1P2-9

# Attenuation characteristics of the leaky T(0,1) mode guided wave propagating in piping coated with anticorrosion grease

防食材が塗布埋設された配管を伝搬する漏洩 T(0,1) mode ガイド波の減衰特性

Hideo Nishino[1†], Kohei Tateishi[1], Masashi Ishikawa[1], Takashi Furukawa[2], and Motoki Goka[3] ([1]Tokushima Univ.; [2]JAPEIC; [3]Mitsubishi Chemical)
西野秀郎 [1†], 立石浩平 [1], 石川真志 [1], 古川敬 [2], 五家基樹 [3] ([1]徳大院, [2]発電技検, [3]三菱ケミカル)

## 1. Introduction

Guided waves have been anticipated for the health monitoring of piping in various kinds of industrial fields because of their capabilities for the long range inspection. However, in the buried pipe, the high attenuation coefficient is the largest obstacle to apply the guided wave inspection to it, even though there are many demands for the buried pipe inspections.

Recently, the petrolutum anticorrosion grease (PAG), instead of the bitumen, has been most widely used for the coating material on outer surface of piping as a preproccessing before being buried in sand or soil. It was confirmed in our experiments [1] that the attenuation coefficients of the piping coated with the PAG were extremely large in comparison to those of the piping buried directly in sand or soil [2].

The leaky T(0,1) mode guided wave (LTGW) propagates along axial direction with leaking the bulk shear wave into the adjacent surrounding material (e.g. sand, soil, or PAG). In this paper, first, the theoretical formula of the LGW was expressed. Several theoretical outcomes, especially in the dependence on the shear wave velocity of the surrounding material, were shown. Secondly, experimental measurements of the attenuation coefficients were shown along with the theoretical values. Preliminary experimental results have shown [1] that the attenuation coefficients have become small when the temperature of the PAG has risen. A reason of this temperature dependence was discussed.

## 2. Leaky T(0,1) mode guided wave (LTGW)

The fomula of the LTGW is as follows:

$$\left.\begin{array}{l}\dfrac{\mu_{petro}}{\mu_{steel}}\dfrac{\beta}{\alpha}\dfrac{H_1^{(1)}(\beta r_2)}{H_0^{(1)}(\beta r_2)}\left\{J_0(\alpha r_2)Y_1(\alpha r_1)-J_1(\alpha r_1)Y_0(\alpha r_2)\right\}\\ \qquad +\left\{J_1(\alpha r_1)Y_1(\alpha r_2)-J_1(\alpha r_2)Y_1(\alpha r_1)\right\}=0\\ \qquad \alpha^2=k_{petro}^2-k^2,\quad \beta^2=k_{steel}^2-k^2\end{array}\right\}, \qquad (1)$$

where, $\mu_{petro}$, $\mu_{steel}$, $k_{petro}$, $k_{steel}$, $r_1$, and $r_2$ are bulk shear moduli of the PAG and steel pipe, shear wavenumbers of the PAG and steel pipe, and outer and inner radii of the steel pipe, respectively. $H$, $J$, and $Y$ are Hankel, Bessel, and Neumann functions, respectively.

**Figure 1** shows the theoretical relation between the attenuation coefficient and the shear wave velocity of the surrounding material. The attenuation coefficient takes small with the large shear wave velocity. It was confirmed theoretically that the attenuation takes small when the pipe wall becomes thick or the diameter becomes large.

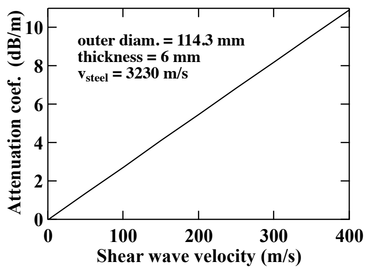



Fig. 1 Attenuation coef. vs. shear wave velocity. (Theoretical)

## 3. Experiments

114.2-mm-outer-diameter and 4.5, 4.9, and 6.0-mm-thick steel pipes were used for the attenuation measurements. The experimental setup was shown in **Fig. 2**. The PAG was coated on the left side surfaces of the pipes. The frequencies were set to be 30, 40, and 50 kHz. The attenuations were measured under five different environmental temperatures, 20, 25, 30, 35, and 40˚C. The viscosity of the PAG changes drastically with temperature, which was fairly hard at 20˚C and was fairly smooth at 40˚C. This means that the shear modulus also changes drastically with

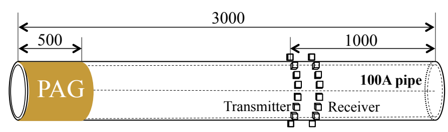


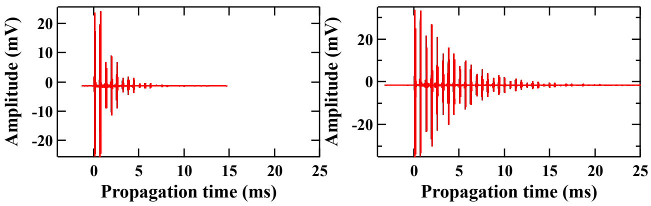

Fig. 2 Setup for attenuation measurement.

hidero.nishino@tokushima-u.ac.jp

temperature.

