*Проведено теоретичні дослідження по моделюванню напружено-деформованого стану фасонних профілів та його впливу на зміну акустичної бази вимірювання при використанні дзеркально-тіньового методу. Встановлені лінійні та кутові зміщення центральної лінії акустичного променя ультразвукової хвилі, що є передумовою розробки конструкції блоку п'єзоелектричних перетворювачів для акустичної діагностики напруженого стану фасонних профілів*

*Ключові слова: акустичний контроль, напружено-деформований стан, фасонні профілі*

*Проведены теоретические исследования по моделированию напряженно-деформированного состояния фасонных профилей и его влияния на изменение акустической базы измерения при использовании зеркально-теневого метода. Установлены линейные и угловые смещения центральной линии акустического луча ультразвуковой волны, что является предпосылкой для разработки конструкции блока пьезоэлектрических преобразователей для акустической диагностики напряженного состояния фасонных профилей*

*Ключевые слова: акустический контроль, напряженно-деформированное состояние, фасонные профили*

UDC 624.014:620.111.3
DOI: 10.15587/1729-4061.2016.79978

# CORRECTING THE POSITION OF PIEZOELECTRIC TRANSDUCERS DURING ACOUSTIC CONTROL OF THE STRESSED-STRAINED ROLLED SECTIONS

**G. Tymchik**
Doctor of Technical Sciences, Professor*
E-mail: deanpb@kpi.ua
**M. Filippova**
PhD, Associate Professor*
E-mail: m.filippova@kpi.ua
**M. Demchenko**
Postgraduate Student*
E-mail: amd.8@meta.ua
*Department of Instrument Making
National Technical University of Ukraine
"Igor Sikorsky Kyiv Polytechnic Institute"
Peremogy ave., 37, Kyiv, Ukraine, 03056

## 1. Introduction

With the increasing pace of construction, there is a growing need for the development and use of new methods and means to ensure their integrity, reliability, performance efficiency, safety, which will make it possible to conduct in a short time diagnostics of critical elements of constructions. The main indicator of technical condition of a building, which is responsible for its performance, is the stressed-strained state (SSS) of structural elements. As the bearing elements of modern buildings of civil and industrial purpose, metal structures (MS) are used, made of welded and rolled shaped sections (SS) [1–4].

All structural elements of steel SS of MS work on bend. Maximum values of stress occur in places of the largest bend. To provide for reliability, when designing MS, the permissible values of stresses are calculated that would not lead to the occurrence of critical stresses in the areas of maximum concentration. However, a change in SSS of a building's MS is caused by several factors: change in the purpose of a facility, reorganization of a technological process with a change in technological lines in the building, operation of facility beyond the limits of design modes, natural disasters, and changes in regulatory requirements.

To ensure integrity of a structure, it is necessary to carry out current control of the technical condition by identifying real values of the stresses in places of their concentration [5, 6]. Therefore, of particular importance is the development of operational methods of non-destructive control, which would allow diagnosing the value of SSS of SS with high reliability.

The relevance of the work is in a comprehensive study of the impact of SSS and the SS geometry on the change in the measurement base for the entire nomenclature row of SS, which will enable designing means for diagnosing SSS of SS under operation conditions.

## 2. Literature review and problem statement

The operation of a facility under conditions that extend beyond operational requirements causes the occurrence of critical situations associated with the change in SSS of SS. To diagnose the actual stresses of metal structures in operation, the acoustic methods are used based on the acoustoelastic effect [7, 8], that is, establishment of functional dependency between delayed distribution of acoustic wave and stress tensors [9]. This is due to the fact that mechanical stresses lead to the change in velocity of sound propagation in medium.

The methods of determining stress in the strained elements of wheels, tanks, pipes, cisterns and rails are fairly well developed and used for diagnostics in ship-building, nuclear, oil and gas, chemical and energy industries. The advantages of acoustic method include relative simplicity, compactness of the measuring equipment and application versatility for all materials [10].

The study of authors [9, 10] is to a greater degree aimed at applying echo-method. This method allows determining uniaxial and biaxial tensions that are averaged by the volume of ensounding. This method is used for the diagnostics of pipes, rails [9, 11]. Authors [10, 12] suggested using this method for determining elastic constants of metal. In this method, the change in geometric dimensions of the object of control is neglected and accepted as invariable. In the considered papers, the authors point out the possibility of expanding the field of application of these methods [8, 9] for a significantly larger number of metal structures. However, when using echo-method for SS that have slopes of internal edges of the shelves, there is beam mixing for a receiving-emitting transducer. Thus, the use of one transducer to control SS is impossible.

