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Non-destructive measurements of fuel cladding thickness

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Abstract

The method of non-destructive measuring the thickness of small-diameter thin-walled pipes consists of using the resonant frequency of vibrations in the plane of the pipe cross-section to determine the pipe wall thickness. The relative ratio of the measured frequencies determines the thickness of the thin-walled pipe with great accuracy. For small pipe diameters, the method achieves the most accurate results. The accuracy of the measurement is directly dependent on the thickness of the pipe wall and for very thin walls the method achieves the highest accuracy. The invention relates to a method of non-destructively measuring the thickness of pipes that can only be accessed from the outside or just possibly from the inside. Particularly good results are obtained with thin-walled pipes of small diameter, such as nuclear fuel cladding or steam generator pipes. Measurement of the cladding thickness is important for downstream activities such as nuclear fuel inspections or thermomechanical calculations. The non-destructive form of measuring the thickness of thin-walled components such as fuel claddings opens the possibility of expanding activities within the inspection of energy equipment to other areas of industry, testing, or structural diagnostics.

Keywords: Wall thickness; Non-destructive testing; Impact-echo; Fuel cladding; Resonant method

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1. Introduction

For decades, the non-destructive testing (NDT) techniques like x-ray radiography, eddy currents or ultrasonic testing (UT) [1,2] control processes of the fuel cladding to verify its behaviour and ensure the best quality of the fuel that directly relates to the nuclear safety and efficient operation of the power unit. The tube wall measurements with the use of NDT are one of the key aspects of the surveillance and monitoring policy during the maintenance of any technological unit based on piping with an internal medium. Among the methods used for the measurements of fuel claddings (and its coatings), the UT technology is probably in the widest use due to the long history of this technology, and not only in the nuclear industry [1,3]. To address the problems of thin-wall measurements of fuel cladding, especially in a still non-active state, the methods from other industry branches can be applied.

Current technologies developed with the high-precision principle allow for the measurements with the precision of low tens of microns [2–4]. The producers of the equipment for the coating and protective layer measurements are working to increase the precision due to the added layer nominal thicknesses being mostly below the standard resolution [5]. In the case of measuring pipes with very thin walls, such as nuclear fuel claddings, where the wall thickness is less than 600 μm, the accuracy of the UT method is in many cases insufficient.

Nomenclature

B_n – multiplier of n-mode of oscillation
d – diameter, m
E – elastic modulus, m^2/s
f – frequency, Hz
f_r – ring mode frequency, Hz
f_n – in-plane mode frequency, Hz
L – length of the tube, m
m – mass, kg
t – wall thickness, m
T – transit time, s
v – wave propagation speed, m/s
V – volume, m^3

Greek symbols

ρ – density, kg/m^3

Subscripts and Superscripts

n – number of high harmonics

Abbreviations and Acronyms

CVR – Research Centre Řež
NDT – non-destructive testing
UT – ultrasonic testing

Especially crucial components, extremely endangered to the material loss, are thin-walled parts widely used in e.g. aerospace industry, technological paths of the medium distribution [6,7] or nuclear fuel claddings [8,9]. In this way, from the gas industry and chemical processes up to the nuclear technologies, the precise measurements of the medium piping are a key factor to estimate the manufacturing quality, wear and endurance of the used tubes.

In the case of nuclear fuel claddings, the control of their wall thickness is important during the manufacturing to ensure the designed condition of the fuel, also during the performance in the power unit to investigate any potential defects.

The measurement of the wall thickness of thin-walled parts in the mechanical engineering industry is most often carried out by micrometric measurement [10]. This measurement is carried out randomly on the production lines to check the accuracy of production, taking into account the requirements of the end customer. The measurement itself is carried out using a micrometre, the accuracy of which is around 10 μm and is mainly influenced by the temperature of the instrument, the object to be measured, but also by the personnel performing the measurement, the roughness of the surface and the degree of surface contamination. This method cannot be applied on closed pipes or in inaccessible locations, for example far from the pipe edges. An example of such a situation is a fuel rod containing nuclear fuel, the opening of which would result in contamination of the immediate environment [11].

