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GUIDED WAVE FOCUSING MECHANICS IN PIPE

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ABSTRACT

Guided waves can be used in pipe inspection over long distances. Presented in this paper is a beam focusing technique to improve the S/N ratio of the reflection from a tiny defect. Focusing is accomplished by using non-axisymmetric waveforms and subsequent time delayed superposition at a specific point in a pipe. A semi-analytical finite element method is used to present wave structure in the pipe. Focusing potential is also studied with various modes and frequencies.

INTRODUCTION

Guided waves in a pipe do not spread like those in a plate. All energy remains in the pipe as it circles and superimposes on itself. Commercially available equipment using guided waves is installed at one location on a pipe to analyze reflected echoes by the presence of corrosion or other defects. The reflected echoes are extremely complex due to such guided wave characteristics as multi-mode existence, dispersion and mode conversion. Axisymmetric modes, which propagate with axisymmetric structures in terms of the center axis of a straight pipe, are easily handled because of simple mechanics, but are limited to finding fairly large defect.

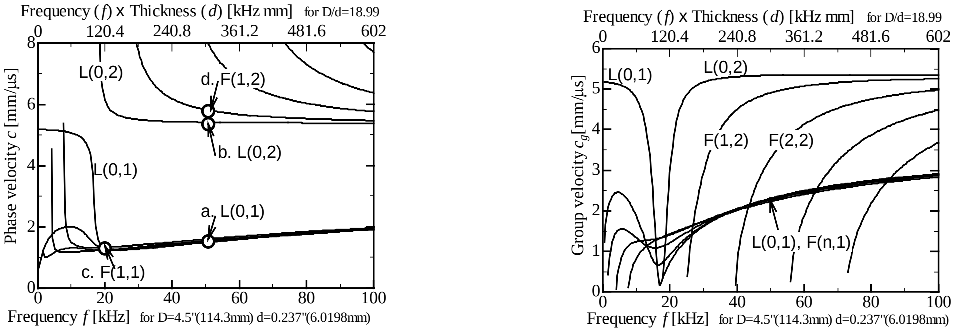
The focusing technique, on the other hand, is expected to become a promising technique for defect detection. This work is reported in 4-7. However, more quantitative detailed and theoretical studies are needed to establish rules for practical use. In this study, therefore, ultrasonic focusing is studied with a special calculation technique for guided waves, called the Semi-Analytical Finite Element Method (SAFEM). Based on detailed studies on dispersion curves and wave structures for a pipe with the SAFEM, focusing potential is clarified with respect to guided wave modes, frequency regions and target distance.

SEMI ANALYTICAL FINITE ELEMENT METHOD FOR STRAIGHT PIPES

Guided waves are usually used in long-range inspection in the meter or kilometer order, which is obviously significantly larger than an ultrasonic wavelength. Using ordinary finite element or boundary element methods, therefore, extremely large calculation times and memory are required for calculations of guided wave propagation in a pipe Since a semi-analytical finite element method (SAFEM) does not require subdiscritization in the propagating direction of the guided waves, it is very useful for long range guided wave calculations[6-8]. Moreover, since the SAFEM provides dispersion curves and wave structures as well as displacements and stresses for each mode, it can be used for a wide variety of guided wave analyses.