Author [13] considers the possibility of using surface waves to determine biaxial and uniaxial stresses. For the excitation of surface waves, author [14] considers the use of laser optical-acoustic excitation. To implement this method, it is necessary to ensure appropriate quality of the surface, which complicates the process of diagnostics. A special attention in this case should be paid to the technology of fabrication of material of the control object. It can affect the result of diagnostics due to the existence of metal anisotropy.

Papers [15, 16] analyze the use of surface waves to determine longitudinal and transverse stresses of welded elements under conditions of instability of the acoustoelastic effect and measurement error for this method. Examples of estimation of components of a general error that affects the result of control of physical-mechanical characteristics of different objects are presented in [17]. The use of surface waves for pipes and railway rails is well explored in [18, 19]. These studies are aimed at establishing values of the residual and actual stresses, due to the difference in velocities for strained and non-strained states. The character of distribution of stresses in rolled SS directly depends on the presence of residual stresses and the quality of the surface after rolling. Design features and the action of loads of SS, used in MS of buildings, are different from those of pipes, rails, pipe lines, tanks. That is, application of this method gives a large error in the results of diagnostics. This method will also require increase in the zone of ensounding. Stresses in the flat metal structures made of SS are distributed in such a way that, to increase reliability, it is necessary to reduce the area of ensounding for the work in the front zone.

Article [20] proposed the use of the mirror-shadow method for determining mechanical stresses in the shelves of SS. In particular, taking into account the velocity of propagation of ultrasonic waves in the non-strained sections of SS. This allows conducting measurement of actual stresses without using of metal samples with zero loads. For the implementation of this method, it is necessary to establish the effect of geometry of the shelf and its change under the influence of the maximum-allowable stresses on displacement of the measurement base. This research will help establish the degree of influence of the geometry of SS on the total error of the result of diagnostics and to develop recommendations for its reduction by introducing correction of position of piezoelectric transducers.

## 3. Aim and tasks of the study

The purpose of the study is to establish the possibility of applying the mirror-shadow method of ensounding of the shelf of shaped sections for the diagnostics of metal structures SSS.

To accomplish the set goal, the following tasks are to be solved:

– to conduct analysis of the factors that occur in the course of implementation of the mirror-shadow method of acoustic diagnostics of SSS of SS of MS;

– to assess the contribution of each factor in the result of acoustic diagnostics of SSS of SS of MS;

– to develop recommendations for the reduction of influence of each of the factors on the result of acoustic diagnostics of SSS of SS of MS.

## 4. Analysis of the factors that occur in the course of implementation of the mirror-shadow method of diagnostics of shaped sections

At bending under the action of load, there is a concentration of maximum stresses on the shelves of sections in the cross section of SS that acts as an element of a beam. Distribution of stresses happens in such a way that one shelf is stretched while the other one is compressed. This makes it possible to use them to establish a connection between a particular kind of stresses with relative change in the velocity of propagation of ultrasonic waves. However, due to the stress, there occurs a deformation of the shelves, in particular, a change in their thickness. In the course of angle ensounding, change in the thickness of control object may lead to displacement of the point of arrival of ultrasonic waves beyond the limits of receiving transducer and significantly affect the result of diagnostics. That is why it is necessary to estimate magnitude of the beam displacement at the deformation of control object under the action of load at the maximum permissible values. Also of special importance is the geometry of SS shelves, which in half the nomenclature series have slopes of internal edges, which causes displacement of the beam of acoustic wave sideways from the center of receiving transducer.

### 4. 1. Impact of change in geometric dimensions of the control object on the position of point of arrival of ultrasonic wave

Let us consider the SS that has a console fixing and is exposed to loading, which is concentrated in a point at its end. For the part of section $\delta_0$=AB (Fig. 1), which corresponds to the distance between receiving and emitting piezoelectric transducers at ensounding at angle Θ, where

$$AB=2t\cdot tg\Theta, \tag{1}$$

there may be a change in the position of the point at which the beam of acoustic signal arrives (Fig. 2). It is linked to the change in thickness of the shelf t by certain magnitude Δt, so that the distance $A_1B_1$, denoted previously as AB, changes when stretched and compressed:

$$A_1B_1=2(t-\Delta t)tg\Theta, \quad (2)$$

$$A_1B_{21}=2(t+\Delta t)tg\Theta,. \quad (3)$$

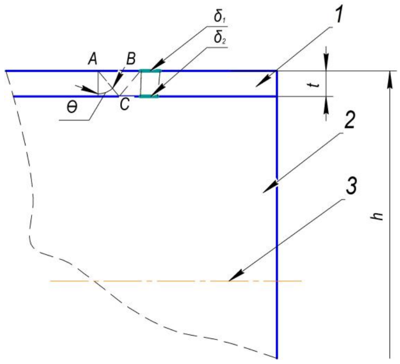


Fig. 1. Stretching the shelf of a beam: 1 — shelf of a beam; 2 — wall of a beam; 3 — neutral line of a beam

