METHODS OF EXCITATION OF ULTRASONIC NORMAL WAVES, PECUALIARITIES OF THEIR PROPAGATION AND FIELDS OF THEIR APPLICATION IN FLAW DETECTION

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Introduction

Normal waves are waves in confined medium (elastic layer) conditioned by waveguide mechanism of propagation. Normal waves representing waves in layers with free boundaries include Lamb waves featured by waveguide propagation mechanism with shifts both in the direction propagation and normally to free boundary and transverse (shear) normal waves (SH-waves) with motion occurring normally to the propagation direction and in parallel with free boundaries. In evaluation of physical phenomena occurred in a Lamb wave, as well as in definition of conditions of its occurrence and propagation, two approaches can be traced. First approach that was substantiated even in 1917 by Lamb Horace [1] is based on explanation of oaccurrence and propagation of Lamb waves from the perspective of elasticity theory. Second approach based on application of apparatus of ray theory for analysis of Lamb waves was stated by A. Schoch [2, 3], who has considered the problem of wave formation in plates supposing that transverse and longitudinal waves propagate in plates reflecting multiply from both surface of plate and called as zigzag ones. Schoch has demonstrated that Lamb wave equation is an optimal condition for propagation of multiply reflected waves in a plate without losses during reflection and without interferential attenuation between falling and multiply reflected wave beams.

Interest to study of ultrasonic (US) normal waves is related with the whole number of their advantages as compared with US waves of other types, and namely:

- monotonous character of the signal amplitude-distance dependence, which reduces requirements to orientation of acoustic units of automated testing systems;
- wide spectrum of Lamb and SH-wave modes ensuring solution of problems of detecting flaws of various types;
- possibility of nondestructive testing of long-length objects;
- implementation of the wide range of NDT methods (echo-, shadow, echo-shadow methods, application of wave transformation and others).

Studies of US normal waves performed by many scientists have made it possible to extend field of their application in nondestructive testing and technical diagnostics [4-7].

Paper discusses methods of excitation of normal waves, peculiarities of their propagation in the event of pulse excitation and fields of application in flaw detection.

Dependences of Lamb wave and SH-wave pulse amplitude on distance during operation with various sections of dispersion curves, as well as Lamb wave oulse length dependences on the elngth of emission pulse and distance are obtained experimentally.

Methods of excitation of ultrasonic normal waves

Ultrasonic (US) normal waves are featured by dispersion dependence of their phase and group velocities on frequency. Dispersion nature of US normal waves predetermines their occurrence and existence in the form of symmetric and asymmetric modes at certain relationships between layer thickness, frequency and parameters of the excitation area of US oscillations. Dispersion curves of phase and group velocities of US normal waves of lower order are presented in Fig.1a (Lamb waves) and Fig.1b

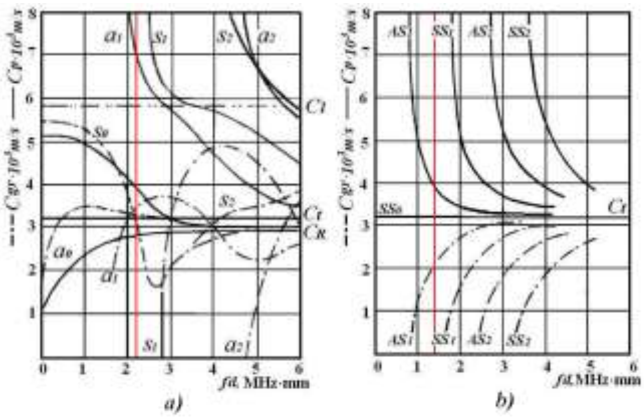
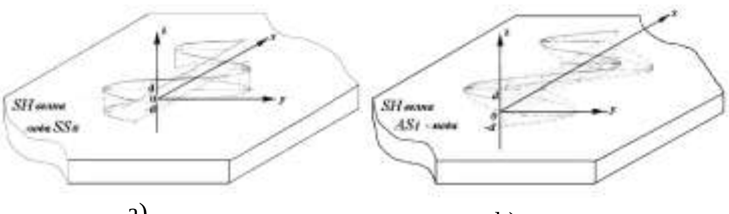