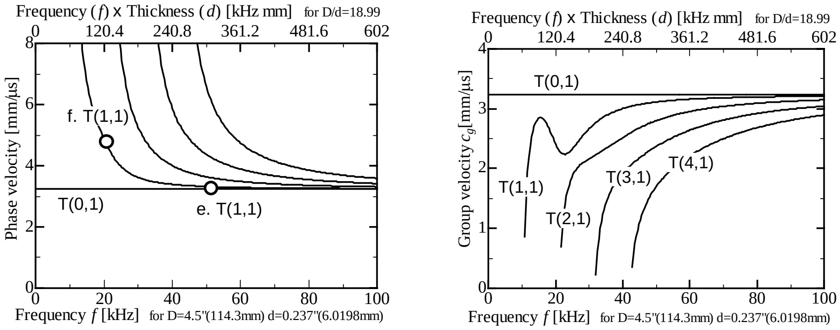
DISPERSION CURVES AND WAVESTRUCTURES

An understanding of dispersion curves, frequency dependence of guided wave velocities, wavestructure and deformation in an elongated object for certain modes are indispensable for guided wave nondestructive evaluation. Dispersion curves present fundamental information on guided waves such as wavelength and dispersivity as well as phase and group velocities at a certain frequency. Wave structures show the dominant displacement components. Such fundamental information plays an important role in transducer design and wave analyses. For example, dispersion curves are used for determining incident and receiving angles of angle beam transducers and spacing of comb type transducers such as EMATs and PVDF films and for estimating the traveling time of each mode The wave structures are useful for determining efficient vibration directions to generate selected modes and for understanding wave propagation and attenuation characteristics. However, there is little theoretical study available for describing the relation between dispersion curves and wave structures, especially for guided waves in a pipe. This



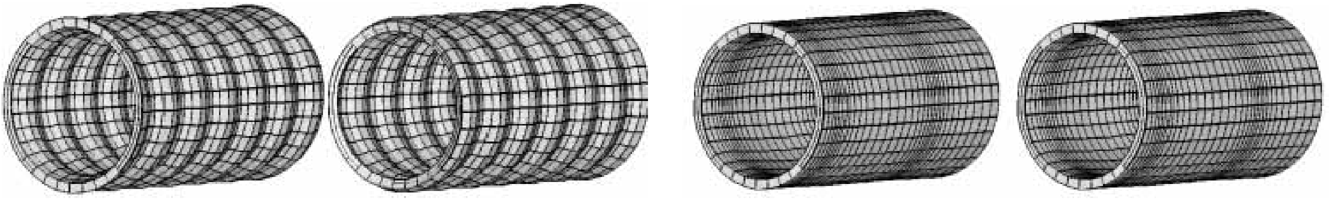
(a) Phase velocity (b) Group velocity

Fig.1 Dispersion curves for Longitudinal and Flexural modes

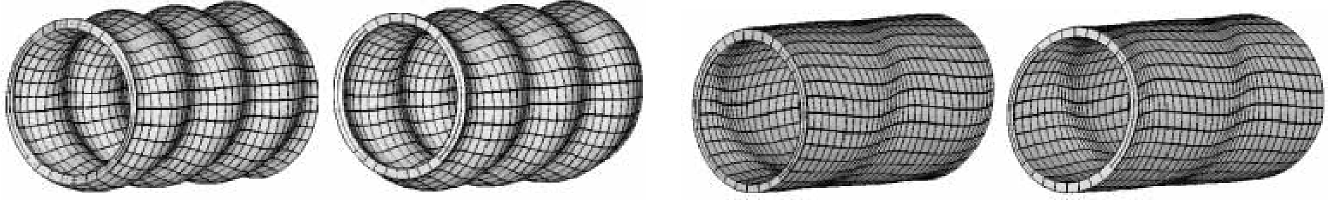


(a) Phase velocity (b) Group velocity

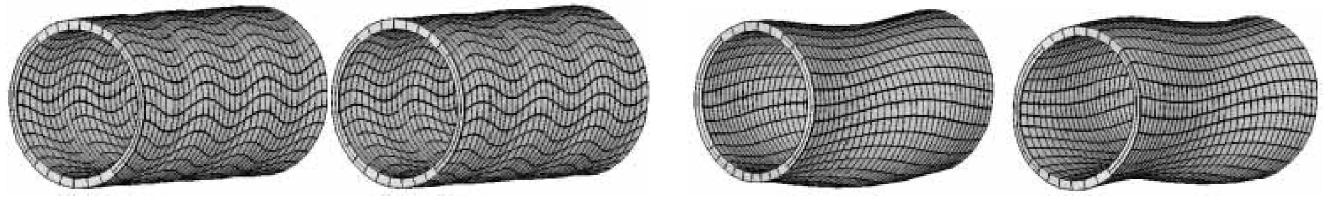
Fig.2 Dispersion curves for Torsional modes



(a) L(0,1) 50kH (b) L(0,2) 50kHz



(c) F(1,1) 20kH (d) F(1,2) 50kHz



(e) T(1,1) 50kH (f) T(1,1) 20kHz

Fig.3 Displacement wavestructures for various points in dispersion curves
The left and right images correspond to ones at $\omega t=0$ at $\omega t=\pi/2$.

is because guided wave modes in a pipe have complex three-dimensional wave structures. Prior to detailed analysis on the focusing technique, the relationship between dispersion curves and wave structures is studied in this section with SAFEM calculation and visualization.