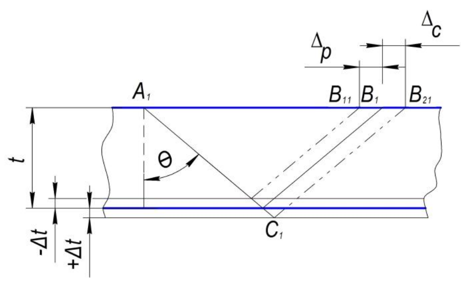


Fig. 2. Displacement of the point at which the beam arrives at the stretch-compression stresses

Deformation of SS metal in the working range of loads occurs by Hooke's law. This enables us to find absolute elongation of shelves of the top $\delta_1$ and bottom $\delta_2$ edges (Fig. 3, 4):

$$\frac{\delta_{max}-\delta_0}{\delta_0}=\frac{\sigma_1}{E}; \quad (4)$$

$$\frac{\delta_{min}-\delta_0}{\delta_0}=\frac{\sigma_2}{E}; \quad (5)$$

$$\frac{\delta_1}{\delta_0}=\frac{\sigma_1}{E}; \quad (6)$$

$$\frac{\delta_2}{\delta_0}=\frac{\sigma_2}{E}, \quad (7)$$

where $\sigma_1$, $\sigma_1$ are the current tensions on the edges of the shelf; E – modulus of elasticity.

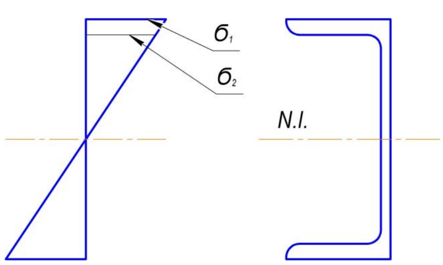


Fig. 3. Character of distribution of stresses in the cross section of the shaped section

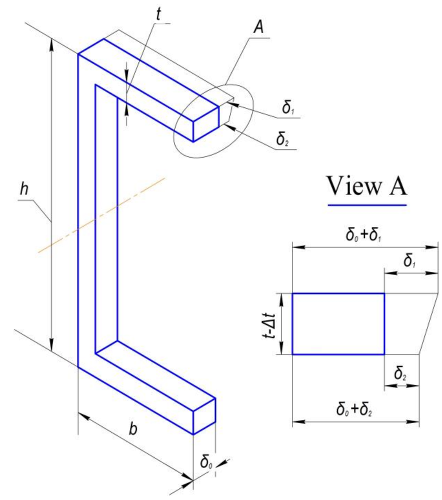


Fig. 4. Change in geometrical parameters of the shelf of a shaped section at stretching

For the top edge of the shelf with the length δ1, stress is accepted as the maximum allowable value [σ], then

$$\delta_1=\frac{[\sigma]}{E}\delta_0. \quad (8)$$

For the bottom shelf, which is located at the distance $\frac{h-t}{2}$ from the neutral line of a shaped section, we have

$$\sigma_2=\frac{M_z}{J_z}\frac{h-t}{2}, \quad (9)$$

where $M_z$ is the moment of force; $J_z$ is the moment of inertia.

Moment of force $M_z$ will be the same for the entire cross-section of a shaped section

$$M_z=W_z[\sigma], \quad (10)$$

where $W_z$ is the resistance moment.

Then we receive:

$$\sigma_2=\frac{W_z[\sigma]}{J_z}\frac{h-t}{2}. \quad (11)$$

Since $W_z/J_z$ is represented for the point of the maximum acceptable value of stress, then [σ]

$$\frac{W_z}{J_z}=\frac{2}{h}. \quad (12)$$

Then

$$\sigma_2=[\sigma]\frac{h-t}{h}. \quad (13)$$

The elongation of bottom edge of the shelf $\delta_2$ at reaching [σ] on the outer surface of the shaped section will be defined

$$\delta_2=\frac{[\sigma]}{E}\frac{h-t}{h}\delta_0. \quad (14)$$

Let us consider the process of change in geometrical parameters of the shelf of a shaped section at loading. Typical for this process is the constancy of the volume, that is, $V_0$ and after $V_i$ deformation:

$$V_0=V_i, \tag{15}$$

where $V_0$ is the volume of the shelf before deformation; $V_i$ is the volume of the shelves after deformation.