Fig.1. Dispersion curves of phase and group velocities of US waves: a) Lamb waves; b) SH-waves

(SH-waves). Unlike to Lamb waves where there is no dispersion at certain sections of dispersion curves only (horizontal sections for phase velocities; zero symmetric mode $\mathbf{S_0}$), zero symmetric mode $\mathbf{SS_0}$ exists without dispersion making its application more preferable in the whole number of cases. Efficiency and method of excitation and reception of one or another US normal wave depends on the nature of shifts in it. Fig.2 shows an example of shifts in shear normal waves with no normal components presented. Zero symmetric mode $\mathbf{SS_0}$ of SH-waves further is featured by uniform distribution of shifts across elastic layer thickness. Anti-symmetric mode $\mathbf{AS}_1$ is featured by concentration of shifts at one and another surface of elastic layer alternatively.

For US normal waves to be excited and received, two main methods are used (Fig. 3): piezoelectric one, when excitation is performed through the layer of coupling liquid or using dry point contact or across the area of piezoelectric probe (PEP), and electromagnetic-acoustic (magnetostrictive or electrodynamic) one using electromagnetic-acoustic transducers (EMAT). Necessity in development of new methods for excitation and reception (recording) of US normal waves requiring no application of coupling means was conditioned by problems of nondestructive testing of articles in the process of production along rough, untreated surface, at high temperature and movement speed and in the process of operation, including cases, when application of coupling liquid is inadmissible. Application of PEP-excited Lamb waves in nondestructive testing is related with the whole number of considerable drawbacks (instability of acoustic contact, complexity of formation of acoustic field with given directivity characteristic, etc.). Studies of EMA excitation and reception of acoustic waves in ferromagnetic and no ferromagnetic metals and alloys were started in USSR in 1933. In the context of problems of acoustic nondestructive testing, studies performed by Yu.M. Shkarlet, G.A. Budenkov, A.V. Malinka *et.al.* were recognized widely both in USSR and abroad and were developed in works of A.N. Vasil'ev, S.Yu. Gurevich, V.A. Komarov, A.V. Kharitonov, I.V. Il'in, George A. Alers, R. Bruce Thompson, G. Hübschen and others. Author with collaborators has proposed and examined magnetostrictive option of the EMA excitation method [8, 12-18] consisting in that surface of ferromagnetic layer is affected by high-frequency electromagnetic field excited by an inductor in the form of discrete emitters and constant or pulse magnetic field is entered into it with intensity vector lying in the plane of layer and oriented at



a) b)

Fig.2. Shifts in shear US normal waves: a) symmetric mode of zero order SS_0; b) anti-symmetric wave AS_1

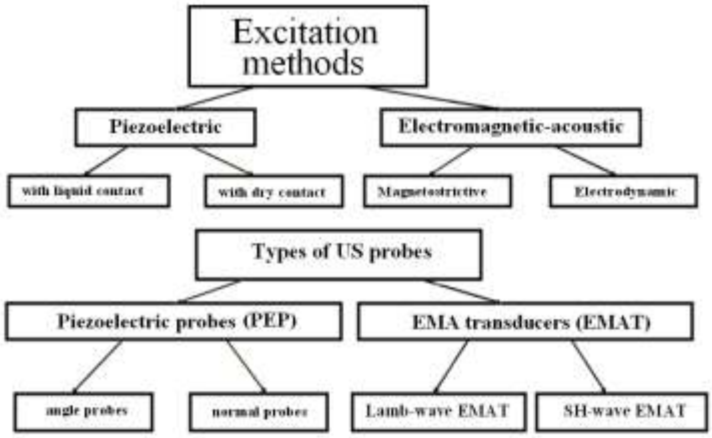
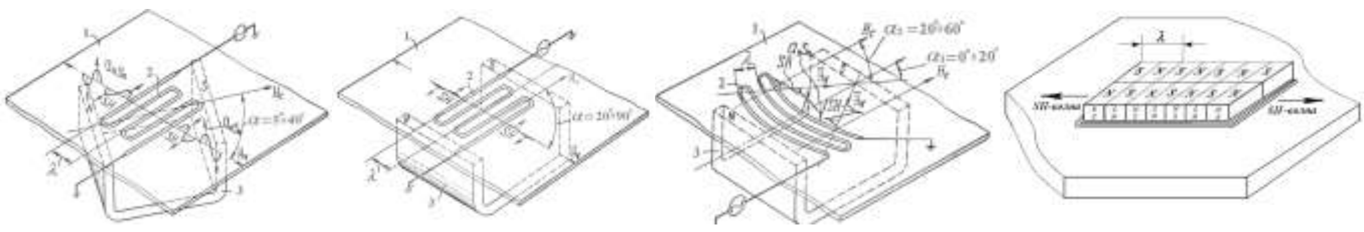