Figures 1 and 2 show dispersion curves for a pipe of 4" schedule 40 (outer diameter D=4.5"(114.30mm), thickness d=0.237" (6.02mm), carbon steel). Fig.1 (a) and (b) show phase and group dispersion curves for Longitudinal modes (L(0,1), L(0,2)) and Flexural modes (F(n,1), F(n,2), n=1,2,3,4), and Fig.2 Torsional modes (T(0,n), n=1,2,3,4). These dispersion curves can be commonly used for a pipe with D/d=18.99 by adopting the frequency and thickness product (*fd*) shown in the upper horizontal axis instead of frequency(*f*). Discussions below are written for a pipe of 4" schedule 40, but available for a pipe with D/d=18.99. Wave structures are shown in Fig.3 (a)-(e) for selected modes and frequencies; (a) being L(0,1) at 50kHz, (b) L(0,2) at 50kHz, (c) F(1,1) at 20kHz, (d) F(1,2) at 50kHz, (e) T(1,1) at 50kHz, (f) T(1,1) at 20kHz. a-e shown in dispersion curves Fig.2 correspond to the wave structures in Fig.3 (a)-(e). The length of the visualization regions in Fig.3 is 200mm for a 4-inch pipe. Two images in Fig.3 (a)-(e) represent the wave structures at $\omega t=0$, $\pi/2$, where ω and t are the angular frequency and time, respectively.

Though L of L(0,1) stands for Longitudinal mode, L(0,1) at 50kHz is the shear vertical type wave dominated by out-of-plain displacement as shown in Fig.3 (a). Similarly, the L(0,1) mode in the frequency range from 20kHz to 100kHz is the shear vertical type wave. On the other hand, the L(0,2) mode at 50kHz shown in Fig.3 (b) is dominated by longitudinal vibration, and L(0,2) mode in the frequency range from 30kHz to 100kHz is also the longitudinal type wave. F(1,1) mode is the shear vertical type wave at the frequency range from 20kHz to 100kHz as shown in Fig.3(c). Differently from L(0,1) mode wavestructure, the phase varies in the circumferential direction since the circumferential order does not equal to zero. F(1,2) mode is the longitudinal type mode as shown in Fig.3(d), which is similar to L(0,2) but the phase varies in the circumferential direction. Torsional mode T(0,1) is the shear horizontal wave that oscillates in the circumferential direction and propagates in the longitudinal direction . T(1,1) at 50kHz (Fig.3(e)) is also the shear horizontal type wave with phase varied in the circumferential direction. On the other hand, T(1,1) at the highly dispersive region (20kHz, Fig.3(f)) is dominated by a flexural type wave.

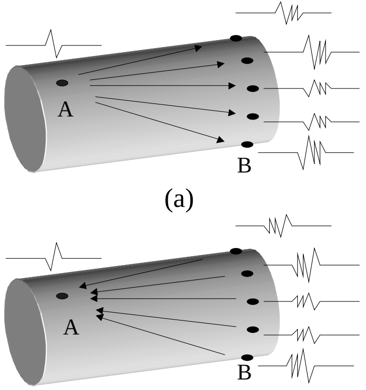
To summarize the above, the following conclusions can be drawn.

1. L(0,1) and L(0,2) are called Longitudinal modes, but all of them are not dominated by longitudinal type waves. L(0,1) is the shear vertical type mode at the frequency range from 20kHz to 100kHz. Similarly, all of F(n,m) and T(n,m) are not dominated by flexural and torsional type waves. F(1,2) mode is a mainly a longitudinal type wave at the frequency range from 30kHz to 100kHz, and T(1,1) mode at 20kHz is the flexural type wave.
2. Even if modes are classified into the different categories like L(0,1) and F(n,1), similar wavestructures can be seen when phase velocity and group velocity are close to each other. For example, both L(0,2) and F(0,2) with a phase velocity of about c=5.4mm/μs are dominated by longitudinal vibration. Both T(0,1) and T(1,1) with about c=3.2mm/ μs are the shear horizontal type modes, and L(0,1) and F(1,1) with the phase velocity from 1.0 mm/ μs to 2.0 mm/ μs are the shear vertical type modes.