The volume of shelf $V_0$ of length $\delta_0$ in the non-loaded condition (Fig. 4) is:

$$V_0=b\cdot t\cdot l_0, \tag{16}$$

and under load

$$V_n = b\cdot(t-\Delta t)\cdot\frac{(\delta_0+\delta_1)+(\delta_0+\delta_2)}{2}. \tag{17}$$

Then

$$b\cdot t\cdot l_0 = b\cdot(t-\Delta t)\cdot\frac{(\delta_0+\delta_1)+(\delta_0+\delta_2)}{2}. \tag{18}$$

We assume the width of the shelf invariable in the process of deflection of the beam b=const. This assumption is adopted in order to maximally take into account possible elongation of the shelf of a beam and, accordingly, deflection of the beam at the deformation of a beam.

Reduction of height of the shelf $\Delta t$ occurs and elongation of the shelf surfaces extending $\delta_1$ and $\delta_2$. Then (18) takes the form:

$$1-\frac{\Delta t}{t}=\frac{1}{1+\dfrac{\delta_1+\delta_2}{2\delta_0}}. \tag{19}$$

By comparing (19) and (2), we obtain:

$$\frac{A_1B_{11}}{2t\mathrm{tg}\alpha}=\frac{1}{1+\dfrac{\delta_1+\delta_2}{2\delta_0}}. \tag{20}$$

The sum of $\delta_1+\delta_2$ will take the form:

$$\delta_1+\delta_2=\frac{[\sigma]}{E}\delta_0\left(2+\frac{t}{h}\right). \tag{21}$$

Then,

$$\frac{A_1B_{11}}{2t\mathrm{tg}\alpha}=\frac{1}{1+\dfrac{1}{2}\dfrac{[\sigma]}{E}\left(2+\dfrac{t}{h}\right)}. \tag{22}$$

Let us select integrated parametric characteristics of the process:

– characteristic of shaped section of the rolled metal by the number of section $2+\frac{t}{h}=\bar{h}$;

– characteristic of material of the rolled metal

$$\frac{A_1B_{11}}{2t\mathrm{tg}\alpha}=\frac{1}{1+\bar{\sigma}\bar{h}}. \tag{23}$$

We will introduce replacement $K=\bar{\sigma}\cdot\bar{h}$ in (23)

$$\frac{A_1B_{11}}{A_1B_1}=\frac{1}{1+K}. \tag{24}$$

From Fig. 2, $A_1B_{11}=A_1B_1-B1B11$, let $B_1B_{11}=\Delta_P$ is the delta of stretching, then

$$\frac{\Delta_p}{A_1B_1}=\frac{K}{1+K}. \tag{25}$$

Similarly we obtain reduction of the beam relative to the center of transducer when compressed:

$$\frac{A_1B_{11}}{A_1B_1}=\frac{1}{1+K}; \tag{26}$$

$$\frac{\Delta_c}{A_1B_1}=-\frac{K}{1+K}. \tag{27}$$

Coefficient ±1 at $\frac{K}{1+K}$ corresponds to the nature of stress observed on the shelf's section.

Shifting the center of the beam at compression $\Delta_C$ and stretching $\Delta_P$ (Fig. 5, 6) occurs within the dimensions of piezoelement of the transducer. The size of piezoelement of a compact transducer is 5×5 mm. For the shaped sections that have plane-parallel edges of shelves, double-T profile and hot rolled double-T profile, we considered deflection of the center of the beam from the center of piezo acoustic transducer of deviation. At permissible load even for the biggest profile of the rolled metal it does not exceed 0.06 mm, which is 2.4 % of half the side of the contact surface of transducer.

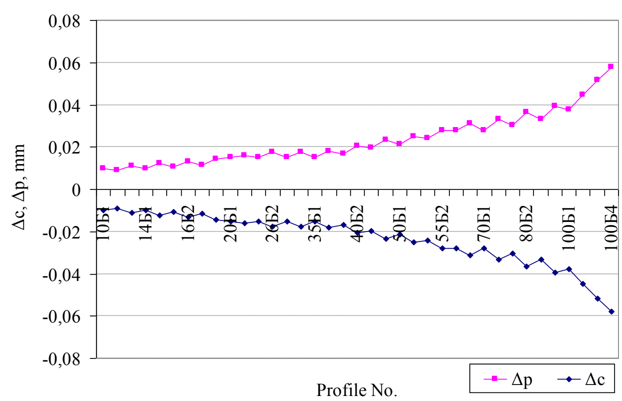


Fig. 5. Displacement of the point of arrival of the beam at stretching $\Delta_P$ and compression $\Delta_C$ for a nomenclature series of double-T profile rolled metal with straight edges of shelves

Data analysis of the graphs on linear displacement of the point of arrival of the beam at stretching and compression revealed that at maximum permissible value of tension, the center of ultrasonic wave is displaced by an insignificant magnitude for all types of SS, which is connected to low linear deformations of the shelf of profile. Thus, for the sections that have parallel inner edges of shelves, there is no need to introduce correction of position of receiving transducer relative to the emitting one.