Fig.3. Methods of excitation of ultrasonic normal waves



a) b) c) d)

Fig.4. EMA methods of excitation of ultrasonic normal waves: a), b), c) - magnetostrictive, d) - electrodynamic

angle α to the direction of propagation of excited wave (Fig.4a). It is established that due to selection of angle α (Fig. 4a), distance between discrete emitters corresponding with wave half-length $\lambda/2$ and frequency f of electromagnetic oscillations, simultaneous or alternative excitation of Lamb waves (of SV-polarization) and shear normal waves (of SH-polarization). Herewith, the length of excited wave is defined as value of phase velocity of selected mode divided by frequency $\lambda=Cp/f$. When inductor is executed in the form of the part of concentric circles (fig. 4c), focusing of Lamb wave or SH-wave within the given area of elastic layer is provided. Figure 5 presents dependence of US normal wave pulse amplitude on angle α between intensity vector of bias field and wave propagation direction that was studied experimentally with options of magnetostrictive excitation (Figs. 4a, 4b). It is seen from this Figure that coincidence of the direction of magnetic field intensity vector and wave propagation direction corresponds with optimal value for Lamb wave. Shear normal waves are excited within the range of angles $\alpha=5^o\div40^o$ and $\alpha=20^o\div90^o$; moreover, amplitudes of shear normal waves obtain their maximal value at angles $\alpha=37^o$ and 90^o. Relationship between zero mode amplitudes of Lamb waves and SH-waves is characteristic: modes $\boldsymbol{a_0}$ and $\boldsymbol{S_0}$ of Lamb waves are excited with similar efficiency, while modes $\boldsymbol{SS_0}$ and $\boldsymbol{SS_1}$ of SH-waves - in ~ 2-3 times weaker.

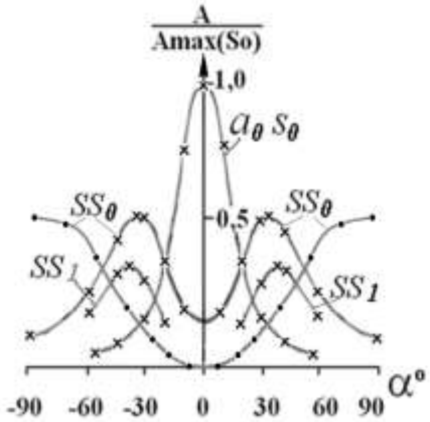


Fig. 5. Dependence of US normal wave pulse amplitude on the angle between bias field vector and wave propagation direction

Dependence of normal wave amplitudes on inductor parameters makes it possible to come to a conclusion that proposed EMAT is, by nature, emitter of comb-structure type; it allows attain amplification of amplitude of one or another normal wave through optimal selection of working point on dispersion curves and EMAT parameters. In order to excite simultaneously of alternatively Lamb wave and SH-wave with single EMAT, it is necessary to select working point on dispersion curves of phase velocities of these normal waves in view of the condition $\lambda=Cp_1/f_1= Cp_2/f_2$, where: Cp_1, Cp_2 – are phase velocities of Lamb waves and SH-waves, respectively, while f_1 and f_2 – are working frequencies these waves are excited at. Amplitude equality of studied US normal waves is ensured by variation of α angle.

Study of EMAT bias systems has shown that due to sharp growth of bias current with increasing of wall thickness of tested article and, especially, with increasing of metal volume (real pipes, multi-layer structures of steels and alloys of ferromagnetic brands), creation of EMAT bias systems based on direct current electromagnets appeared to be inefficient; therefore, methods and devices for pulse biasing of local sections of tested article were developed [13-18]. This made it possible to improve efficiency of EMA transformation, as well as to reduce EMAT overall dimensions and weight, power consumption and force of EMAT attraction to the test object surface.

