

# The use of pulsed Lamb waves for nondestructive testing of pipes

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## Abstract

For pipe diagnostics pulsed Lamb waves excited by omnidirectional emitter are usually used. Waves reflected from some unevenness and/or arrived from the emitter in the shortest way and spun around a number of times reach the point of reception. The latter pulses disturb the observation of the reflections from the defects in the wall and should be shortened as possible. From the other side, the information is extracted only from the rising edge of the received pulse. Therefore the further part of each received pulse is damped by randomizing. For this purpose some parameters of the excited pulse (the length or frequency of filling) are being changed. The received signal corresponding to some medium parameter is used as a reference. Other signals are multiplied by the reference one and summed. The product is maximal for the first wave of the signal, the other waves are damped. The experimental results, their analysis, and conclusions are presented in the paper.

**Keywords:** Lamb waves, pipe, exciting burst, signal – noise ratio.

## Introduction

The use of most easily excited Lamb waves (antisymmetric zero order) for pipe diagnostics has a number of positive features. An integrated estimation of the entire section can be obtained from a single measurement (e.g. damping), once the used waves are longer than the thickness of the wall. Damping allows determining the amount of sediments on the inner surface of the pipe [1]. Excited in the wall waves can reach any point by a number of ways, and this usually allows the realization of interferometric measurements, and even to determine whether the inner cavity of the pipe is empty, or filled with fluid [2]. Two-dimensional Fourier transformation (2DFFT) is used in more complex cases studying interfering signal envelope [3], unlike the same signal, as in [4]. The pulse system was developed besides interferometric test system [5]. The newest experiments show that it is possible to scan the pipe wall using a single omnidirectional emitter in transmitting mode or receiver in a receiving mode [6]. In the first case the emitter is excited by the series of pulses with the radiation instants chosen so that the waves come to a given point at the same time: the first spun around for several times, the last straightly. The pulses in a receiving mode are selected similarly. In this case typical longitudinal wave transducers placed to the object under a test are used for Lamb wave transmitting and receiving. They are adjusted to the object acoustic impedance only for longitudinal waves. Therefore their transient characteristics for Lamb waves have distinctly expressed oscillating character and received pulse has a significant "tail", which essentially narrows the scanning sector. The present work is devoted to reduction of such a phenomenon and non-coherent noise.

## Method

The reaction of system with at least one resonance (e.g. emitter) excited by the wave burst with the filling

frequency close to its own - resonance frequency can be expressed as:

$$U(t) = a_s e^{-\alpha t} \cos(\omega_s t + \varphi_s) + a_p \cos(\omega_p t + \varphi_p) \quad (1)$$

where  $U(t)$  is the displacement,  $a_p$  is the amplitude of the forced oscillation,  $a_s$ , and  $a'_s = a_s e^{-\alpha t}$  are the starting and time-depending amplitudes of eigen oscillation,  $\omega_s$  and  $\omega_p$  are the corresponding frequencies,  $\varphi_s$  and  $\varphi_p$  are the initial phases,  $\alpha$  is the damping factor. The following three areas can be distinguished:

1. At the burst starting time (switching on the forced oscillations)  $a'_s$  is enough big, so the oscillation beat can be observed;
2. The reaction consists only of the forced oscillations when the eigen oscillations are damped;
3. Only the eigen damped oscillations remain in the reaction at the end of the burst (switching off the forced oscillations).

In our case, the information is carrying by the arrival time of the first wave of the received signal, i.e. the beginning of the first area. The arrival time, and the form of the first oscillation scarcely depends on the excitation signal form and does not depend on its length. The possibility of reducing the useless signal at the second half of the first area and at the second and third areas occurs by randomization.

For this case the emitter was excited by series of  $N$  bursts realization with a slightly modified parameter (the filling frequency or the burst length) in each of them and the appropriate received signals were recorded. It is clear that the product in the invariable part of interest of the received signal is

$$U_i(m\Delta t) \cdot U_k(m\Delta t) = \max, \quad (2)$$

where  $i = 1 \dots N$ ,  $k = 1 \dots N$  are the numbers of realization, time  $t$  is replaced by a discrete  $m\Delta t$ ,  $\Delta t$  is the sampling step,  $m = 0, 1, 2, \dots$ . In all other cases the product is less. So,

the changing of the frequency or the length of the burst makes random the useless part of the received signal, and then it is decreased as a non-coherent noise.

