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Propagation properties of longitudinal surface acoustic waves (creeping waves) on the cylindrical convex surface

S. Sajauskas, Z. Navickas, D. Karalienė

Department of Electronics Engineering, Kaunas University of Technology
Studentų st. 50, 51368 Kaunas, LITHUANIA, Phone +370 37 435431.
E-mail: stanislovas.sajauskas@ktu.lt, zenonas.navickas@ktu.lt, dovile.karaliene@stud.ktu.lt

Abstract

The properties of longitudinal surface acoustic waves (LSAW) (creeping waves) when they are propagating on the cylindrical convex surface are experimentally analyzed in this research. The analysis was done with the physical seismic shock wave model from duralumin. It was experimentally observed that LSAW are the fastest propagated acoustic waves with the speed and especially strength increasing when they are propagating on the cylindrical convex surface. LSAW are the specific whispering gallery effect manifestation form in the solid.

Keywords: ultrasonic non-destructive testing, surface waves, creeping waves, whispering gallery effect

Introduction

Specific propagation properties of the longitudinal surface acoustic waves (LSAW) [1-3] give new use opportunities in ultrasonic non-destructive testing [4]. On the other hand, they have much bigger natural attenuation in comparison with Rayleigh waves. So this property restricts their ability for testing sound-absorbent materials objects (e.g., metal alloy with the polycrystalline structure). It is conditioned by a weak interaction between LSAW and flat surface as a maximum of the acoustic energy travels by LSAW away from the surface.

This research deals with the experimental investigation of LSAW propagation on the cylindrical convex surface in order to find the character and quantitative relationships of cylindrical surface and wave propagation. The parameters under analysis were: phase velocity of LSAW propagation on cylindrical convex surface and variation dependences of signal amplitude and testing surface curvature radius *R*. Accurate digital technique and discrete signal processing were used to increase measurement accuracy and reliability.

Theoretical research

Longitudinal surface acoustic waves (LSAW, creeping waves) are a new surface wave type. They have a property to propagate by phase velocity which is close to bulk longitudinal wave velocity. It is because LSAW oscillatory tangential component is exceeding the normal one. Through this property LSAW first propagates into destruction place after the earthquake. Other important property of LSAW is the propagation on pre-surface layer. Unlike the Rayleigh waves, wave's energy peak is not on the surface but in the depth that is approximately equal to the wavelength λ_{LSAW}. For this reason, the surface structure does not prevent their propagation. LSAW are propagating on the rough and threaded surface and these waves are not influenced by liquid on the surface. These are important factors of seismic waves propagation on rough Earth surface and ocean floor.

At the same time it was found that LSAW maximum energy depth is gradually moving away from the surface (Fig. 1) owing to interaction with surface and diffraction when they propagate. It is the reason of enlarged wave decrement when LSAW propagate on the smooth surface.

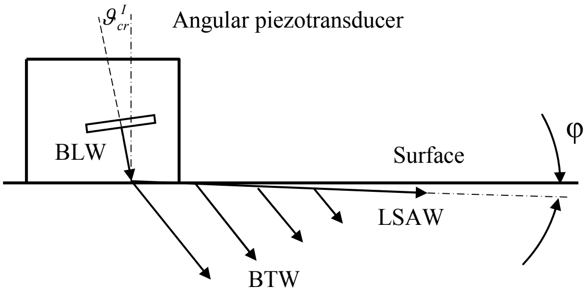


Fig. 1. **LSAW excitation with angular transducer schema**

On a flat surface LSAW are usually excited by angular method. For this purpose a variable-angular transducer oriented for the first critical angle ϑ^I_{kr} is used. These waves may be excited by a local method too. Using this method, a solid surface point is affected e.g. thermo-impulse caused by a pulsed laser [3] or by seismic shock in the Earth. The other types of acoustic waves, such as bulk longitudinal waves (BLW), bulk transversal waves (BTW), and transversal surface (Rayleigh) waves are excited using these methods also.