Metallographic cuttings and subsequent microscopic measurements represent a very precise destructive method [12]. The great advantage of this method is its accuracy which is in the order of several microns, Fig. 1. The disadvantage is the low flexibility in terms of determination of the thickness location, and the time and technologically consuming process of sample preparation for microscopy. In terms of industry, the use of this method is very limited and is reserved almost exclusively for laboratory environments. The technology can be performed on radioactive samples such as nuclear fuel claddings [13]. However, the transport of fuel assemblies to the hot cells usually takes place several years after the fuel has been removed from the reactor core and the method is therefore in principle unsuitable.

The shortcomings of the conventional methods are eliminated by the resonant method measuring the pipe's wall thickness. It works without the need to disassemble or damage the structure, in a relatively short time and at an arbitrarily chosen location in the pipe. It uses one or more resonant frequencies of the pipe, which are allowed to oscillate in the plane of the pipe cross-section.

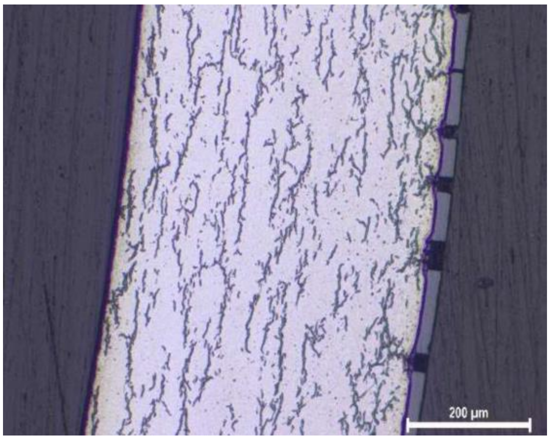

Fig. 1. The metallographic cross-section for E110 fuel cladding of 585 μm wall thickness [14].

The Research Centre Řež (Czech − *Centrum výzkumu Řež*, CVR) during the last few years has been working on the UT technology being able to measure the thin-wall tube thickness with a resolution of less than 1 μm. The main motivation for this activity was to investigate the fuel rod batches for their homogenous production (quality) and its following issues: fuel pellet gap, on-surface sedimentation, mechanical degradation of the fuel cladding and wear determination [15,16]. Currently, CVR is able to introduce a method that is capable of reaching the precision of 1 micrometre. The method was verified and validated on the fuel rod mock-ups prepared from Zr-1%Nb cladding tubes with the end caps and able to be pressurized to verify the cladding behaviour under real conditions. The conducted research and development (R&D) activities lead towards the patenting of the method with the potential use in a whole variety of industrial branches [17].

2. Resonant frequency of O-tube wall

Non-destructive method of thickness measurement of pipes works uses one or more resonant frequencies in the plane of the pipe cross-section. It can be triggered by a short blow with a rigid object such as a hammer. This is the so-called impact-echo method.

It is also possible to excite by gradual sweeping, i.e. forced harmonic oscillation, where its wavelength gradually changes over time to cover a wider frequency spectrum, while the amplitude of the excited signal remains the same. This is a classical resonance method. Tested O-shape pipes oscillate more intensely at fundamental frequencies, with a greater amplitude. This is then scanned by an electro-acoustic probe, recorded and displayed by an oscilloscope. The oscillations with the highest amplitudes then correspond to the fundamental frequencies, i.e. the resonant frequencies of the pipe.

The pipe's excited oscillations come in a variety of different shapes, but this method only deals with some of them. For thickness measurements of small diameter thin-walled pipes, it has been proven useful to work with higher frequencies and to use the frequency of oscillation of the pipe in the plane of its cross-section. These natural fundamental frequencies can not only be measured but also predicted by calculation.

Important parameters that enter the fundamental frequency calculation are the material and geometrical properties of the pipe, and possibly also external influences that affect the pipe. The method does not consider these external influences further for the calculations. However, they cannot be neglected. It is therefore advisable to avoid such influences during the measurement. These are mainly external boundary conditions such as the way the pipe is supported or suspended, the filling or wrapping of the pipe or its pressurisation. A specific case of such external conditions are coatings or oxidation layers. The use of these circumstances will be shown in the section with examples of implementation of the invention.