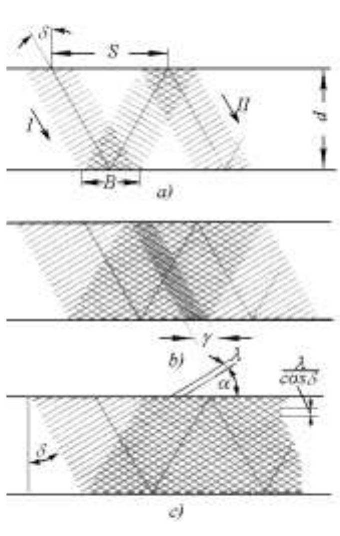


Fig. 6. Scheme of Lamb wave excitation under Schoch

Process of EMA excitation of acoustic waves of respective types is affected by conductivity, magnetic properties, crystalline structure, magnetic and acoustic anisotropy of metals and alloys, topography and non-uniformity of polarizing magnetic field, as well as by EMAT structural parameters.

Electrodynamic method of EMA excitation of ultrasonic normal waves (Fig.4c) was proposed by A.V. Kharitonov and A.V. Pashutin [9]. In essence, method consists in application of an inductor in the form of solid bed (elongated flat coil) and magnetic system based on permanent magnets with alternating poles. Depending on mutual orientation of inductor and magnetic system located above test object, it becomes possible to excite Lamb waves or shear normal waves. Unlike to magnetostrictive method of EMA excitation, method under consideration is more versatile, because it is suitable for testing parts and structures of both ferromagnetic and non-ferromagnetic metals and alloys.

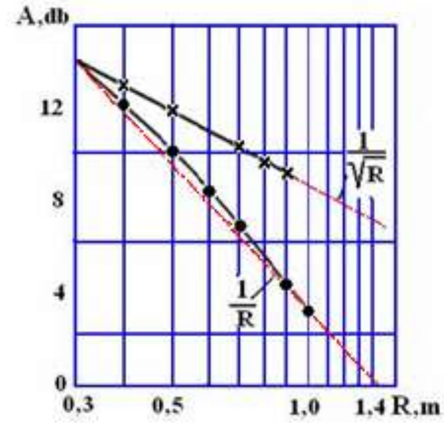
In addition to such parameters as working frequency, type and orientation of bias field, selection of excitation area, length of exciting pulse, etc. plays significant role in evaluation of excitation efficiency. Importance of these parameters consideration is confirmed by ray pattern of Lamb wave excitation corresponding with EMA excitation option and presented in Figure 6. If angle δ, pitch S and area B (Figs. 6a, 6b) does not correspond with the given thickness of studied object, there is no phase matching between incident and reflected waves or interference in γ area is observed. Option presented in Fig.6c corresponds with propagation of waveguide nature.

Studies of Soviet and Russian scientists have promoted activating of works on EMA transformation both in our country and abroad. It is sufficient to note that XIV volume of "Physical Acoustics" under editorship of W.P. Mason published in 1979 discloses many works of domestic scientists, including one of the first author's work [20], while 45 of 163 cited source materials belong to Soviet authors. In many cases, studies of our scientists have defined works of foreign authors developing in their publications and patents ideas of A.V. Malinka, laureate of the USSR state prize, PhD in Technical Sciences, and A.V. Kharitonov, professor. In article under impressive title «Russian progress spurs US» published in the American magazine «Ultrasonics», vol. 13, no. 3, 1975, it was noted that successes of Russians in the EMA field have caused the Ministry of Defense to allot additional means for funding similar works in USA.