It is very important task to investigate the surface curvature influence on LSAW propagation, because the Earth surface is spherical and some products (e.g., railway rolling stock) are cylindrical too. In this research the propagation of LSAW on the cylindrical convex surface will be analyzed also. LSAW is continually "approaching" by digressive LSAW propagating on this surface (Fig. 2). By this reason the interaction between the waves and the surface is increasing permanently. So, as it was found at [4], LSAW phase velocity gets particular change *Δc* LSAW which depends on the Poisson's ratio μ and the cylindrical convex surface curvature radius R ratio with the wavelength λ LSAW [3]:

$$c^{+c}_{LSAW} = c_{LSAW} + \Delta c^{+c}_{LSAW}\left(\mu \frac{R}{\lambda_{LSAW}}\right) \qquad (1)$$

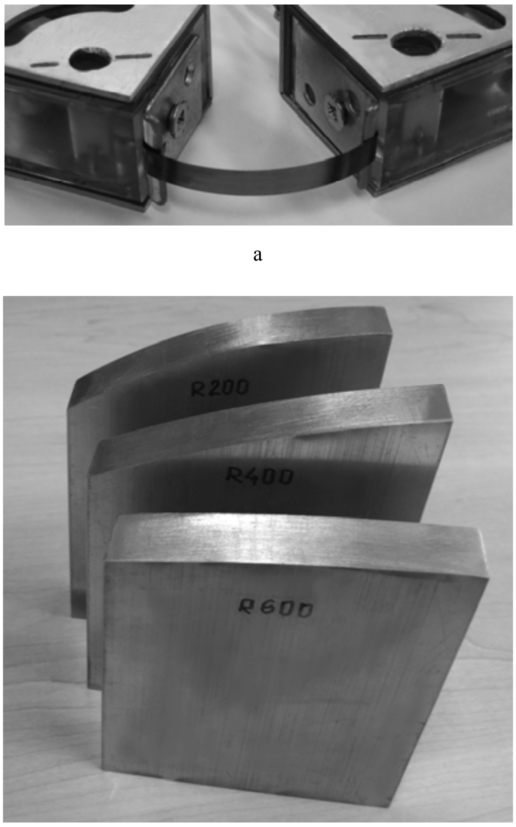
Theoretically, LSAW phase velocity increment can be negative also (concave surface case), but this case is not typical, because LSAW attenuation should increase even more considering by accelerated digression from the wave of the concave surface.

Although the number of LSAW research is growing and the number of theoretical research is growing also [5], unfortunately, there are no known mathematical equations for computing the dependence of LSAW velocity increment $\Delta c^{+c}_{LSAW}\left(\mu \frac{R}{\lambda_{LSAW}}\right)$. So, it would be done experimentally in this research.

Investigation methodology and equipment

Classical ultrasonic pulse evaluation method with LSAW pulses excited and receivable by variable-angular prismatic 4.0 MHz transducer was used for LSAW velocity and signal amplitude measurement [6]. The variable-angular prismatic transducers were connected by the mechanical resilient steel band so that the distance between transducer is constant not depending on the testing cylindrical surface curvature (Fig. 2).

The received signals are recorded by the digital two-channel oscilloscope GDS-2062. The signals were processed by computer for a greater accuracy.



a

b

Fig. 2. **Conjugated pair of prismatic LSAW transducer (a) and cylindrical samples (b)**

The scheme shown in Fig. 3 was used for the research measurements.

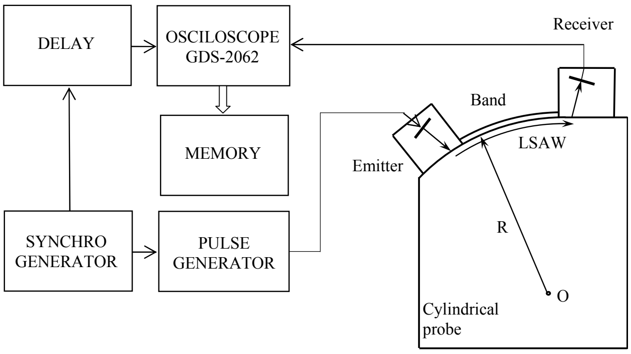


Fig. 3. **Structural measurement scheme**

The samples with different curvature radius (R=600mm; 400 mm, 200 mm, 35 mm) were made for testing LSAW propagation characteristics. LSAW velocity on a flat duralumin surface is calculated according to:

$$c^{\infty}_{LSAW} = \frac{\Delta d}{\Delta t} = 6462 \text{ m/s} \qquad (2)$$

where Δd is the distance change between the emitter and the receiver; Δt is the LSAW pulse change in the time domain.