Among the material properties of the pipe, the elastic modulus and the density of the pipe material are particularly important properties for predicting the fundamental frequency. Both these properties can also be expressed in terms of the propagation speed of longitudinal elastic waves.

Among the geometrical properties, the diameter of the pipe and its wall thickness are important for frequency prediction. From the following equations for predicting the selected natural frequencies, it is possible to express just the pipe wall thickness as a function of the above-mentioned variables [18–20]:

$$f_r = \frac{v}{\pi d}, \tag{1}$$

$$f_n = \frac{n(n^2-1)}{\pi d^2\sqrt{n^2+1}}\sqrt{\frac{1}{3}\frac{Et^2}{\rho}}, \quad n = 1, 2, 3. \tag{2}$$

Here f_r and f_n are the ring mode and in-plane bending mode frequencies, n is the number of high harmonics, v is the P-wave propagation speed, d is the diameter of the circular pipe, E is the elastic modulus, t is the wall thickness, and ρ the specific density of the pipe material.

Generally, the method works for all pipe sizes and shapes. However, its extraordinary accuracy is depended on the wall thickness, and also on the diameter of the pipe. For very small, thin-walled pipes, such as nuclear fuel claddings, the precision can be achieved even in the range of microns.

Probes for measuring the local thickness of the cladding can be part of the standard equipment used for fuel inspection, for example in spent fuel pools. Being watertight and having high resistance to radiation are prerequisites.

The undeniable advantage of the non-destructive thickness measurement method is that the oscillation sensor can be an ultrasonic probe that is sufficiently resistant to water and radioactive gamma radiation. It is advantageous that the evaluation equipment, which is sensitive to radioactive radiation, can be concealed at a sufficient distance from the source of ionising radiation.

The invention is further elucidated by means of the drawings, where Fig. 2 shows the oscillation shapes of a circular cross-section pipe. Figure 3 shows an example of the frequency spectrum of the measured signal including the peaks of some interesting resonant frequencies of the pipe.

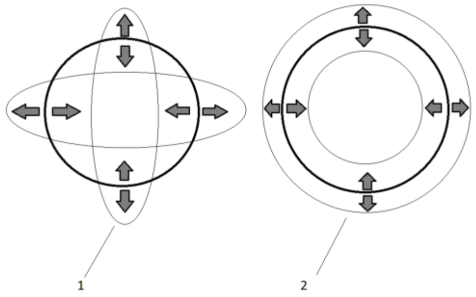

Fig. 2. The shape of the pipe oscillation in the cross-section plane via in-plane bending mode – *1*, ring mode – *2*.

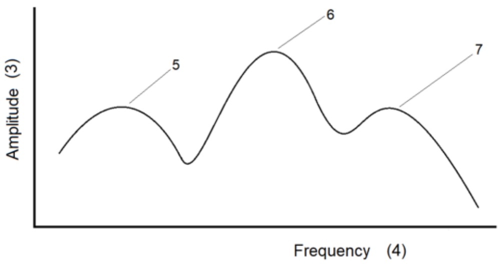

Fig. 3. Example of frequency response diagram: *3* – amplitude axis, *4* – frequency axis, *5* – resonance frequency peak of the cross-section for the in-plane bending mode and *6* – for the ring mode, *7* – for a higher harmonic.

2.1. Thin-walled tube measurement

One specific example of the use of this method is the measurement of the local thickness of nuclear fuel claddings during periodic inspections where the local geometry enters in a further calculation and/or measurement. An example is the measurement of the pressure inside a fuel rod, where the wall thickness is determined by the design of the specific fuel, but long-term measurements show standard deviations of up to 20 µm from the designed value. However, such accuracy cannot be counted on in sensitive fuel rod calculations.

Another application of the method is to verify the thickness of the oxidation layer, or the thickness of the healthy pipe material. This is particularly advantageous when oxidation occurs inside the pipe and the accuracy of conventionally used methods is not sufficient.

The method can be used even if the pipe is coated with a coating that cannot be removed for some reason. Even in this case, it is possible to determine the thickness of the pipe material accurately enough. However, slight variations due to the unknown stiffness of the coating must be taken into account.