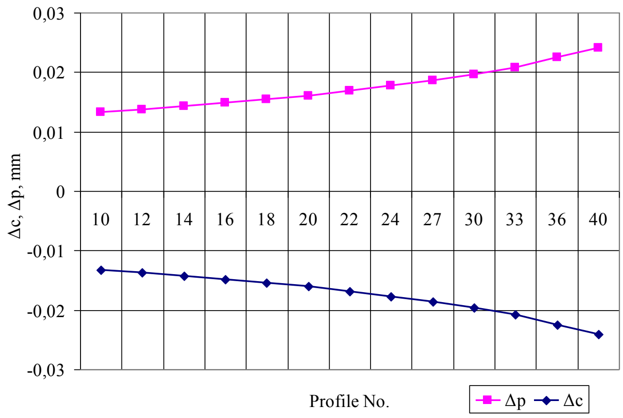


Fig. 6. Displacement of the point of arrival of the beam at stretching $\Delta_P$ and compression $\Delta_C$ for a nomenclature series of double-T profile rolled metal with straight edges of shelves

**4. 2. Effect of geometry of the control object on the position of the point of arrival of ultrasonic wave**

Let us consider the scheme of displacement of the beam at angle ensounding, when the edges of beam's shelf have a slope.

Sections that have sloping edges of shelves are defined according to the following standards:

1. GOST 8239-89 "Steel hot-rolled double-T profiles" up to profile Number 60 with a slope from 6 to 12 %.

2. DSTU 3436-96 "Steel hot-rolled channel bars" up to profile 40U with a slope to 8 % at h<300 mm and to 5 at h>300 mm.

It was determined for the shelves with parallel faces that there is no need to move transducers. However, in the shelves with sloping edges, the beam is moved in several planes due to nonparallelism of planes. That is why it is necessary to set the dimension of the beam's displacement and the need for the introduction of correction of the point of location of receiving transducer relative to the emitting one (Fig. 7–9).

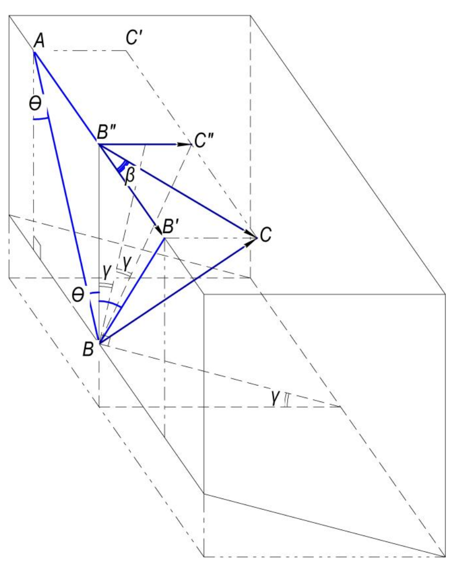


Fig. 7. Displacement of ensounding base in the shelf with sloping edges

Point A (Fig. 7–9) of the introduction of the beam in material. The beam at angle $\alpha$ passes to the opposite surface of the shelf, which has slope $\gamma$, to point B (its projection onto the top edge of the shelf – point B″).

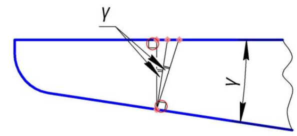


Fig. 8. Projection of ensounding base in the shelf with sloping edges: side view

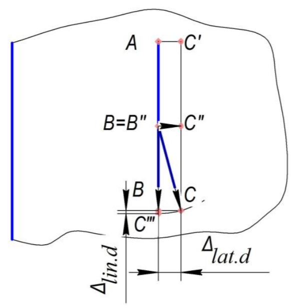


Fig. 9. Projection of ensounding base in the shelf with sloping edges: top view

The expected point which the beam will reach at parallel shelves is B′. However, the angle of inclination of the shelf $\gamma$ implies shifting the beam relative to the perpendicular plane that is shows by points BB″C. Then point C, which the beam will reach, is found by adding vectors of direction of the beam within the plane $\overline{B''C''}$ and $\overline{B''B'}$ and the resultant vector $\overline{B''C}$

$$AC' = BC' = t\,tg2\gamma; \tag{28}$$

$$BB' = AB = t\cos\theta; \tag{29}$$

$$B''C = \sqrt{(BB')^2 + (B'C)^2}; \tag{30}$$

$$B''C = t\sqrt{tg^2 2\gamma + tg^2\theta}; \tag{31}$$

$$tg\beta = \frac{B'C}{BB'} = \frac{tg2\gamma}{tg\alpha}. \tag{32}$$

From Fig. 9 we determine lateral displacement $\Delta_{\lambda at.d}$=B′C and linear $\Delta_{lin.d}$=B″C–B″B′.