The output signal is formed according to this algorithm:

$$U_i^2(m\Delta t) = \sum_{k=1}^{i-1} U_i(m\Delta t) \cdot U_k(m\Delta t) + \sum_{k=i+1}^N U_i(m\Delta t) \cdot U_k(m\Delta t). \quad (3)$$

The case when  $i = k$ , is not included into the sum (3) because it has limited amount of information. The realization  $U_i(m\Delta t)$  is chosen to some average value of a variable.

The sum  $U_i^2(m\Delta t)$  at a given value of  $m$  is close to a correlation coefficient and is maximal when all realizations are the same, and less in other cases.

### The scheme of the experiment

The transducers 1 and 2 (Fig. 1) of longitudinal waves are attached to the pipe P under a test. The distances from the pipe end are  $h_1$  and  $h_2$ . Both transducers can be used as emitter and as receiver. The emitter is excited by Arbitrary Waveform Generator Agilent 33220A, the receiver is connected to Digital Storage Oscilloscope Tektronix TDS 2022 and both devices are connected to PC through interfaces. Contact area between the flat transducer surface and the test pipe has the elongated elliptical shape. Therefore, the transducers are not omnidirectional and radiate more effectively in the direction where from the point of observation the transverse dimension of the contact area is greater (and vice versa). This direction is perpendicular to the pipe axis. Transducers radiate/receive worse along the pipe.

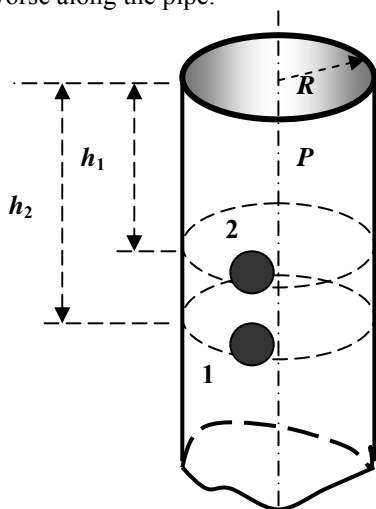


Fig. 1. The scheme of the experiment:  $R$  is the diameter of the pipe P under a test, 1 and 2 are the transducers;  $h_1$  and  $h_2$  are the distances from the pipe end.

### Randomization in frequency domain

Randomization is efficient only for broadband transducers, since a removal of significant part of the received signal is possible only changing the frequency in

a wide range without a significant change in the amplitude. In our experiments we used two narrowband 2.5 MHz longitudinal wave transducers attached to the steel pipe with the outer diameter of 48 mm, the wall thickness 3 mm. The transducers are arranged along the pipe at the distance of 35 mm from each other and far from any defects ( $h_1$  and  $h_2 \gg R$ ). The operation frequency was approximately 10 times lower than the resonant frequencies, therefore the resonant properties are almost imperceptible. Obviously energetic efficiency is poor.  $N = 5$ ,  $i = 3$ ,  $\Delta t = 0.1 \mu s$ , there were 2 periods in the excitation burst, the filling frequencies were 133...250 kHz.

Experimentally registered reactions  $U_i(m\Delta t)$  are shown in Fig. 2a, b, c.  $U_i^2(m\Delta t)$  is calculated according to Eq.3. The first signal in the left at 15  $\mu s$  corresponds to the direct Lamb wave passing from the emitter to the receiver, the other peaks of the signal at 55  $\mu s$ , 100  $\mu s$  and 145  $\mu s$  corresponds to the waves spinning one and more times around the tube. The amplitude of the waves that have propagated directly from the emitter to receiver is small. It is explained by the fact that transducers in the reality are not exactly omnidirectional, so the radiation in parallel to the pipe axis direction is weaker.

Having compared Fig. 3c with any of the Fig. 2a - c, or Fig.3a-b we see a significant improvement in ratio "signal - noise", particularly in the intervals between the signal peaks. The peaks themselves also become shorter.

### Randomization in time

The tests were carried out with a pipe of  $\varnothing 150$  mm, the wall thickness of 8 mm.