There are many inherent oscillation shapes that could be used to predict pipe thickness. However, the best results are achieved by combining the fundamental frequency of oscillation in the plane of the pipe cross-section with in-plane bending mode and ring mode, Fig. 2. Incorporating both frequencies *5* and *6* into the appropriate relationship along with the pipe diameter will give a reasonably accurate pipe thickness result. One of the above-mentioned frequencies can then be replaced in the calculation of the pipe wall thickness by the velocity of propagation of longitudinal elastic waves, or by the square root of the ratio of the elastic modulus and density of the pipe material

$$v = \sqrt{\frac{E}{\rho}}, \tag{3}$$

where v is the propagation speed of longitudinal elastic waves, E is the elastic modulus and ρ is the specific density of the pipe's material.

The fundamental frequencies can be found in Fig. 3 where the amplitude (axis *3*) is a function of frequency (axis *4*). Fundamental frequencies appear as so-called frequency peaks (*5* to *7*). However, without the first estimation of the two peaks *5* and *6* as accurately as it could, it is impossible to find the frequency peaks in the complex frequency spectrum, Fig. 2. The spectrum contains also a number of high harmonic's peaks *7*, noise and other obscured peaks.

Nevertheless, the method, location and intensity of excitation must be adapted to the measurement of each frequency. All instruments must be set up for the particular oscillation that may be measured. It is also recommended to verify the gain of the correct values by fitting them to the pre-prepared relations, Eqs. (1) and (2). Those have been based on a good estimation of the pipe wall thickness and the longitudinal elastic-wave propagation velocity.

2.2. Fuel cladding computer model and oscillation

The Abaqus program was used for modelling the nuclear fuel cladding type Zr-1%Nb and its oscillation modes. Results fit well with the measurement, see Section 4. The best results of in-plane bending mode oscillation f_n, within n = 2 to 4, were obtained using a 23.4 mm long model (see Figs. 5 to 7). The outer diameter of Zr-1%Nb cladding is 9.1 mm. The ring mode oscillation f_r correlates more with the reality in the case of a short tube or ring of the length L = 2.34 mm, Fig. 4.

The material was modelled as elastic, using Young's modulus and Poisson's ratio of Zr-1%Nb at room temperature. Quadratic finite elements were applied in a static analysis, which was conducted just prior to the frequency analysis (using the Lanczos solver) to enable the modelling of various conditions. The examples of the oscillation shapes at frequencies f_2 (or f_2'), f_3 (or f_3') and f_4 (or f_4') are shown in Figs. 5, 6 and 7, respectively.

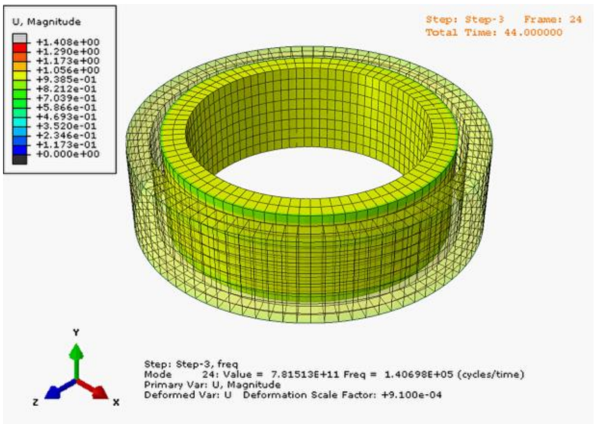

Fig. 4. Ring mode of Zr-1%Nb cladding oscillation modelled in the Abaqus program: mode 24, frequency f_r = 140 698 Hz).

