Electromagnetic ultrasonic testing

Contrôle non destructif

par la méthode électromagnéto-ultrasonore

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SUMMARY

An overview is given of the EMUS transduction technique, its physical foundations, transducer construction, laboratory developments and applications. The flexibility in transducer construction permits the excitation of a large variety of bulk waves and guided wave modes. Important application fields for the EMUS transducers are nondestructive testing with Rayleigh waves, SH waves and shear waves with normal incidence since, for these wave types, conventional excitation through a couplant suffers serious drawbacks.

KEY WORDS

Surface waves, EMUS, EMAT, magneto-acoustic conversion.

RÉSUMÉ

On présente un aperçu de la technique de transduction électromagnétique ultrasonore (EMUS) comprenant les fondements physiques, la construction du transducteur, les développements en laboratoire et quelques applications.

Par sa souplesse de construction, le transducteur permet l'excitation d'une grande diversité d'ondes ultrasonores et de modes guidés. Un domaine important d'application des transducteurs EMUS est le contrôle non destructif par utilisation des ondes de Rayleigh, des ondes de cisaillement polarisées horizontalement et des ondes de cisaillement sous incidence normale, parce qu'il n'est alors pas nécessaire d'utiliser un liquide de couplage ce qui est un inconvénient sérieux avec les transducteurs convenventionnels.

MOTS CLÉS

Ondes de surface, EMUS, EMAT, conversion magnéto-acoustique.

CONTENTS

1. Introduction

The development of electromagnetic-ultrasonic transducers (EMUS transducers) has offered new possibilities in the field of mondestructive testing by ultrasonic waves. The main reasons are: EMUS transducers don't need liquid couplants; they offer a high degree of reliability; they can operate at elevated temperatures; the flexibility in layout and construction provides a large variety of excitable wave modes; especially tangential motions in the surface of the test piece can be exited. The reader who wants to get a deeper insight into the development of the EMUS transduction technique is referred to a review article by H. M. Frost [1].

2. Physics of EMUS transduction

Electromagnetic generation of a ultrasonic wave is performed by superimposing high frequency eddy currents to a low fresuency magnetic bias field in conducting non- or ferromagnetic material. The eddy currents are induced through a HF transmitter coil energized by a current pulse or burst. In many cases a meanderlike shape HF coil (*Fig.* 2.1) is used. In the inverse process, an ultrasonic wave, impinging on the surface of a material with the aforesaid properties, under the action of a magnetic bias field generates an electromagnetic field which leads to induction of a HF voltage signal in a receiver coil. The generating phenomena can be described through a physical model which comprises Lorentz forces, magnetic forces and magnetostriction. Such a model has been developed and used to calculate the transfer impedance of a system consisting in the EMUS transmitter and receiver and the elastic material to be tested [2]. The transfer impedance is the ratio between the voltage amplitude U_R induced in the received coil and the current amplitude I_T flowing in the transmitter coil and is an absolute measure of transducer efficiency.

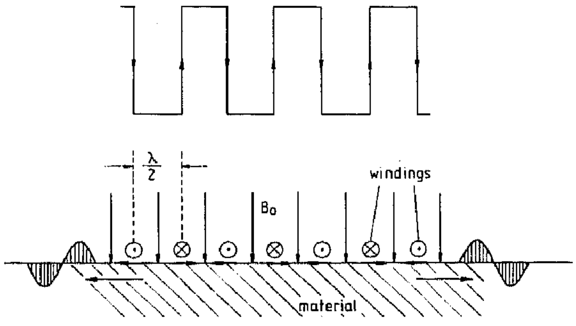


Fig. 2.1. — Principle of the electromagnetic excitation of ultrasonic waves vibrating in the plane of incidence.

Figure 2.2 shows the theoretical and experimentical and experimental directivity patterns of SV waves generated by a meanderlike coil in a soft steel half cylinder with a magnetic bias field normal to the transfer impedance drawn in a logarithmic scale picked up by a received-line-probe, which was moved along the cylindrical surface of the sample. The transmitter coil has a Dolph-Tschebyscheff-tapering in order to obtain the lowest side lobe levels and the smallest main lobe width which are simultaneously possible. The transfer impedance measured at the maximum main lobe is about 20% lower than, and the measured side lobe level is somewhat higher than, the calculated values.

