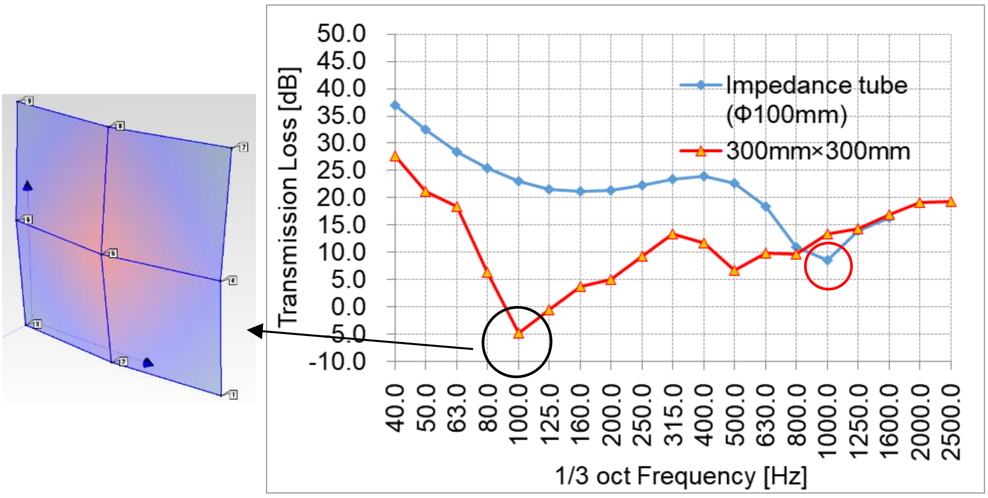


Fig. 3. Experimental results of transmission loss.

3. Calculation result

3.1 Calculation result of acoustic tube

Figure 4 shows the FE model (PP part only) used in this calculation. The upper and lower films and the air inside the honeycomb are not shown for easy viewing. In addition, a spring was set on the side surface as a boundary condition. Figure 5 shows a comparison between the measurement result of the transmission loss by the acoustic tube and the calculation result of the transmission loss of the thick tube FE model. By changing the boundary conditions such as spring hardness and film damping, values close to the experimental results could be obtained.

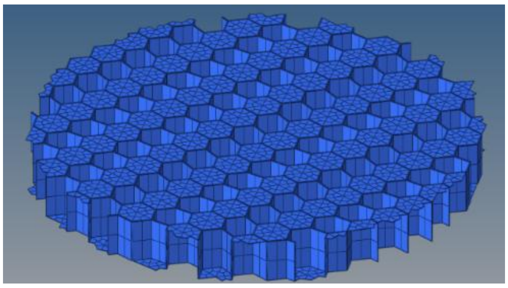


Fig. 4. FE model.

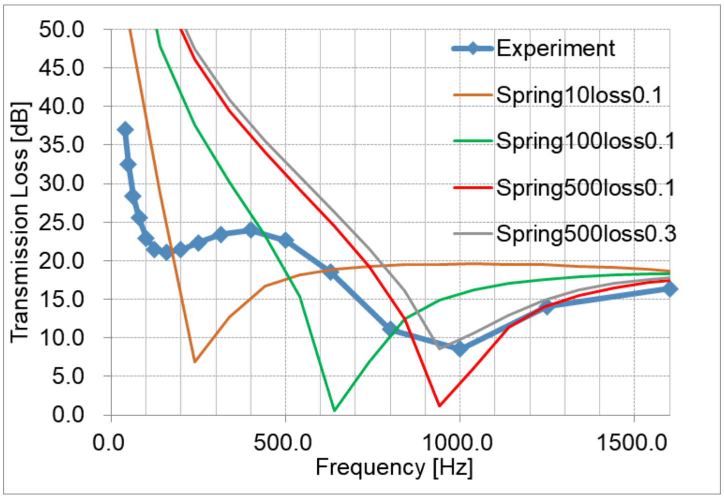


Fig. 5. Comparison between experimental results and calculated results (Impedance tube).