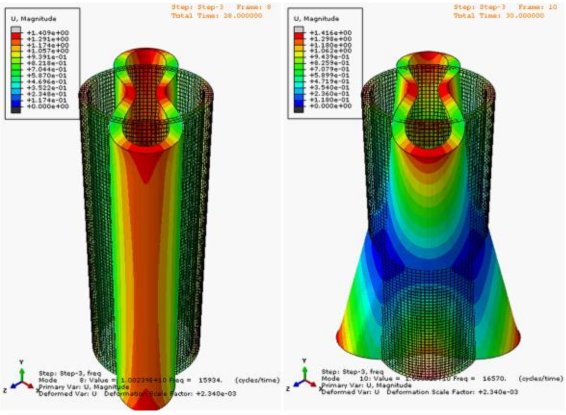

Fig. 5. In-plane bending mode of Zr-1%Nb cladding oscillation modelled in Abaqus: mode 8, frequency f_2 = 15 934 Hz (left); mode 10, frequency f_2' = 16 570 Hz (right).

3. Analog calculation of the wall thickness

The O-tube wall thickness can be measured either by commonly used destructive and non-destructive testing methods or by a newly developed resonant method.

3.1. Resonant method

One specific when it is necessary to express the wall thickness of the pipe t based on the constant speed of the ultrasonic signal propagation v, the outer diameter d_1, and the frequency of the in-plane bending mode of the cross-section f_n, for n = 1 to infinity, the following approach can be taken on the basis of Eq. (2):

$$f_n = \frac{\sqrt{B_n}}{\pi} \frac{v}{(d_1 - t)^2} t. \tag{4}$$

Thus

$$(d_1 - t)^2 = \frac{\sqrt{B_n}}{\pi} \frac{v}{f_n} t,$$

$$t^2 - 2d_1 t + d_1^2 = \frac{\sqrt{B_n}}{\pi} \frac{v}{f_n} t,$$

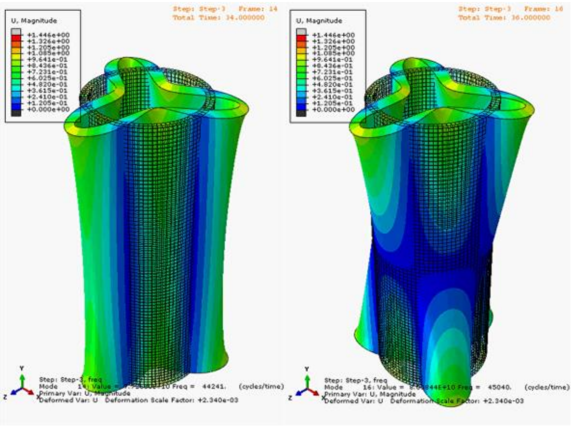

Fig. 6. In-plane bending mode of Zr-1%Nb cladding oscillation modelled in Abaqus, mode 14: frequency f_3 = 44 241 Hz (left), mode 16: frequency f_3' = 45 050 Hz (right).

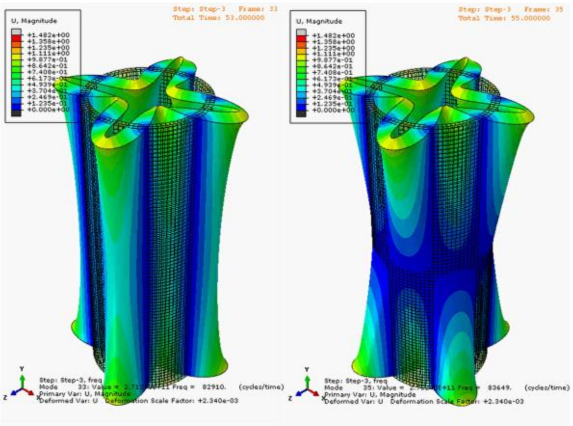

Fig. 7. In-plane bending mode of Zr-1%Nb cladding oscillation modelled in Abaqus, mode 33: frequency f_4 = 82 910 Hz (left), mode 35: frequency f_4' = 83 649 Hz (right).

$$t^2 + \left(-2d_1 - \frac{\sqrt{B_n}}{\pi}\frac{v}{f_n}\right)t + d_1^2 = 0,$$

and since

$$at^2 + bt + c = 0,$$

we get

$$a = 1, \quad b = -2d_1 - \frac{\sqrt{B_n}}{\pi}\frac{v}{f_n}, \quad c = d_1^2.$$