Results of LSAW experimental investigations

The typical LSAW pulse registered by 25 000 points resolution is shown in Fig. 4. The errors are inevitable setting signal start moment because of quite high noise level. Signal digital filtering and slab detection will be used for noise reduction.

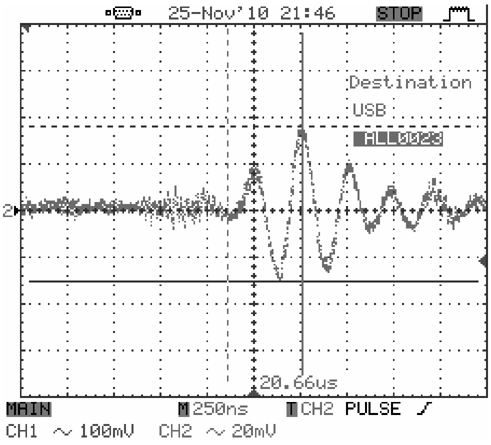
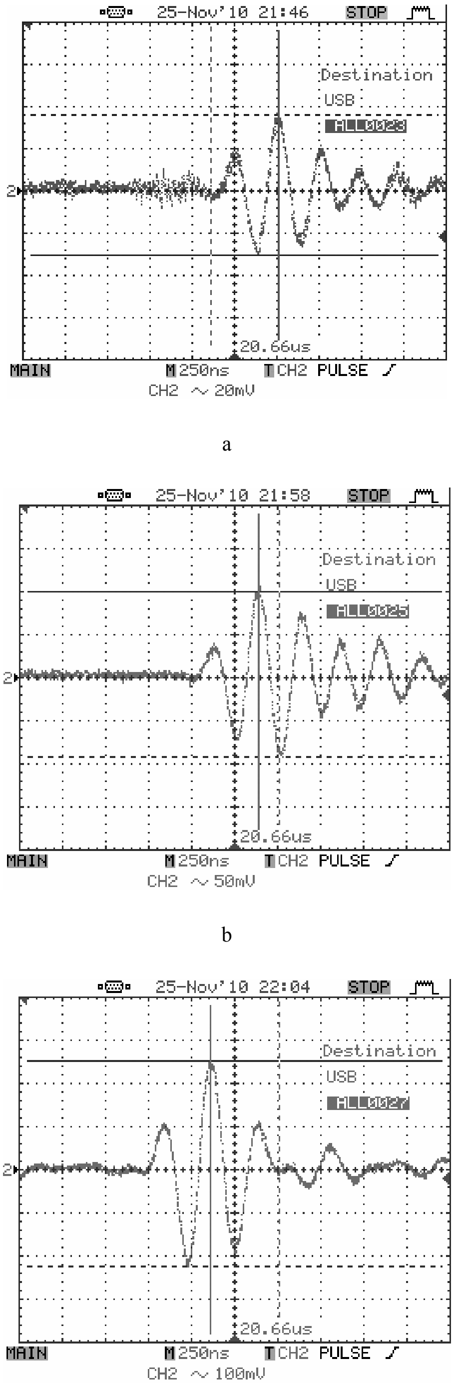


Fig. 4. **LSAW pulse registered on the smooth duralumin surface**

The signals registered in cylindrical convex surface samples made of duralumin with a maximal 25 000 point resolution are shown in Fig 5. The measurement data are given in Table 1. The Δc^{+c}_{LSAW} dependence of $R/\lambda^{\infty}_{LSAW}$ was calculated evaluating measured signal amplitude $c^{\infty}_{LSAW} = 6462$ m/s, the central frequency of the transducer f = 4,0 MHz, and the LSAW wavelength $\lambda^{\infty}_{LSAW} = c/f = 1{,}61$ mm (Table 1, Fig. 6). The measured signal amplitude dependence on the curvature parameter $R/\lambda^{\infty}_{LSAW}$ of the cylindrical convex surface is given in Fig. 7



a

b

c

Fig. 5. **LSAW pulse position in the time scale dependence on the duralumin sample cylindrical convex surface curvature radius *R*: a – *R* = ∞; b – *R* = 400 mm; c – *R* = 35 mm**