Let us use valid data for the channel-type SS to consider the graph of the lateral $\Delta_{lat.d}$ and $\Delta_{lin.d}$ linear displacements (Fig. 10). We can see from the graph that $\Delta_{lin.d}$ for the given sections does not cross the boundary of half the dimension of piezo electric plate of transducer of 2.5 mm. That is, ultrasonic waves will proceed within the limit of piezoelectric converter and $\Delta_{lat.d}$ takes a very low value, such that it can be neglected.

According to standards [3, 4], SS of channel type of height up to 300 mm are made with a slope up to 8 % ($\Delta_{lin.d}$ – 8 %, $\Delta_{lat.d}$ – 8 %), and after 300 mm – with a slope up to 5 % ($\Delta_{lin.d}$ – 5 %, $\Delta_{lat.d}$ – 5 %). Displacement of the point of arrival of ultrasonic waves in the shelves with slopes of inner edges of the shelves of 8 % does not exceed 1.75 mm, and of 5 % – 1.5 mm for the biggest number of profile. This makes it possible not to adjust the position of receiving transducer for the channel-type SS that has sloping internal edges of the shelves, because displacement of the center of the beam occurs within the limits of its piezoelement.

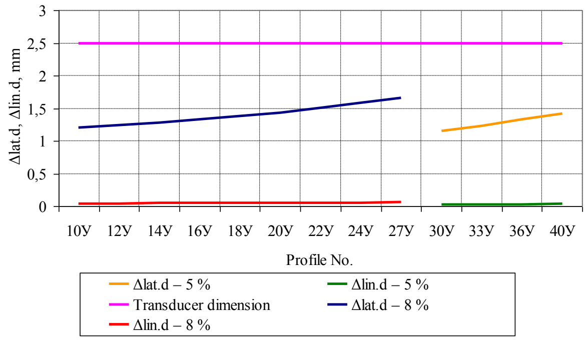


Fig. 10. Lateral $\Delta_{lat.d}$ and linear $\Delta_{lin.d}$ displacement of the beam for the channel-type SS with sloping internal edges of the shelves of 6 % and 12 %

For SS of the double-T profile type, according to the standard, we defined a range of angles of the inner edge of the shelf of 6–12 %. Lateral displacement of the beam $\Delta_{lat.d}$ will be within two boundary curves $\Delta_{lat.d}$ – 6 % та $\Delta_{lin.d}$ – 12 %.

At a 12 % slope of the edge of shelf, correction of position of receiving transducer will be needed starting from profile No. 27 (Fig. 11). However, if a shelf is made with a slope of 6 %, the adjustment is not required even for the biggest profile number.

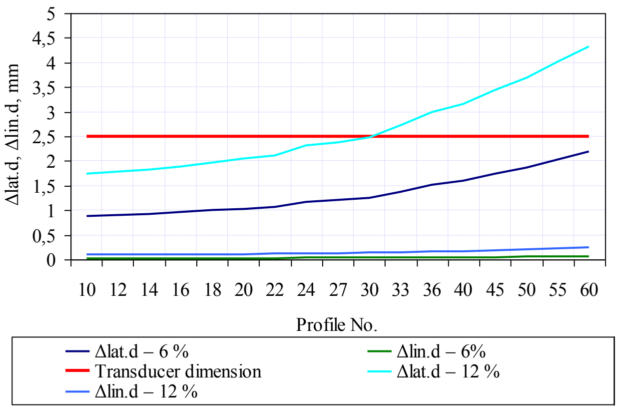


Fig. 11. Lateral $\Delta_{lat.d}$ and linear $\Delta_{lin.d}$ displacement of the beam for SS of the double-T profile type with sloping internal edges of the shelves of 6 % and 12 %

Dependencies, shown in Fig. 11, of displacement of the point of arrival of the beam at a maximum value of stress indicate the need for mandatory inspection of the slope angle of the inner edge of SS shelf. If lateral displacement $\Delta_{lat.d}$ of the point of arrival of the beam exceeds half the dimension of transducer's piezoelement, then it is necessary to introduce correction of position of the receiving transducer. This must be taken into account when designing a block of piezoelectric transducers for the diagnostics of SSS of SS.

## 6. Discussion of results of the study of the influence of stressed-strained state and geometry of shaped sections on the change in measurement base

Thickness of the shelf at the maximum permissible stress in metal occurs by a low magnitude that does not affect displacement of the point, which the beam from the emitting transducer reaches. This enables us to ignore change in the thickness of control object when determining the stresses in SS of MS by angle ensounding and confirms the possibility of implementation of the mirror-shadow method of SS ensounding.