This results in

$$t = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} = \frac{2d_1 + \frac{\sqrt{B_n}}{\pi}\frac{v}{f_n} \pm \sqrt{\left(-2d_1 - \frac{\sqrt{B_n}}{\pi}\frac{v}{f_n}\right)^2 - 4d_1^2}}{2}. \qquad (5)$$

Equation (5) can use the speed of ultrasonic signal propagation v calculated by Eq. (3), where E is the known modulus of elasticity and ρ is the known density of the material. For Eq. (4), to work well, it is necessary to determine the quantities v, E, or ρ sufficiently accurately, which can pose a minor challenge, especially when measuring only a single pipe. The coefficient B_n varies for each mode shape n from 1 to infinity. For illustration, several values will be provided in Table 1.

Table 1. Values of the coefficient B_n for individual mode shapes (number n).

Shape of oscillation *n*	1	2	3	4
B	0	2.400	19.20	70.60

A more precise but harder-to-measure method is the comparison of two resonance frequencies f_n and f_r for n = 1 to infinity. The frequency f_r is the so-called ring mode of the tube's cross-section, and Eq. (2) is expressed as

$$f_r = \frac{v}{\pi d} = \frac{v}{\pi(d_1 - t)}. \qquad (6)$$

The velocity v can be expressed using Eq. (4) or (6):

$$v = f_r\pi(d_1 - t) = \frac{f_n\pi(d_1 - t)^2}{\sqrt{B_n}t},$$

$$f_r\sqrt{B_n}t = f_n(d_1 - t),$$

$$f_r\sqrt{B_n}t + f_n t = f_n d_1,$$

The wall thickness t can be derived from:

$$t = \frac{f_n d_1}{f_r\sqrt{B_n} + f_n},$$

$$t = \frac{d_1}{\frac{f_r}{f_n}\sqrt{B_n} + 1}. \qquad (7)$$

Equation (7) has the undeniable advantage of being independent of the material properties and characteristics, eg. modulus E, density ρ or velocity v. However, it requires measuring two different frequencies f_r and f_n for n = 2 or higher, which may necessitate two different measurement methods, and possibly two separate devices, probes, frequency filters, etc. Ideally, if the frequencies are not too far apart, e.g. 15 kHz and 44 kHz, everything can be measured with a single apparatus.

Other methods for determining the tube wall thickness include measurements using a micrometre and bore gauge or they are based on the mass and known material density comparison.

3.2. Mass/density method

Although the density of basic materials is known, it varies across different alloys. If the alloy type is known, it is possible to calculate thickness t using Eq. (8), derived from the formula for material density, based on the known volume V and mass m:

$$\rho = \frac{m}{V} = \frac{m}{AL},$$

where

$$A = \frac{m}{\rho L} = \frac{\pi(d_1^2 - d_2^2)}{4}.$$

Here, d_1 is the outer diameter of the tube measured with a micrometre; the inner diameter of the tube d_2 can be expressed as:

$$d_2 = d_1 - 2t.$$

Out of this:

$$d_1^2 - d_2^2 = d_1^2 - (d_1 - 2t)^2 = d_1^2 - d_1^2 + 4d_1t - 4t^2$$

$$= 4d_1t - 4t^2 = \frac{4}{\pi}\frac{m}{\rho L}.$$

Hence

$$\frac{m}{\rho L\pi} = d_1t - t^2,$$

and therefore

$$t = \frac{d_1 - \sqrt{(-d_1)^2 - 4\frac{m}{\rho L\pi}}}{2}, \tag{8}$$

where L is the length of the tube.

For the reasons mentioned above, Eq. (8) is considered the most realistic.

3.3. Micrometre – bore gauge method

In the case of measuring the inner diameter d_2 with a bore gauge, the following applies:

$$t = \frac{d_1 - d_2}{2}. \tag{9}$$

Compared to Eq. (8), Eq. (9) can determine the thickness t at any end of the tube. However, it does not reach nearly the same level of accuracy as in Eq. (8).