Table 1. **Measurement data**

R, mm	$\frac{R}{\lambda^{\infty}_{LSAW}}$	Δt, μs	Δc^{+c}_{LSAW}, m/s	$\frac{\Delta c^{+c}_{LSAW}}{c^{\infty}_{LSAW}}$, %	$\frac{U^{+c}_{m}}{U^{\infty}_{m}}$,
∞	∞	0	0	0	1
600	372	-0.06	46	0.71	2.53
400	248	-0.12	93	1.44	2.89
200	124	-0.15	116	1.80	4.34
35	22	-0.40	861	13.3	7.17

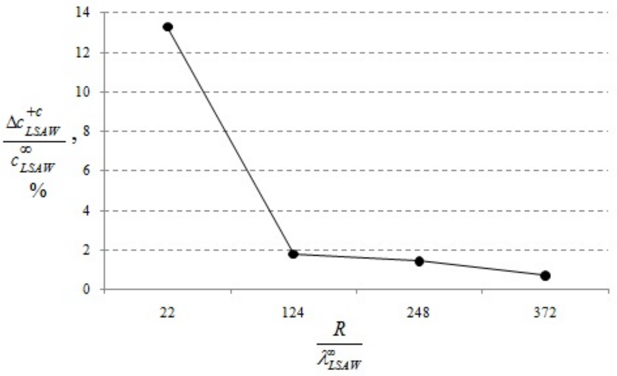


Fig. 6. **Phase velocity change of LSAW versus the cylindrical surface normalized curvature $R/\lambda^{\infty}_{LSAW}$**

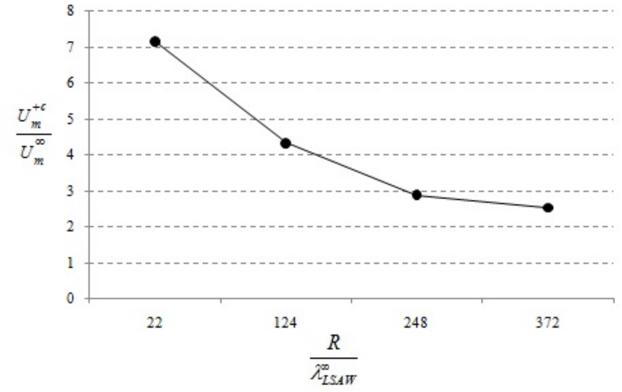


Fig. 7. **LSAW normalized amplitude dependence versus the cylindrical surface normalized curvature $R/\lambda^{\infty}_{LSAW}$**

The LSAW phase velocity increases non-linearly (Fig. 6). It is influenced by the curvature of the cylindrical convex surface. The signal amplitude changes much stronger (up to 7 times) because of the same reason. This effect in architectural acoustics is known as whispering gallery effect [7].

It would be more correct to call this phenomenon "ruining gallery effect" in the case of seismic earthquake evaluating the increased energy level of LSAW propagation on the cylindrical surface (≈ 50 times).

By the way, the measured signal (Fig. 8) exceeded the LSAW signal on the flat sample surface from 26 (*R* = ∞) to 29 (*R* = 600 mm) times when the tangential component of LSAW was picked-up. This occurred because the receiving angle $\vartheta = 0^0$ using the same angular piezotransducer in the sidelong surface of the sample was observed.

On the one hand, this indicates that the tangential component of the displacement in LSAW is much stronger than the normal; on the other hand it shows that the angular excitation by longitudinal LSAW waves using small angle ϑ^I_{kr} (angle was ϑ^I_{kr} = 24,7^0 when LSAW was excitated in duralumin through plexiglas prism) is not so effective. This happened because a big part of BLW transform into BTW.

LSAW excites more effectively on the Earth surface during seismic shock moment, when they could be exciting not only by creeping longitudinal waves on the surface, but also by the shock of transverse wave, when this shock is directed to the surface at an angle $\gamma_{BTW} \approx (24...25)^0$.

Apparently it can be seen from the measurements using cylindrical Earth model. The strongest LSAW shock is appearing when the LSAW pulse is crashing into the plane perpendicular to the surface.

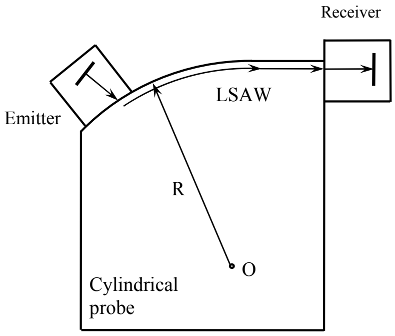


Fig. 8. **Registering schematic of LSAW tangential components**

Accurate measurements in this model also showed that $c_{LSAW}^{+c} > c_{BTW}$ (for duralumin $c_{LSAW}^{+c} = 6462$ m/s, $c_{BTW} = 6446$ m/s), so LSAW are the fastest acoustic waves.