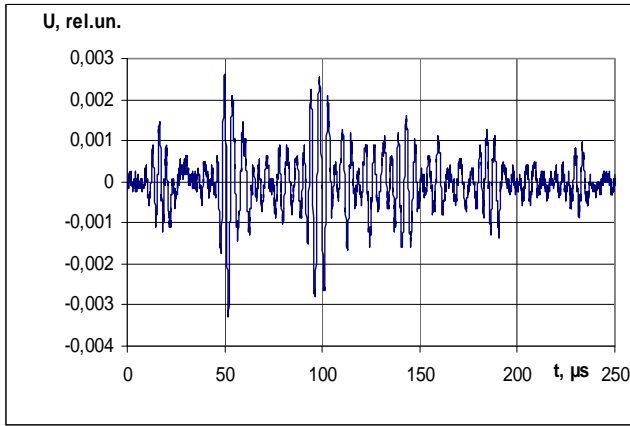
The alternating voltage of 120 kHz frequency in a burst mode with the number of periods 1 ... 5 in the burst was used. It means that changing the length of the burst in one period,  $N = 5$ ,  $i = 3$  were used for excitation. Broadband transducers, with the frequency as well of 120 kHz were located along the pipe at 20 mm distance from each other at particular the distances  $h_1$  and  $h_2$  from the pipe end. Pipe's end, perpendicular to axis, ensures a specular reflection.

The results of the experiment where  $h_1 = 130$  mm and  $h_2 = 150$  mm are shown in Fig. 4a - 1 period in the burst ( $k = 1$ ), and Fig. 4b - 5 periods ( $k = 5$ ). The signal we obtained from all cases (not shown and Fig. 4 - with 2, 3 and 4 periods in burst), according to Eq. 3, where  $N = 5$ ,  $i = 3$  is shown in Fig. 4c. This clearly shows the direct wave passing from the emitter to the receiver at 20  $\mu s$  and the waves that have spun the pipe 1, 2 and 3 times (the instants 160, 300 and 440  $\mu s$ ). The waves reflected from the end of the pipe are observed at the time instants of 110  $\mu s$ , 200  $\mu s$  and 310  $\mu s$ , respectively reflected directly and having spun 1 and 2 times. These reflections already allow the receiver to locate reflection of the emitter or the other source of the signal (the reflecting defect or the center of acoustic emission). The ratio "signal - noise" using Eq. 3 significantly improves. It should be noted that the case with 1 period in the burst ( $k = 1$ ) corresponds to the already described in literature [6, Fig. 4.]. The emitter in the cited work was excited by a square pulse of 5  $\mu s$  width the received signal is very similar to Fig. 4a of this

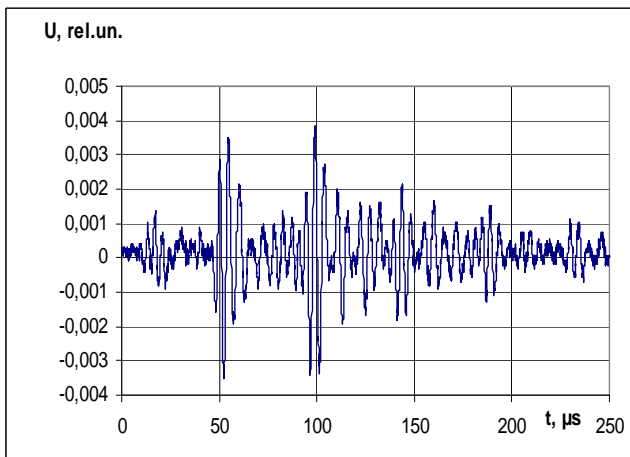
work. The dimension  $U_i^2(m\Delta t)$  used in Eq. 3 is essentially energetic parameter. The signal of piezoelectric transducers is proportional to the wave amplitude, but not to the energy. Therefore  $U_i(m\Delta t)$  better reflects amplitude relations.

$U_i(m\Delta t)$  for the case shown in the Fig. 4 (square root of the modulus of the function Fig 4c) is seen at the Fig. 5a. The latter diagram is more informative than Fig. 4c.