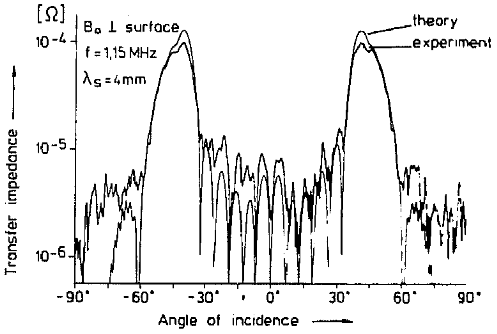


Fig. 2.2. — SV wave directivity pattern of an EMUS angle transducer with tapered HF coil in soft iron.

The angle of incidence of the main lobe depends on the frequency. Figure 2.3 shows calculated and

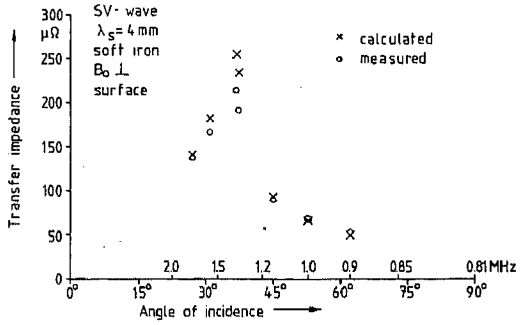


Fig. 2.3. — Transfer impedance at the main lobe maximum (EMUS angle transducer-EMUS line probe).

measured values for the transfer impedance at the maximum main lobe of the same system as in the foregoing figure for different frequencies and corresponding angles of incidence. The largest dicrepancy between experimental and theoretical values is about 20%. These results demonstrate the usefulness of the applied model to calculate absolute transducer efficiencies and directivity patterns.

The small value of the ratio between the transfer impedance and the electrical resistance of EMUS transducers (≅10 Ω) shows that the insertion loss of EMUS transducers is considerably higher than that of piezoelectric transducers. The numerical model is a strong engineering tool which optimizes transducers and especially reduces their insertion loss; it has already been used in this way.

3. Wave types and transducer configurations

Depending on the geometry of the HF coil and the orientation of the magnetic bias field a large variety of wave types and modes can be excited (*Fig*. 3.1). Meanderlike coils with magnetic bias fields alternatively parallel or normal to the surface and perpendicular to the HF current are used for the transduction of oblique-incident *SV waves*, *Rayleigh* waves and *Lamb* waves. The model, cited above, shows that in these cases with bias field *parallel* to the *surface*, transduction occurs in paramagnetic conducting materials through Lorentz forces and in ferromagnetic materials mainly through magnetostriction; whereas with bias field *normal* to the *surface*, it occurs through Lorentz forces and in ferromagnetic materials additionally through magnetic forces. Meanderlike coils with *bias field parallel to the surface* as well as to the *HF current* are used for the transduction of *SH waves* in magnetostrictive materials. Transduction of *SH* waves in *paramagnetic* conducting materials is performed by transducers with a *periodic bias field* produced by a stack of magnets with alternating orientation. The last mentioned configuration was proposed by R. B. Thompson [3, 4] in 1979. *Normal incidence* of *linearly polarized shear waves* and *longitudianl* waves is performed by flat rectangular frame HF coil in a bias field with altering flux direction; radially polarized shear waves are excited by flat spiral (pancake) coils in a homogeneous bias field normal to the surface. The angular ranges, where these wave types be excited with EMUS transducers most efficiently, are shown in Figure 3.2.

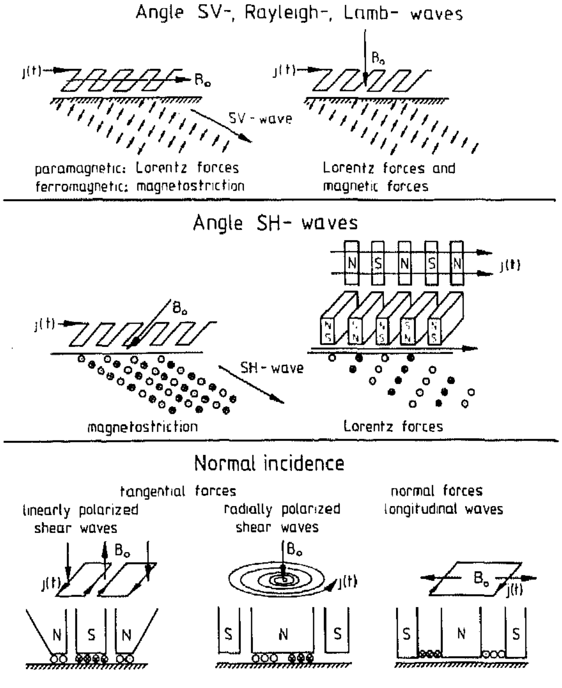


Fig. 3. — Variants of EMUS excitation.