3.2 Calculation result of 300mm × 300mm model

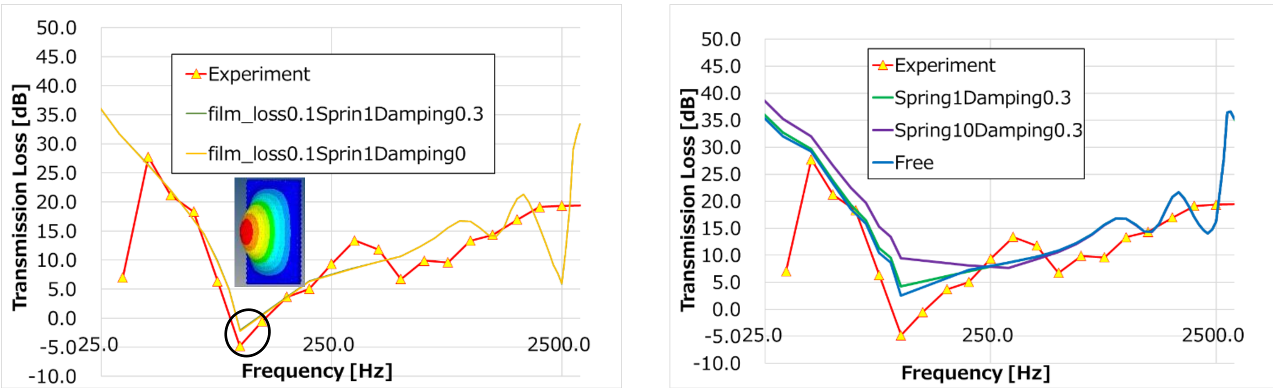
Figures 6 to 10 show a comparison of the experimental results and calculation results of a 300 mm × 300 mm sample. Figure 6, the left figure shows the case where the damping value of the spring used under the boundary condition is changed, and the right figure shows the case where the spring coefficient of the boundary spring is changed. Boundary spring damping had no effect. The hardness of the spring affected the low frequency stiffness line and the initial dip (about 100 Hz: black circle in the figure). The first dip was due to the vibration mode in which the entire honeycomb was deformed out of plane, which was in agreement with the experimental mode analysis results in Fig. 3. There was no effect of the spring in the frequency range higher than the dip frequency. In this calculation, the boundary spring has a rigidity of 1.0 [N/m] and a damping value of 0.3 so as to be close to the experimental results.

Figure 7, the left figure shows a comparison between the calculation results and the experimental results in which the attenuation of PP (honeycomb material) is changed. It was confirmed that increasing the attenuation value increases the transmission loss in all frequency ranges and has a large effect. In reality, it is considered to be related to the adhesion between the film and the honeycomb, and the performance of transmission loss may change depending on the bonding method and adhesive. The figure on the right shows a comparison between the calculation results and the experimental results in which the attenuation value of the film is changed. It affects the first dip (about 100 Hz) and the next dip (about 2300 Hz). The drop of about 2300 Hz is due to the film resonance of the film. In this calculation, the PP attenuation was 0.01 and the film attenuation was 0.3 as the initials in the following calculations so as to be close to the experimental results.

Figure 8, the left figure shows the calculation results of changing the Young ratio of the film. Increasing the Young's modulus of the film increases both the frequency and value of the initial dip (red circle in the figure). There was almost no change in the frequency range higher than the dip frequency. The figure on the right shows the calculation results of changing the film density. When the film density is increased, the frequency of the first dip does not change much, but the dip value decreases (red circle in the figure). In the frequency range higher than the frequency of the first dip, the transmission loss was roughly according to the mass law of the film.

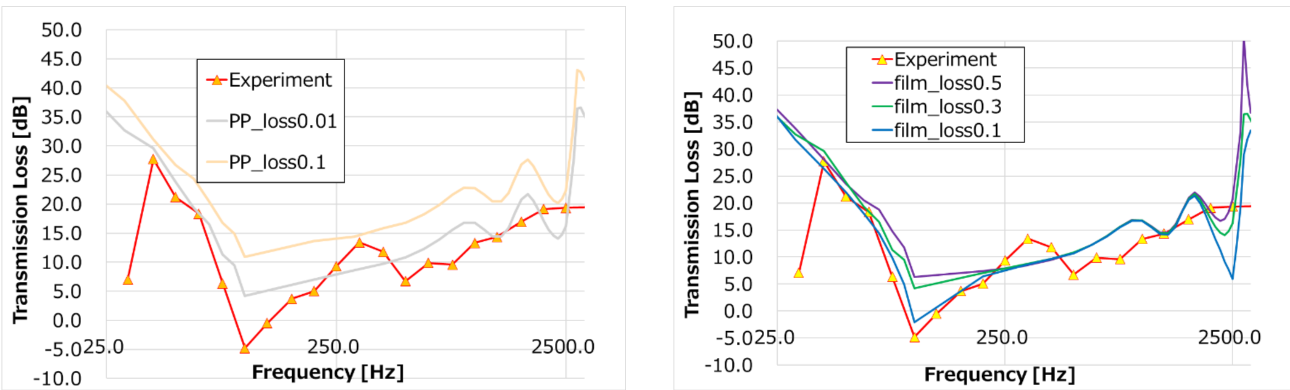
The left figure of Figure 9 shows the calculation results of changing the Young's modulus of PP (honeycomb part). When the Young's modulus of the honeycomb is increased, the value of the initial dip decreases and the value of the dip of about 2300 Hz increases. There was almost no change in other frequency ranges. The figure on the right shows the calculation results with the PP density changed. When the density of PP was increased, both the frequency and value of the first dip became smaller, and in the higher frequency range, the transmission loss was roughly according to the mass law of the film.