FOCUSING CHARACTERISTICS

The importance of the focusing technique in pipe inspection has been reported by the Penn State group [4-7]. These studies report the following: 1. Energy of guided waves can be converged into a certain point in a pipe by the use of non-axisymmetric modes. 2. Energy focusing can be obtained by independently controlling time delays and amplitudes in a number of transducers mounted at regular intervals in the circumferential direction. 3. When there is a defect at the focal point, large reflection echoes can be obtained, and this could be applied to defect characterization in a pipe.

Based on the above knowledge, the authors have studied focusing phenomena by a simulation of guided wave propagation in a pipe with the SAFEM, in which we present that focusing phenomena can be explained by ultrasonic time reversal. To obtain the focusing, first of all, signals from a single transmitter at a certain point A on a pipe are detected at many receivers B mounted in a row in the circumferential direction (Fig.4(a)). Next, the time reversed signals of the detected signals are emitted back from the transducers B toward the transducer A (Fig.4(b)). Then, guided wave energy converges at the original source point A. Using the SAFEM calculation, we show that ideal focusing can be obtained at the designed target point in a pipe 6). The focusing was seen experimentally by generating tone burst signals from eight transducers with time delays and amplitudes independently controlled, instead of time reversal signals. Focusing characteristics are shown for many frequency regions and excitation modes, and a guideline for focusing is drawn.



(a)

(b)

Fig.4 Focusing with time reversal waves

1) TIME DELAY AND AMPLITUDE CONTROL

Focusing by controlling time delays and amplitudes has been done with phased array transducers in bulk materials. Therefore, waveforms with controlled time delays and amplitudes can be excited with existing instruments. The convolution algorithm developed by Li [4, 5] gives necessary time delays and amplitudes for focusing at a designed target point in a pipe. Also, authors presented similar algorithms for the necessary time delays and amplitudes, and the relation between these focusing algorithms and time reversal was revealed[7]. Fig.5 shows one example of the SAFEM calculation results for focusing with controlled time delays and amplitudes. The shift of grid point represents the absolute values of complex amplitude at the point and the right circle chart show the circumferential profile (maximum displacements) at the point shown by the arrows. Eight transducers are mounted at the right end of the pipe and can control time delays and amplitudes independently. Focusing can be seen at the designed focusing point. See details in 7.

Time delays and amplitudes used in this study are obtained with the time reversal idea as follows. First, waveforms emitted by one transmitter and received at eight receivers mounted in a through-transmission configuration as shown in Fig.4(a) are calculated with the SAFEM. Then time delays and amplitudes are obtained from time reversal signals. If the waveforms are largely deformed, time delays and amplitudes are determined at the time when the largest amplitude of the time reversal signals is detected.

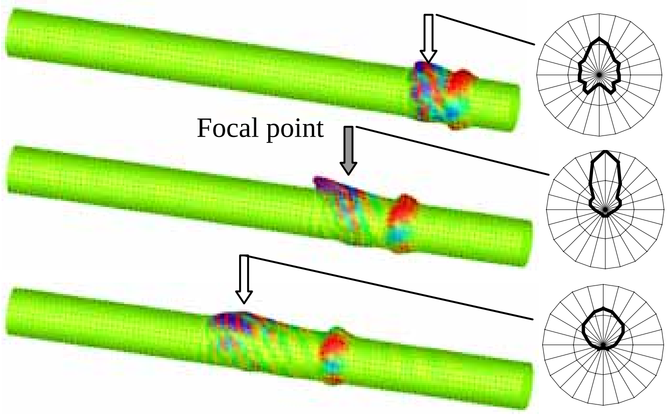


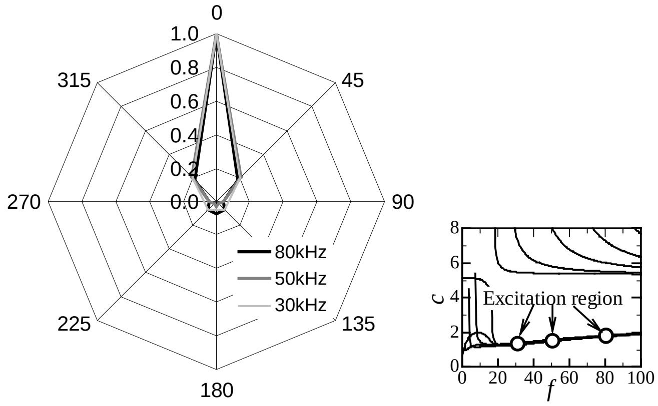
Fig.5 Focusing with controlled time delays and amplitudes. Visualization results and circumferential profiles