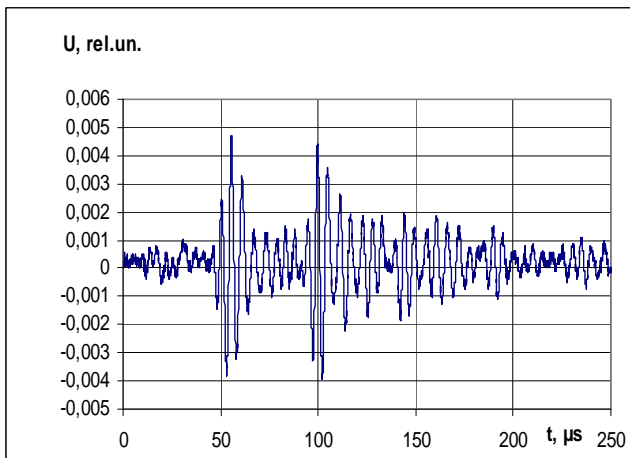
An analogous experiment was carried out when  $h_1 = 220$  mm and  $h_2 = 240$  mm (Fig. 5b). The direct reflection passes to the time instant of 220  $\mu$ s, the reflection with one wave spin around to 330  $\mu$ s, etc.



a

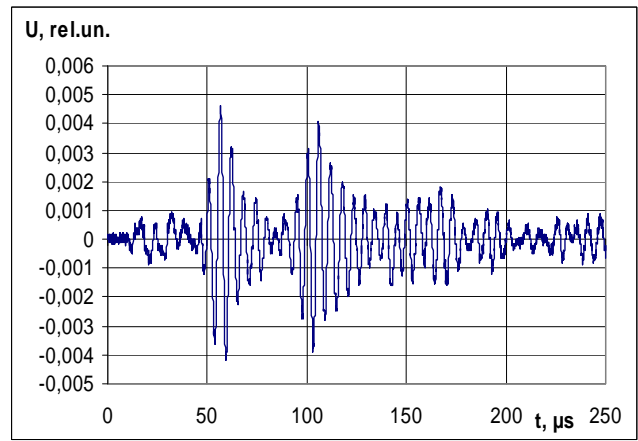


b

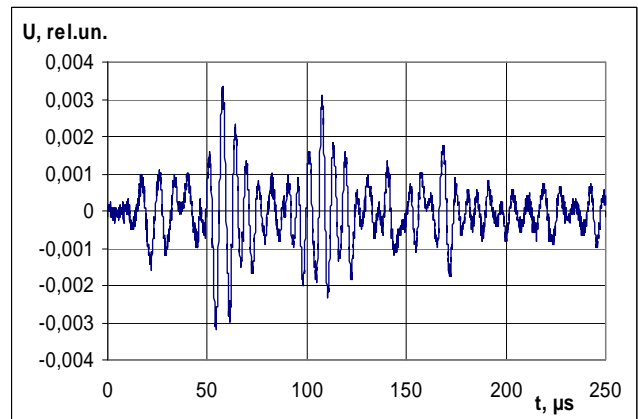


c

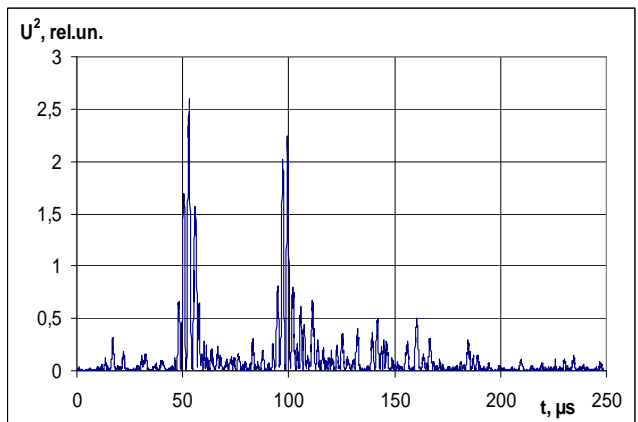
Fig. 2. The received signal in the pipe of  $\varnothing 48$  mm; the distance between transducers is 35 mm. The frequency of filling a - 250 kHz, b - 222 kHz, c - 200 kHz .