The left figure of Figure 10 shows the calculation results of changing the height of the honeycomb. The higher the value, the larger the frequency and value of the first dip (red circle in the figure). The figure on the right shows the calculation results of changing the core size of the honeycomb. As the core size increases, the frequency of the drop in transmission loss increases and the value of the drop decreases (red circle in the figure). In the frequency range higher than the dip frequency, the transmission loss decreased as the core size increased.



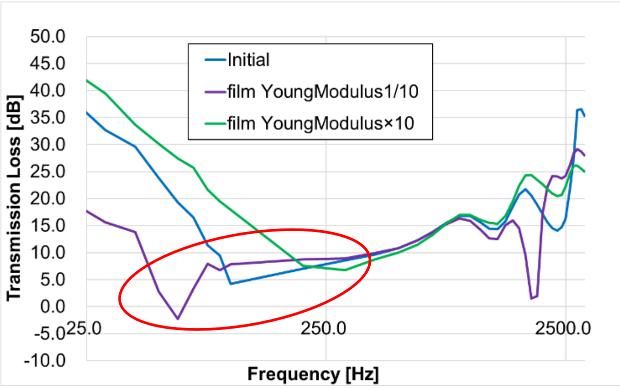
(a) Changed loss factor of boundary condition (b) Changed stiffness of boundary condition

Fig. 6. Comparison between experimental results and calculated results.

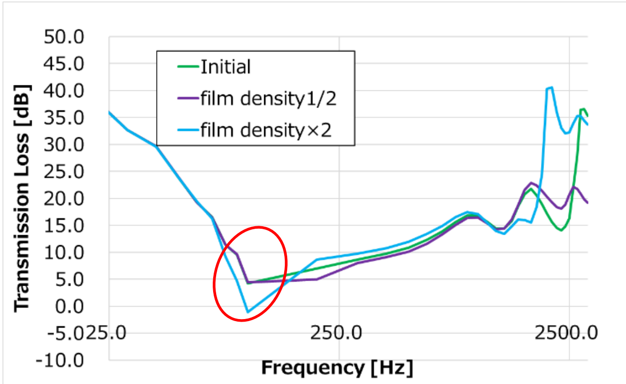


(a) Changed loss factor of PP (b) Changed loss factor of film

Fig. 7. Comparison between experimental results and calculated results.

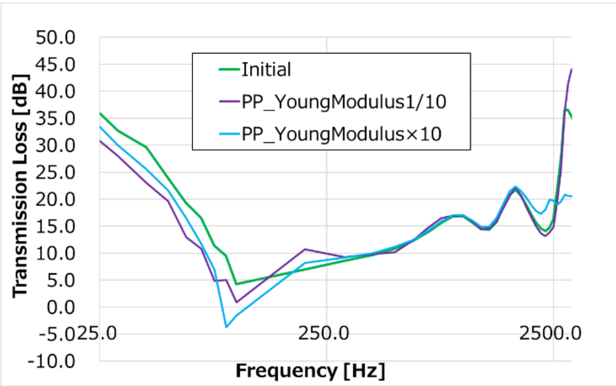


(a) Changed Young modulus of film

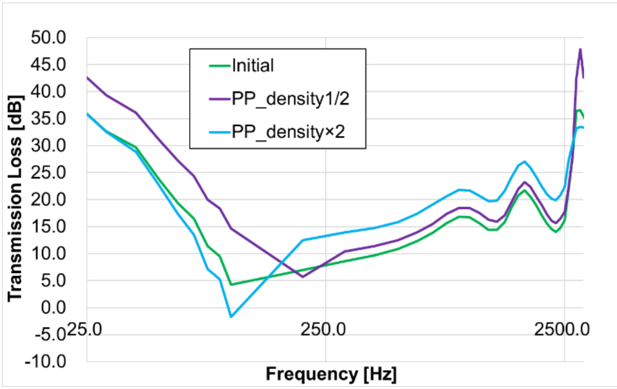


(b) Changed density of film

Fig. 8. Calculation results for effect of film material date.