2) FOCUSING POTENTIAL ON VARIOUS WAVE MODES AND FREQUENCY REGIONS

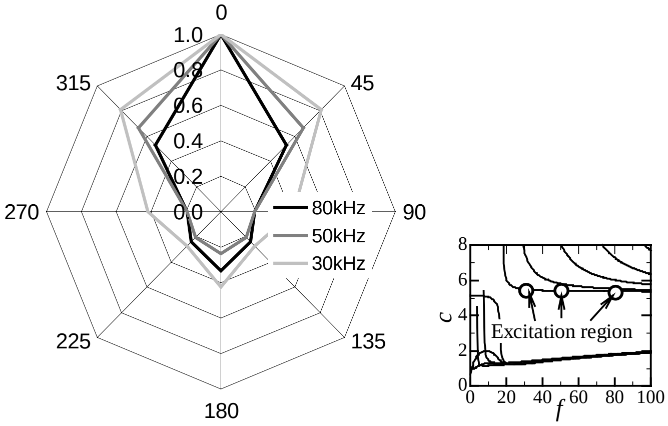
Since focusing potential could vary with various exciting modes and frequency due to their variety of wave structures and strong frequency dependence, focusing potential is investigated as a function of guided wave modes and frequency. With partial loading on a pipe, many guided wave modes are excited at the same time. This combination of axisymmetric modes and non-axisymmetric modes presents a large variety of waveforms in a pipe. When the axisymmetric and non-axisymmetric modes are well tuned, focusing can be obtained at a target. Modes with close phase velocities have similar wave structures. Since excitation modes are decided by the direction of the excitation loading and frequency range, focusing potential is discussed with three excitation conditions of longitudinal, shear vertical and shear horizontal loading at three frequency values, 30kHz, 50kHz and80kHz, as typical excitation modes. Focusing resolution in the circumferential direction can be shown by sketching circumferential profiles (maximum displacement distribution in the circumferential direction).

Figure 6 shows circumferential profiles at two meters away from the source point when the target point is at the distance L=2m and $\theta=0^o$. Since all values are normalized by the value at $\theta=0^o$, a sharper peak at $\theta=0^o$ means better focusing. Fig.6(a) shows the circumferential profiles for shear vertical type modes at 30, 50 and 80kHz as shown in the dispersion curves in the inset. Similarly, Fig.6(b) and (c) are for longitudinal and shear horizontal type modes, respectively. For SV type modes, very good focusing at 0^o can be seen at all frequency values. On the other hand, in the case of L type and SH type modes, the poorest focusing is seen at 30kHz, and the best at 80kHz.

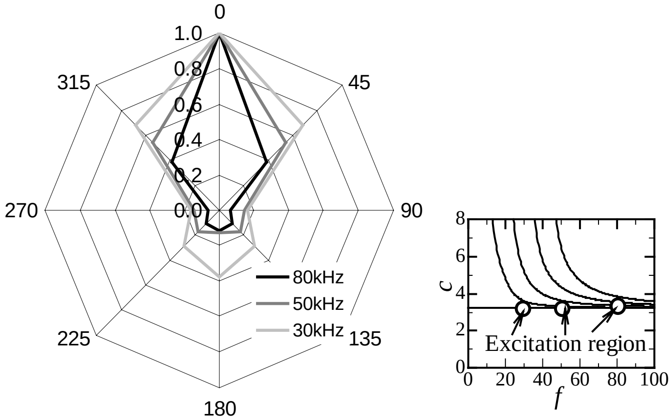
This can be explained by the time reversal idea and appropriate dispersion curves. In the time reversal technique, the incident waves necessary to obtain ideal focusing are the time reversal waveforms. Now, tone burst waves with controlled time delays and amplitudes are used instead of the time reversal waveforms. When the difference between the time reversal waveforms and the tone burst waves with controlled time delays and amplitudes are large, the focusing becomes far from ideal. In other words, when the waveforms emitted by a single transmitter are largely deformed from the original input signal, the focusing can be poor. For example, in the case of longitudinal type modes with the phase velocity of about 5.2mm/μs, the difference of the phase and group velocities between L(0,2) and F(n,2) is large at 30kHz. In this frequency region, waveforms emitted by a single transmitter are largely deformed at two meters away from the single source. The time reversal waveforms necessary for ideal focusing also largely differ from the tone burst waveforms. Thus the tone burst waves with controlled time delay and amplitudes are not well controlled for good focusing. Dispersion curves of SV type waves (L(0,1) and F(n,1)) that give good focusing are close. Contrary, in shear horizontal type and longitudinal type modes in the low frequency regions as 30kHz, each mode has a totally different phase and group velocity. In order to have good focusing, we should choose exciting modes and a frequency region with small differences in phase and group velocities.