3.4. Ultrasonic testing

The most popular method for the non-destructive determination of thickness, and not only of metal products, is the ultrasonic reflection method (ultrasonic pulse echo), based on the measurement of the transit time of flight of ultrasonic pulses [21–23]. The principle of the method is that the signal sent by the ultrasonic probe passes through the material of the body under examination, is reflected from its opposite wall and returned to the receiving probe (this might be the same ultrasonic probe as the sending one). The thickness is then determined according to the physical properties of the material under test and the measured time of flight. This method is a very frequently used non-destructive method in the engineering industry as well as in testing and diagnostics of structures, it is included in Czech and European standards, e.g. ISO 16809 [24]. The accuracy of this method depends on the sensitivity and resolution of the probes and the sensing device. For thin-walled components, measurement accuracy is in the tens of microns.

4. Nuclear fuel cladding measurement

In a specific case, the determination of wall thickness for a small-diameter zirconium tube will be compared using different approaches, based on various measured quantities. This example involves a model of a fuel rod, or in other words, nuclear fuel cladding. The measured values are shown in Table 2. An example of measure frequencies f_r is shown in Fig. 8. Table 3 presents a comparison of the results and accuracy of calculations based on the individual Eqs. (5), (7), (8) and (9).

5. Conclusions

The presented method for measuring the thickness of small-diameter thin-walled tubes using the resonant frequencies of the tube's cross-section can determine the wall thickness with an accuracy of up to 1 μm. This sets it apart from convention-al methods, such as the ultrasonic thickness gauge, which typically measures with an accuracy of ±10 μm.

The method can be applied in all areas of industry where non-destructive determination of the wall thickness of a closed pipe is required. It is particularly suitable for thin-walled closed pipes and tubes where the accuracy of standard methods is not sufficient, and the measured value can have a significant influence on further work with the measurement results.

The method can be used, for example, to check the thickness of nuclear fuel cladding, which is also essentially a closed thin-walled tube of small diameter. The method might be applicable for the qualification of nuclear fuel assemblies for a deep underground repository where a repeat verification of the fuel condition will be required. It can be used for non-destructive investigation of radioactive fuel in the hot cells using mechanical manipulators.

Outside the nuclear industry, the method can be applied to the inspection of piping in laboratory apparatuses where highly abrasive media are used, e.g. liquids or gases with solid particles

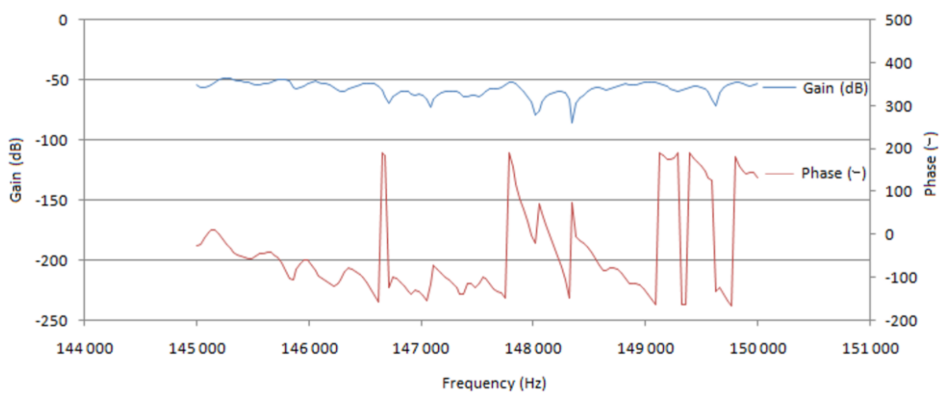

Fig. 8. Ring mode measurement in fuel rod No. 7 using classical resonance method approach, sweeping the signal (frequency f_r = 148 000 or 148 300 Hz).

or acid admixtures. In this way, it is possible to check the degree of wear of the piping without dismantling the installation and without interrupting the technological process for a significant length of time and without leaking liquids or vapours into the surroundings.

The above presented data come from the classical resonance approach whose accuracy reaches one or more micrometres. Future work will focus on refining measurements using the impact-echo method, combining different approaches, also on the more precise modelling of oscillation modes under various external or internal conditions. All these could decrease the measurement error by 50% or more. This would make the approach very effective and attractive for all fields of industry, not just the nuclear one.

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