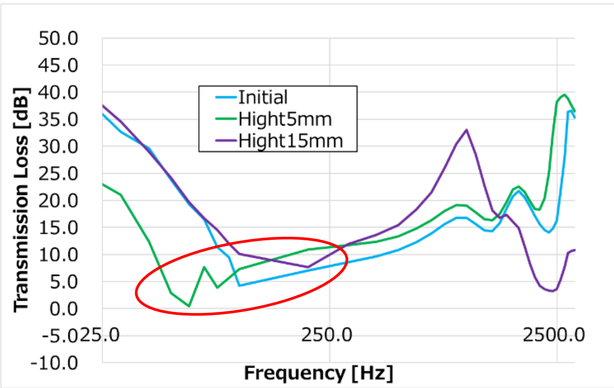


(a) Changed Young modulus of PP

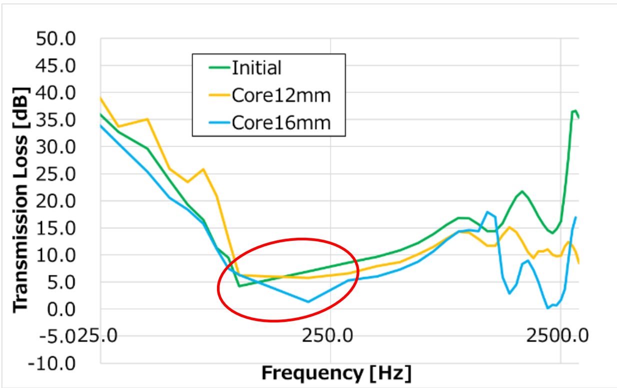


(b) Changed density of PP

Fig. 9. Calculation results for effect of honeycomb material date.



(a) Changed honeycomb height



(b) Changed core size for honeycomb

Fig. 10. Calculation results for effect of honeycomb size.

4. Conclusion

Using an acoustic metamaterial in which PP is processed into a honeycomb structure and films are pasted on the top and bottom, an acoustic tube (thick tube) and a 300mm × 300mm FE model used in the transmission loss experiment were created, and the numerical value of the acoustic transmission loss was created. The following findings were obtained by comparing with the calculation and experimental results.

- In the calculation of the transmission loss of the FE model of the acoustic tube (thick tube), values close to the experimental results could be obtained by changing the spring hardness and film attenuation, which are the boundary conditions.
- The damping of the boundary spring has no effect on the transmission loss of the 300 mm×300 mm FE model. The hardness of the spring affects the low frequency stiffness line and the initial dip (about 100 Hz). The first dip is due to the vibration mode in which the entire honeycomb is deformed out of plane. There is no effect in the frequency range higher than the dip frequency.
- Attenuation of PP (honeycomb material) has a large effect. When the value was increased, it increased in all frequency ranges. Film attenuation affects the first dip (about 100 Hz) and the second dip (about 2300 Hz). The drop of about 2300 Hz is due to the film resonance of the film.
- When the Young's modulus of the film is increased, both the frequency and value of the initial dip increase. There was almost no change in the frequency range higher than the dip frequency. When the film density is increased, the frequency of the first dip does not change much, but the dip value decreases. In the frequency range higher than the frequency of the first dip, the transmission loss was roughly according to the mass law of the film.
- When the Young's modulus of PP is increased, the value of the initial dip decreases and the value of the dip of about 2300 Hz increases. There was almost no change in other frequency ranges. When the density of PP was increased, both the frequency and value of the first dip became smaller, and in the higher frequency range, the transmission loss was roughly according to the mass law of the film.
- When the height of the honeycomb is increased, both the frequency and value of the first dip increase. As the core size increases, the frequency of the drop in transmission loss increases and the value of the drop decreases. In the frequency range higher than the dip frequency, the transmission loss decreased as the core size increased.

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