(a) Shear vertical



(b) Longitudinal

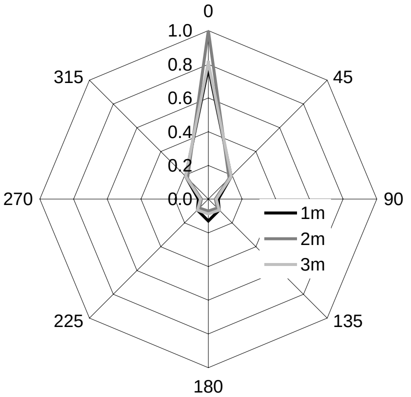


(c) Shear Horizontal

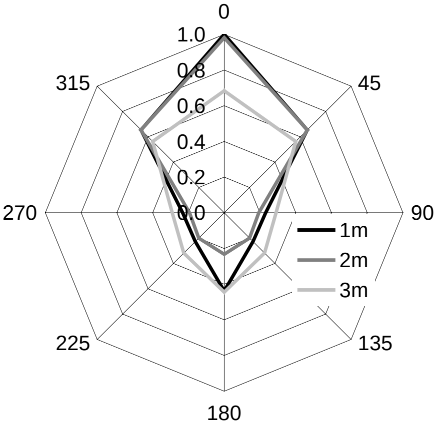
Fig.6 Circumferential profiles for various modes and frequencies showing focusing at 0^{o}.

3) FOCUSING POTENTIAL ON DISTANCES

The typical examples that show the effect of distance between target and source transmitters in focusing resolution are shown in Fig.7. Fig.7(a) is the example where focusing resolution does not vary with the distance (SV type, 80kHz). Fig.7(b) is the example where focusing resolution varies largely with distance (L type, 50kHz). In the dispersion curves of the SV type waves at 80kHz, phase and group velocities of the excitation modes (L(0,1), F(n,1)) are close. On the other hand, phase and group velocities of the L type waves at 50kHz are largely differerent (L(0,2) c=5.3mm/μs, F(1,2) c=5.8mm/μs, F(2,2) c=8.0mm/μs). Thus the differences in phase and traveling time of the exciting modes become larger with distance, hence causing focusing degradation.



1) Shear vertical input 80kHz



(b) Longitudinal input 50kHz

Fig.7 Circumferential profiles for various distance showing focusing at 0^{o}.

CONCLUDING REMARKS

Guided wave dispersion curves and wave structures in a pipe and focusing characteristics are analyzed with a semi-analytical finite element method.

The following conclusion can be drawn from the study on dispersion curves and wave structures. The names of longitudinal, torsional and flexural modes do not always denote wave structures of the corresponding modes. Wave structures of longitudinal, torsional and flexural waves are determined by phase velocity. Non-dispersive modes with a phase velocity roughly close to the longitudinal wave velocity are longitudinal type waves, non-dispersive modes with the phase velocity close to the transverse wave velocity are shear horizontal type waves, and non-dispersive modes with the slowest phase velocity are shear vertical type waves.

Focusing can be explained by the time reversal concept. When focusing is obtained by incident waves with controlled time delays and amplitudes, good focusing can be seen in the regions where the differences in phase and group velocities are small. On the other hand, focusing is poor in the large velocity difference regions.

ACKNOWLEDGEMENTS

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