a



b

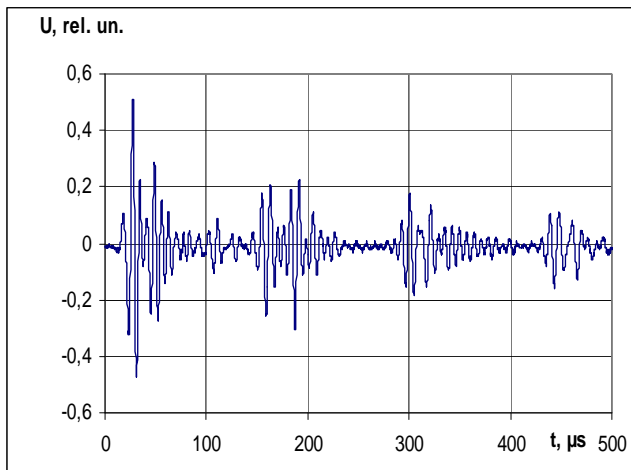


c

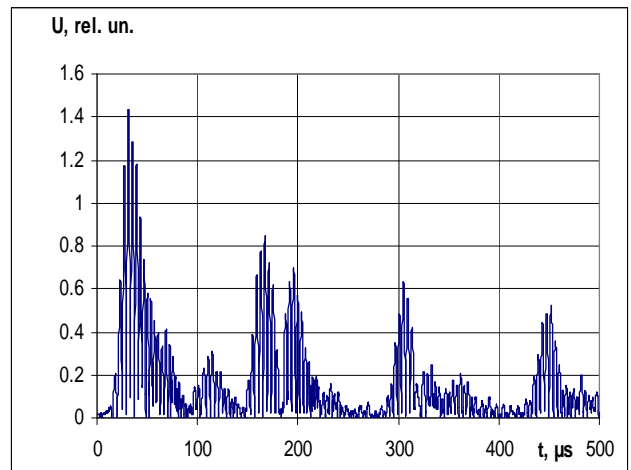
Fig. 3 a, b - the received signal in the pipe of  $\varnothing 48$  mm; the distance between transducers is 35 mm, c - is the output signal obtained from Fig. 2 a,b,c and Fig. 3 a,b according Eq. 3, when  $i = 3$ . The frequency of filling is a - 160 kHz, b - 133 kHz.

### Randomization by excitation with square pulse

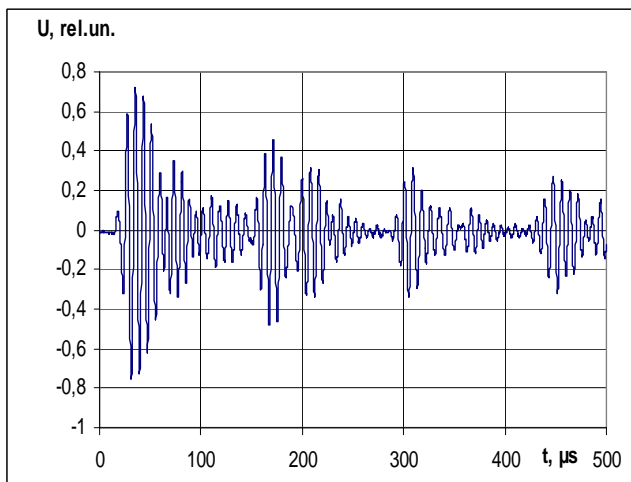
In this case only native oscillations occurring at the beginning and the end of the excitation pulse remains in the reaction. The pulse width of 6...8  $\mu$ s,  $N = 5$ ,  $i = 3$ ,  $h_1 = 220$  mm and  $h_2 = 240$  mm were chosen for the experiment. The obtained dependence  $U_i(t)$  is shown in Fig. 5c. The signal peaks there are even more narrow than in Fig. 5b. Excitation by a square pulse is easier in the sense that  $N$  can be significant and the steps of duration changes can be small.