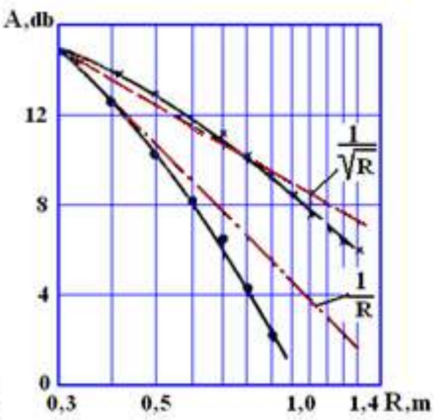
Peculiarities of propagation of ultrasonic normal waves

In papers [4, 5], it is demonstrated theoretically that attenuation of Lamb waves must depend on location of working point on a dispersion curve. It is shown that dispersion manifests itself in the form of variation of the amplitude attenuation nature and increasing of length of propagating pulses of US normal waves. It is demonstrated in our works that pulse amplitude of Lamb waves and SH-waves excited on horizontal sections of phase velocity dispersion curves varies under $1/\sqrt{R}$ law and is defined by the divergence of US oscillation beam; moreover, in this case, variation of pulse length is negligibly small. For steep sections of phase velocity dispersion curves for waves of both types, pulse amplitude varies under 1/R law, while variation of pulse length is of similar nature.

Measurement results for the dependence of pulse amplitude of modes $\mathbf{SS_0}$, $\mathbf{S_0}$, $\mathbf{S_1}$, $\mathbf{S_2}$ on distance are



a)



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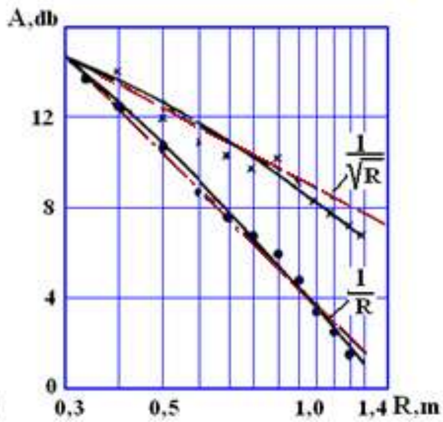
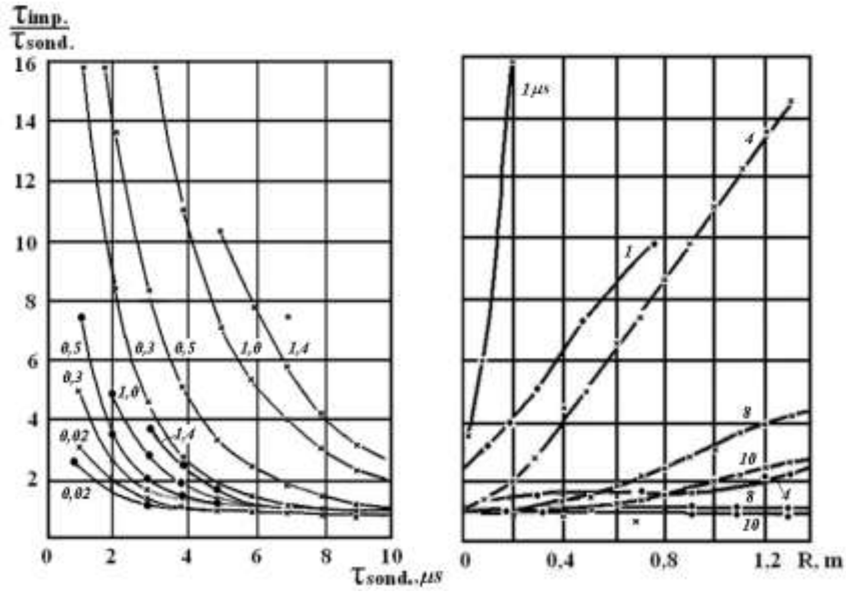


c)

Fig. 7. Character of US normal wave pulse attenuation with distance: **x** – is SS_0 mode (*fd = 1.4 MHz* x *mm*), ● - is S_0 mode (*fd = 2.2 MHz* x *mm*), S_2 mode (*fd = 4 MHz* x *mm*)

presented in Figures 7 - 8. It is established (Fig. 7a) that amplitude of Lamb wave pulses varies with