## 4. Results

**Figures 3(a)** and **3(b)** show the 40 kHz time domain signals regarding the 4.5-mm-thick pipe for temperatures 20˚C and 40˚C, respectively. In both cases, the multiple reflections at the both end of the pipe could be observed. Because of the number of the multiple reflections, it was confirmed clearly that the attenuation coefficient at 20˚C is much larger than that at 40˚C. It must be one of the clear evidences for the temperature dependence of the attenuation coefficient. In the previous chapter, it was shown qualitatively that the bulk shear modulus decreased with increasing the temperature, and was also shown theoretically that the attenuation coefficient increased with increasing the bulk shear wave velocity (or bulk shear modulus). Therefore, the attenuation coefficient must be dependent on the bulk shear wave velocity and it increases with increasing the bulk shear wave velocity.




(a) 20˚C (b) 40˚C

Fig. 3 Multi-reflected signals at both pipe ends.

**Figure 4** summarizes the attenuation coefficients regarding 40 kHz as a function of the temperature. It was clearly shown that the attenuation coefficient decreased when the temperature increased. It was also shown that the attenuation coefficient decreases monotonically with increasing the wall thickness. These experimental results underpin the theoretical outcomes deduced from eq. (1).

The Attenuation coefficient (40 kHz) as a function of the wall thickness regarding all the temperatures is shown in **Fig. 5**. It can be clearly confirmed that the attenuation decreases with increasing both the temperature and the wall thickness. The five solid lines in Fig. 5 indicate the theoretical relations corresponding to the five temperature groups, respectively. The five theoretical relations were obtained by calculating separately with the bulk shear wave velocities, 276, 220, 163, 116, and 91 m/s, respectively. The shear wave velocities used in the calculations were decided so as to take the smallest least-square difference between the theoretical calculations and the three experimental results regarding the same temperature group. It is much difficult to measure the temperature variation of the shear wave velocities (or the bulk shear moduli) of the viscous material like PAG and those are actually unknown. However, the theoretical behavior agreed relatively well with the experimental attenuations regarding the three wall thicknesses in every five temperatures (Fig. 5).

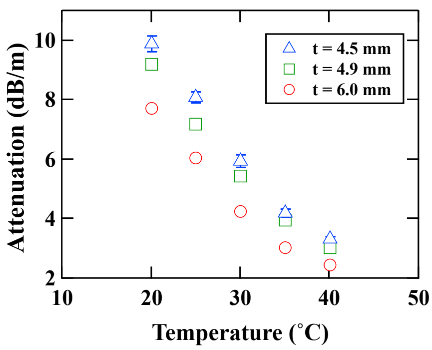



Fig. 4 Attenuation coefficient of the LTGW buried in PAG as a function of temperature at 40 kHz.

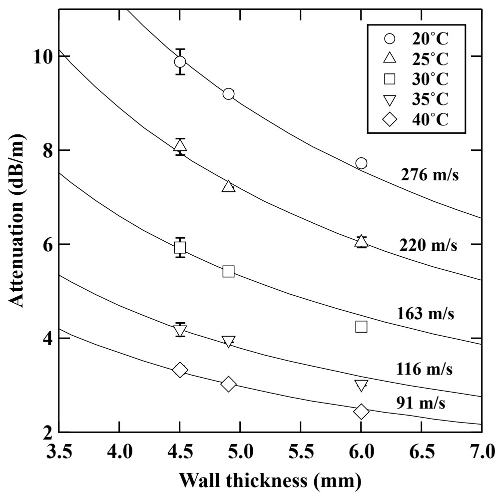



Fig. 5 Attenuation coefficient vs. wall thickness of pipe (outer diam. = 114.3 mm, f = 40 kHz).

## 5. Conclusion

In this paper, the attenuation characteristics of the leaky T(0,1) mode guided waves (LTGW) propagating in the steel pipe buried in the petrolatum anticorrosion grease (PAG) were shown theoretically and experimentally. The theory of the LTGW explained well about the attenuation characteristics. The attenuation coefficient changed monotonically with the bulk shear modulus that was due to change with the temperature.

## References

1. M. Goka, I. Miura, H. Nishino, T. Furukawa, T. Yamamoto, M. Sotowa, H. Nagata, Y. Hattori, and K. Asami: The 14th Symp. on Eval. and Diagn. JSME (2015) 21-25, [in Japanese].
2. E. Leinov, P. Cawley, and M. J. S. Lowe: Rev. QNDE **33A** (2014) 271-278.