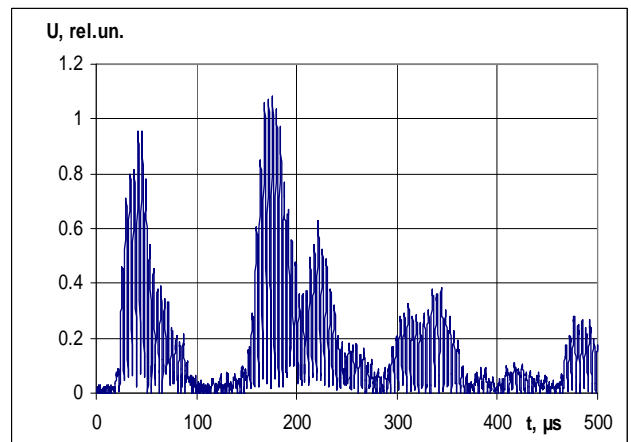
a



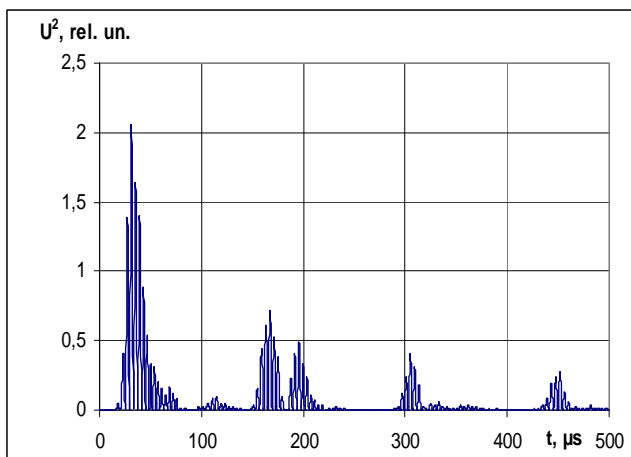
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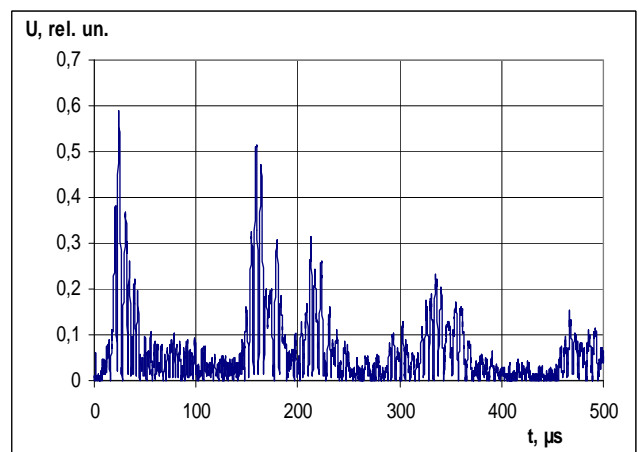
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b



c



c

Fig. 4 a,b. The received signal in the pipe of  $\varnothing 150$  mm; a - one period in the burst ( $k = 1$ ), b - 5 periods ( $k = 5$ ); the distance between transducers is 20 mm, the frequency of filling is 120 kHz,  $h_1 = 130$  mm,  $h_2 = 150$  mm c - is the output signal obtained according to Eq.3, when  $N = 5, i = 3$ .

Fig. 5. a -  $U_i(t)$  – is the square root from Fig. 4 c, b -  $U_i(t)$  for the same pipe when  $h_1 = 220$  mm and  $h_2 = 240$  mm, c -  $U_i(t)$  for the case as in Fig. 5 b by exciting by a rectangle pulse 6...8  $\mu$ s,  $N = 5, i = 3$

## Conclusions

The measurement method, where not required part of the received pulse is randomized and canceled occurred to be the effective improvement of the ratio "signal – noise". There are several versions of this method disposal depending on the concrete acoustic system. Complicated algorithms are unnecessary for signal processing, but the acoustic system remains a rather simple.

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L. Vigricitė, V. Sukackas

## Impulsinių Lembo bangų naudojimas neardomiesiems vamzdžių bandymams

### Reziumė

Aprašomas vamzdynų diagnostikos impulsinėmis Lembo bangomis metodas. Į objektą spinduliuojami impulsai, kurių pradinė dalis vienoda, o tolimesnė skiriasi. Tokiu būdu gauta priimtųjų impulsų serija geometriškai sumuojama. Sumoje išryškėja impulso pradinė dalis, kuri visoje serijoje vienoda. Tolimesnė dalis slopinama, sutrumpėja impulsas ir padidėja tikslumas.

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