distance under the 1/√R-to-1/R law, while one of dispersion-free zero symmetric mode of shear normal wave SS_0 (curve **x**) excited by EMAT - under 1/√R law and is defined by the beam divergence only.
As is seen from Figures 7b, 7c, pulse amplitude in areas with strong dispersion — $\mathbf{S_0}$ mode at *fd* = 2.2 *MHz* **x** mm (curve ●); $\mathbf{S_2}$ at *fd* = 4 *MHz* **x** mm (curve ●) – drops with distance in proportion to ~1/R, while in areas with weak dispersion - $\mathbf{S_0}$ mode at *fd* = 4 *MHz* **x** mm (curve 2) – decreases with distance approximately under the 1/√R law. Attenuation conditioned by internal losses manifests itself at large distances only.
Dependences of the pulse length of propagating Lamb waves on the length of emission pulse and distance that are presented in Fig. 8 differ considerably from similar dependences for volumetric waves and demonstrate that pulse extension is in proportion to distance and depends on position of working point on the dispersion curve.
From Fig. 8a,it is evident that pulse extension in near zone (0.02 m) does not depend practically on the position of working point on the dispersion curve and, at $\tau_{sond}>4\mu s$, $\tau_{imp} \approx \tau_{sond.}$ At distances larger than 0.5 m, working point position on the dispersion curve influences pulse extension as follows: on the section with strong dispersion, pulses are extended considerably larger than on the section with weak dispersion. On the section with weak dispersion at $\tau_{sond} > 7\mu s$, $\tau_{imp} \sim \tau_{sond}$, while on the section with strong dispersion at $\tau_{sond}>10\mu s$, all pulses are extended. Fig. 8b also demonstrates influence of dispersion on pulse extension with distance.



a) b)

Fig.8. Influence of dispersion on the Lamb wave pulse length: a) $\tau_{imp} = f(\tau_{sond}.)$, b) $\tau_{imp} = f$ (R, m)

Obtained results are confirmed by data in paper of S.E. Baryshev *et al.*, where it is shown that due to Lamb wave pulse extension, "dead zone" is formed near sheet edge that achieves 5—10 cm.
Photos of similar scale made from oscilloscope screen and presented in Figs. 9a,b,c demonstrate the character of variation of the Lamb wave pulse length depending on the steepness of dispersion curve working section. Also, there (Fig. 8d) is shown lamb wave pulse obtained using emission pulse of exponential shape (as exciting one) generated by series-produced flaw detector. Comparison demonstrates that exponential-shape pulse with spectrum being considerably wider than one of rectangular pulse expands larger by an order of magnitude.

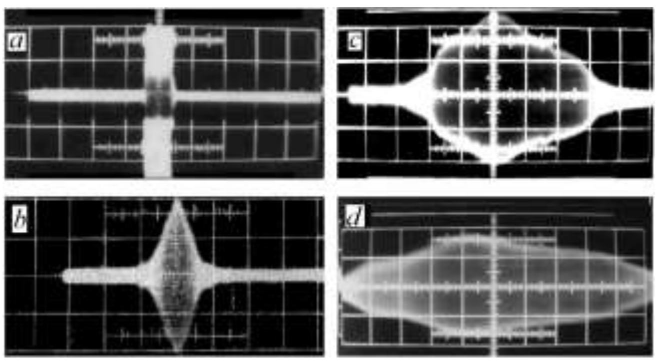


Fig.9. Influence of dispersion on the shape of Lamb wave pulse: $\tau_{sond} = 8\ \mu s$, $f = 2.5\ MHz$ - a), pulse of a_1 mode at 1.0 m distance at: *fd* = 9.6*MHz* **x** mm - b), *fd* = 4.0 *MHz* **x** mm - c), $\tau_{sond} = 1.0\mu s$

Performed studies make it possible to state the following recommendations:
1. For NDT of welded joints, it is optimal to use EMAT's with focusing.

2. For NDT of elongated articles, it is reasonable to select on dispersion curves horizontal working sections, i.e. sections within the field of small values of *fd* parameter.
3. In order to reduce dead zone during testing of long-size articles, exciting pulses of bell-like shape with narrow spectrum should be used.
4. In order to improve sensitivity during testing of delaminations, it is reasonable to use steep sections of dispersion curves.
5. When testing of rolled articles with contaminated surface is required, it is necessary to apply shear normal waves with horizontal polarization.

Application of ultrasonic normal waves in NDT and TD

Basing on performed studies, automated installation for ultrasonic testing in production conditions of internal overlap weld seam of multi-layer shells (Fig.10). Since shells had to be welded following testing operation, application of coupling liquid was not permitted. Therefore, ultrasonic normal waves were excited in the inner layer of shell with 5-6 mm thickness by means of EMAT focused in the area of weld seam. Symmetric mode $\mathbf{S_1}$ was excited at frequency f = 0.7 *Mhz*, which corresponds with dispersion curve section with *fd* = 3.5-5.2 *MHz* ***x*** *mm*.