LSAW signal processing

Signals were processed by a computer for reaching better accuracy. The main computing task was to find the LSAW pulse change in the time scale (Δt) of LSAW propagation on the samples surface with different curvature radius (R= ∞, 600 mm, 400 mm, 200 mm, 35 mm).

The discrete signals data obtained using the previously described equipment are used for signal discrete processing. The obtained signals data were centered: $\tilde{f}_t = f_t - \bar{f}$, where $\bar{f}$ is the data mean.

First of all signal processing signals data sets $\tilde{f}_t$, $t_b \le t \le t_\varepsilon$, were formed choosing the interval beginning (t_b) and end (t_ε) of 25 000 signal's point (Fig. 9) in each case at the time.

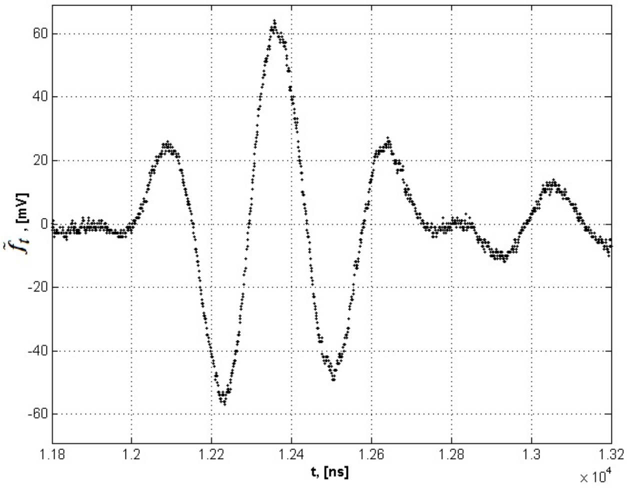


Fig. 9. **LSAW signal (R = 35 mm) with noise**

The obtained signals had a big noise level (Fig. 9). Signals filtering was the next step. Savitzky-Golay filter was chosen for this task [8]. The Savitzky-Golay filter method essentially performs a local polynomial regression to determine the smoothed value for each data point. This method is superior to adjacent averaging because it tends preserving features of the following data: the peak height and the width that are usually 'washed out' by adjacent averaging.

The simplest type of digital filter replaces each data value $\tilde{f}_t$ by a linear combination u_t and some number of neighboring samples

$$u_t = \sum_{n=n_1}^{n_2} c_n f_{+n}\,, \tag{3}$$

where n_1 is the number of points used "to the left" of the data point i, while n_2 is the number used to the right.

The idea of the Savitzky-Golay filtering is to find the filter coefficients c_n that preserve higher moments.

The Savitzky-Golay filter was made using the 2nd order polynomial and 79 (n_1 = –39, n_2 = 39) data points for analysis of filtering signals (Fig. 10).

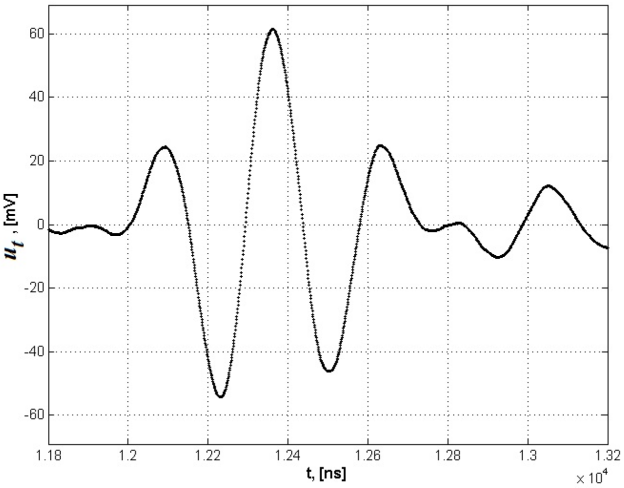


Fig. 10. **Filtered LSAW signal (*R* = 35 mm)**

New data sets were btained by taking a module of the filtered signal u_t: $U_t = |u_t|$. These data sets were used finding LSAW pulse change in the time scale (Δt).