In order to eliminate the error caused by the presence of nonparallelism of surfaces of the shelves of SS, it is recommended to measure the angle of slope of the inner edge of the shelf $\gamma$ and calculate the angle of beam displacement $\beta$ for each particular SS of the double-T profile type, which has sloping inner edge of the shelves.

For each SS of the double-T profile type with sloping edges of the shelves, it is necessary to calculate position of the receiving and emitting transducers relative to one another:

1. Calculate the distance AB″ from anchor point to the emitting transducer:

$$AB''=t\cdot tg\theta. \tag{33}$$

2. Calculate the distance B″C from the anchor point to the receiving transducer and rotation angle $\beta$:

$$B''C=t\sqrt{tg^2 2\gamma+tg^2\theta}, \tag{34}$$

$$\beta=\mathrm{arctg}\left(\frac{tg2\gamma}{tg\alpha}\right). \tag{35}$$

Using the adjustments for the calculation of position of receiving transducer relative to emitting transducer, in particular, the angle of displacement of the beam $\beta$ and the distance between the anchor point and receiving transducer B″C will help in the cases of significant non-plane-parallelism of control object in the point of arrival of the beams to reach the dimensions of piezoelement of the receiving transducer. In the case when the lateral displacement $\Delta_{lat.d}$ will be less than half the dimension of piezoelement of the receiving transducer, correcting its position can be avoided, which will not affect quality of the signal.

Conducted theoretical studies allowed us to develop recommendations on designing a block of piezoelectric transducers. This will reduce an error caused by a misalignment of the measurement base with geometric dimensions of emitting and receiving transducers when applying the mirror-shadow method.

This research enabled us to take into account the effect of geometry of the SS shelf and change in its geometry under the action of maximum allowable stress on the change in the acoustic base of ensounding. However, the nature of ultrasonic wave implies propagation of acoustic field from the emitting transducer. Thus, it will be necessary to take into account a magnitude of attenuation of acoustic field that reaches the receiving transducer, and the error, caused by it, when diagnosing SSS of SS. This work is a continuation of and justification for the use of the mirror-shadow method for the diagnostics of SSS of SS of MS [20].

## 7. Conclusions

1. Conducted theoretical research into evaluation of possibilities for realization of the mirror-shadow method of ensounding of the shelf of shaped sections for the diagnostics of stressed-

strained state of metal structures allowed us to analyze factors that occur at ensounding and assess their contribution.

2. It was found that changing geometric dimensions of shelves of the shaped sections under the action of maximum permissible load does not lead to displacement of the point of arrival of the beam of ultrasound wave beyond the boundaries of piezo electric plate of receiving transducer at ensounding of the control object.

3. Results of theoretical studies demonstrated the need to adjust position of the receiving transducer for SS, in which the non-plane-parallelism of surfaces of control object leads to displacement of the point of arrival of the beam beyond the dimension of piezoelement of piezoelectric converter. We developed recommendations to reduce the impact of the slope of the inner edge of the shelf on the result of acoustic diagnostics of SSS of SS of MS by such parameters as angle and distance relative to the anchor point.

Thus, the solution of the set problem allowed us to prove the possibility of implementation of the mirror-shadow method for the diagnostics of SSS of SS of MS.