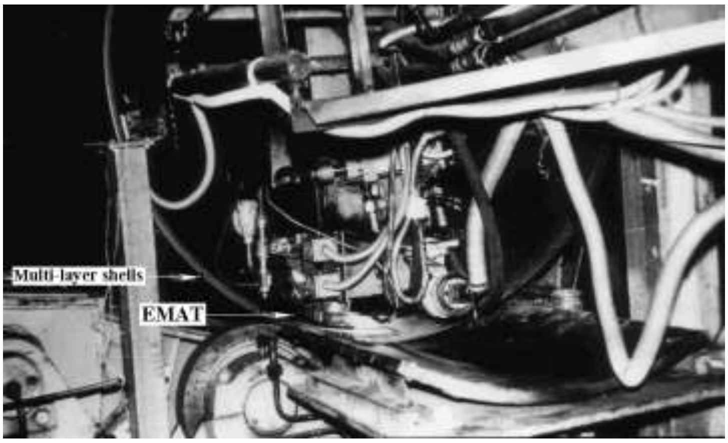


Fig. 10. EMA in-production testing of multi-layer shell weld seam

When area of weld seam with thickness that can amount up to 15 mm is achieved, $\mathbf{S_1}$ mode is transformed into volumetric shear wave, which interacts with weld seam flaws like pores, lack of fusion, cracks, slag inclusions, transforms during reflection into $\mathbf{S_1}$ mode propagating in the direction of EMA probe and is recorded by it. Focusing provides high sensitivity during detection of above listed flaws and, especially, ones like pores with extension along the length of weld seam being equivalent by reflective surface to through boring of 1.6 mm diameter (Fig.11).

Installation is equipped with mechanization, automation and data processing means. Electronic part of installation consists of the generator of powerful radio pulses, pulse bias system, receiving amplifier and computational means. In the process of operation, installation was subjected to selective tests for testing trustworthiness as compared with traditional testing method using PEP, magnetographic and X-ray TV testing means. These tests covered 40 thousands shells and have confirmed 5-10 times higher detectability of weld seam , flaws. High reliability of detection of the typical welding flaws like lack of fusion, hot cracks and pores with application of EMA method was confirmed also by metallographic analysis.

a) b)

Fig. 11. Flaws in multi-layer shell weld seam detected by EMA equipment: a) lack of fusion, b) pore

For manual testing of weld seams, sheets and strips of low-carbon cold-rolled steels with thickness of 1.0 to 5.0 mm, specialized EMA flaw detector was developed. It was tested in the process of testing of weld seams of multi-layer shells, rolled sheet products and lead-plated sheets used in production of refrigerator bodies and truck fuel tanks. It was established that EMA flaw detector detects reliably flaws of “delamination” type with minimal opening of 0.03-0.035 mm, as well as cavities, gas pockets, blisters and notches. Results of studies were used during elaboration and implementation of GOST 14782-86 «Nondestructive testing. Welded joints. Ultrasonic methods» providing for the first time EMA testing of welded joints.

EMA excitation methods of Lamb waves and SH-waves, as well as probes based on these methods were developed in works of domestic and foreign scientists and specialists [10, 11, 19-27]. High-efficiency testing systems for weld seam of tubes within the flow of tube-welding mills, internal pipe scanners for autonomous testing of pielines, etc. were created on their basis. Scientists and specialists of CJSC “NIIIN MNPO “SPEKTR”, LLC NPC “Acoustic testing systems” (Russia) and others are working actively on EMA systems for NDT and TD.

Conclusions

1. Magnetostrictive methods of EMA excitation of ultrasonic normal waves (Lamb waves and SH-waves) are proposed and studied.
2. Recommendations on selection of working sections on dispersion curves are given; influence of dispersion distortions of US normal wave pulses on resolution and selection of insonification base during flaw detection of weld seams and elongated articles is noted.
3. Examples of application of EMA methods of NDT and TD for detecting flaws in rolled sheet articles, pipes and weld seams are considered.

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