Further local maximums of the signal data Um_t were found. The largest local maximums were approximated by parabola: $at^2 + bt + c$. Thus five parabolas of every analyzed signal were obtained. Let's denote a parabola, which was obtained using the signal data set, when R= ∞ with maximum coordinates $(t_{ax}^{\infty}, Um_{\max}^{\infty})$. For Δt computation this point was used as a starting point. For example, lets denote, that $(t_{ax}^{400}, Um_{\max}^{400})$ is the maximum of the parabola (Fig. 11) obtained by approximating signal data when R= 400 mm, then $|\Delta t| = \left|t_{\max}^{400} - t_{\max}^{\infty}\right| = 0.063\,\mu$s The other results are given in Table 2.

Comparing the results of Table 1 and 2 it is seen that change (Δt) of the LSAW phase velocity was revised from 0.5% to 8.5 %.

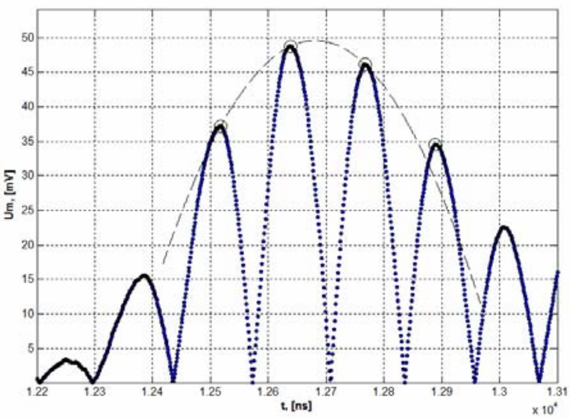


Fig. 11**. LSAW signal (*R* = 400 mm) approximation by a parabola**

Table 2. **The revised measurement**

R, mm	$\frac{R}{\lambda^{\infty}_{LSAW}}$	Δt, µs	Δc^{+c}_{LSAW}, m/s	$\frac{\Delta c^{+c}_{LSAW}}{c^{\infty}_{LSAW}}$, %
∞	∞	0	0	0
600	372	–0.033	15	0.23
400	248	–0.063	48	0,74
200	124	–0.128	99	1.53
35	22	–0.403	312	4.83

Conclusions

Investigation results of LSAW in duralumin samples allow making the following conclusions about propagation of those waves on the cylindrical convex surface:

1. Phase velocity of LSAW increases up to several percents because of a cylindrical convex surface; the phase velocity increase depends on curvature of the cylindrical convex surface and increases when curvature radius *R* is decreasing.

2. Convexity of **a** cylindrical surface has a big influence on signal attenuation. LSAW signal amplitude increased to 7,17 times in the investigated curvature radius interval ($R/\lambda^{+c}_{LSAW} = \infty$ ...22). The exhibition of whispering gallery effect in solids on cylindrical convex surfaces is the main reason of LSAW intensification. This LSAW characteristic could be very important for seismic LSAW propagation as the result of Earth seismic shocks.

3. The Sacitzky-Golay filter was successfully used for signal filtering because it preserved features of the signal data, such as: peak height and width.

4. Signals data approximation by a parabola revised the measurement results of the LSAW phase velocity change from 0.5% to 8.5%.

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S. Sajauskas, Z. Navickas, D. Karalienė

Paviršinių išilginių bangų sklidimo išgaubtu cilindriniu paviršiumi tyrimai

Reziumė

Pateikiamia paviršinių išilginių bangų (PIB) sklidimo išgaubtu cilindriniu paviršiumi ypatybių eksperimentinių tyrimų rezultatai. Nustatyta, kad PIB fazinis greitis didėja mažėjant išgaubto cilindrinio paviršiaus kreivumo spinduliui. Labai didelę įtaką išgaubto cilindrinio paviršiaus kreivumas daro PIB signalų lygiui, kuris, palyginti su plokščio paviršiaus įtaka, padidėja iki 7,17 karto. Tai šnabždančių skliautų efekto pasireiškimas kietuosiuose cilindrinių paviršių kūnuose PIB sklindant šių kūnų paviršiumi. Ši PIB sklidimo savybė gali būti ypač svarbi Žemės seisminių smūgių sužadintų seisminių PIB sklidimui ir įvertinimui.

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