References


1. Derzhavni Budiveljni Normy V.2.6-198-2014 [Text]. – Stalevi konstruktsii. Minrehion Ukrainy, 2015. – 205 p.
2. Derzhavnyj standart 26020-83 [Text]. – Dvutavry stalnye horiachekatannye s parallelnymy hraniamy polok. Sortament. Yzdatelstvo standartov, 1998. – 10 p.
3. Derzhavnyj standart 8239-89 [Text]. – Dvutavry stalnye horiachekatannye. Sortament. Yzdatelstvo standartov, 1989. – 6 p.
4. Derzhavnyj standart 3436-96 [Text]. – Shvellery stalnye horiachekatanye. Sortament. Hosstandart Ukrayny, 1997. – 10 p.
5. Derzhavni Budiveljni Normy 362-92 [Text]. – Otsinka tekhnichnoho stanu stalevykh konstruktsii vyrobnychykh budivel i sporud, shcho znakhodiatsia v ekspluatatsii. Derzhbud Ukrainy, 1995. – 98 p.
6. Normatyvno-pravovyj akt po okhroni praci 45.2 1.01 98 [Text]. – Pravyla obstezhen, otsinky tekhnichnoho stanu ta pasportyzatsii vyrobnychykh budivel i sporud. Minrehion Ukrainy, 1999. – 98 p.
7. Li, Z. Internal Stress Monitoring of In-Service Structural Steel Members with Ultrasonic Method [Text] / Z. Li, J. He, J. Teng, Y. Wang // Material. – 2016. – Vol. 9, Issue 4. – P. 223. doi: 10.3390/ma9040223
8. Guz, A. N Ultrasonic nondestructive methods of stress analysis in materials and structural members (review) [Text] / A. N. Guz // International Applied Mechanics. – 2011. – Vol. 46, Issue 11. – P. 3–11. doi: 10.1007/s10778-011-0413-x
9. Nikitin, N. E. Preymushchestva metoda akustoupruhosty dlia nerazrushaiushcheho kontrolia mekhanycheskykh napriazhenyi v detaliakh mashyn [Text] / N. E. Nikitin, S. V. Kazachek // Vestnyk nauchno-tekhnycheskoho razvytyia. – 2010. – Vol. 4, Issue 32. – P. 18–28.
10. Myshakyn, V. Dyahnostyka materyalov konstruktsyi na rannykh stadyiakh ustalostnoho razrushenyia y otsenka NDS materyala konstruktsyi metodamy nerazrushaiushcheho kontrolia [Text] / V. Myshakyn, V. Danylova, K. V. Kurashkyn, V. A. Klyushnykov // Vestnyk SHAU. – 2011. – Vol. 3, Issue 27. – P. 299–307.
11. Myshakyn, V. V. Yssledovanye razrushenyia pry statycheskom nahruzhenyy svarnukh soedynenyi akustycheskym metodom [Text] / V. V. Myshakyn, A. V. Gonchar, K. V. Kurashkyn, N. V. Danilova // Tiazholoe mashynostroenye. – 2009. – Vol. 7. – P. 27–30.
12. Myshakyn, V. V. Yspolzovanye ultrazvuka dlia otsenky sostoianyia metallycheskykh splavov pry plastycheskom, upruhoplastycheskom deformyrovanyy y termycheskoi obrabotke [Text] / V. V. Myshakyn, V. N. Perevezentsev, V. A. Klyushnykov, N. V. Danilov // Vestnyk Nyzhehorodskoho unyversyteta ym. N. Y. Lobachevskoho. – 2010. – Vol. 5, Issue 2. – P. 102–108.
13. Lu, H. Ultrasonic stress evaluation on welded plates with Lcr wave [Text] / H. Lu, X. S. Liu, J. G. Yang, S. P. Zhang, H. Y. Fang // Science and Technology of Welding and Joining. – 2008. – Vol. 13, Issue 1. – P. 70–74. doi: 10.1179/174329307x249405
14. Karabutov, A.. Laser ultrasonic diagnostics of residual stress [Text] / A. Karabutov, A. Devichensky, A. Ivochkin, M. Lyamshev, I. Pelivanov, U. Rohadgi et. al. // Ultrasonics. – 2008. – Vol. 48, Issue 6-7. – P. 631–635. doi: 10.1016/j.ultras.2008.07.006
15. Kim, N. Measurement of axial stress using mode-converted ultrasound [Text] / N. Kim, M. Hong // NDT & E International. – 2009. – Vol. 42, Issue 3. – P. 164–169. doi: 10.1016/j.ndteint.2008.09.005
16. Jhang, K. Y. Estimation of clamping force in high-tension bolts through ultrasonic velocity measurement [Text] / K. Y. Jhang, H. H. Quan, J. Ha, N. Y Kim // Ultrasonics. – 2006. – Vol. 44. – P. e1339–e1342. doi: 10.1016/j.ultras.2006.05.190
17. EN 14127:2004 (E) [Text]. – Non-Destructive Testing – Ultrasonic Thickness Measurement.
18. Javadi, Y. Using LCR Ultrasonic Method to Evaluate Residual Stress in Dissimilar Welded Pipes [Text] / Y. Javadi, V. Plevris, M. A. Najafabadi // International Journal of Innovation, Management and Technology. – 2013. – Vol. 4, Issue 1. – P. 170–174.
19. Manchem, L. D. Analytical Modeling of Residual Stress in Railroad Rails Using Critically Refracted Longitudinal Ultrasonic Waves With COMSOL Multiphysics Module [Text] / L. D. Manchem, M. N. Srinivasan, J. Zhou // Volume 9: Mechanics of Solids, Structures and Fluids. – 2014. – 58–63. doi: 10.1115/imece2014-38619
20. Filippova, M. V. Opredelenye napriazhennoho sostoianyia elementov metallokonstruktsyi metodom akustycheskoi tenzometryy [Text] / M. V. Filippova, G. A. Bohdan, M. A. Demchenko // Visnyk Natsionalnoho Tekhnichnoho Universytetu Ukrainy «KPI». Seriia pryladobuduvannia. – 2016. – Vol. 51. – P. 53–60.