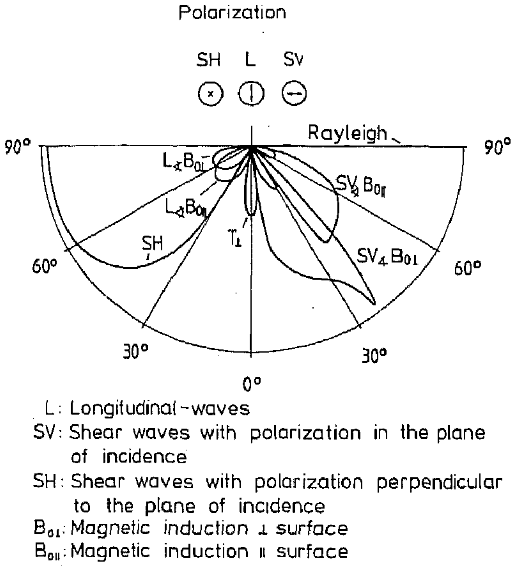


Fig. 3.2. — Angular range of electromagnetically excited ultrasonic wave modes.

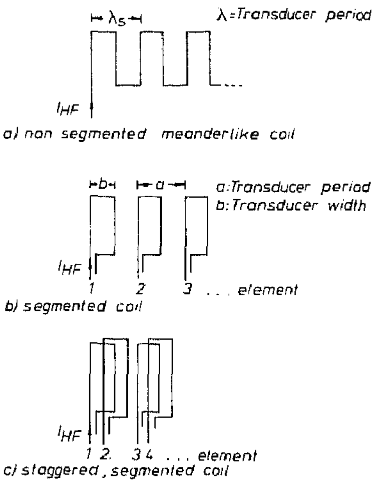


Fig. 3.3. — EMAT coil configurations.

Since they extend over several wavelengths, transducers with a meanderlike coil create a *narrowband* signal. In order to produce *broadband* signals, the HF coil has to be segmented into several elements, and the HF pulses energizing the different elements have to be shifted against each other by certain time delays corresponding to the time-of-flight which the ultrasonic wave requires to propagate from one element to the other (*Fig.* 3.3). The signal received in the different elements has to be shifted analogously. Such *phased-array-systems* have been built up successfully at laboratory and prototype stages. Pulse lengths of two wave lengths have been achieved [5].

4. Laboratory developments and applications

At the IzfP the development of the EMUS transduction technique for the solution of NDT problems has been concentrated on plate modes [6], tube modes [7], surface waves [8] and bulk waves [5, 9]. Rayleigh-, SH- and shear-waves with normal incidence are of a special importance for industrial applications; these wave modes *require* no liquid couplant, respectively tangential HF-forces for excitation.

A system for the automatic surface inspection of railway engine wheels is presently in its testing phase [10]. The transducer system is integrated into the rail (*Fig.* 4.1); the testing is performed while a wheel is passing. Triggered by the wheel when it contacts the transducer two Rayleigh wave bursts are excited simultaneously travelling along the wheel tread clock- and counter- clockwise. Deffect echoes are detected by two recaiver systems (channel A and B). At the present time up to six wheel pairs can be tested in one inspection cycle. Figure 4.2 shows a test result with a defect echo of a wheel appearing in the oscilloscope traces (channel A and B).

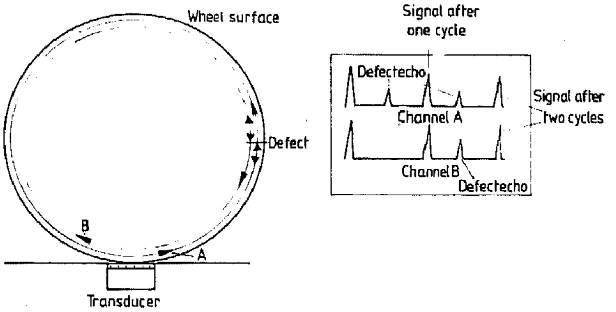


Fig. 4.1. — Principle of the surface testing of railway wheels.

SH waves can be used advantageously in the testing of structures with columnar grains like weldments and calddings. These structures have an anisotropic acoustic impedance which, in the case of shear waves, also depends on their polarization. This results in significant reflections of SV waves at the interface between the base- and the weld-metal while SH waves are transmitted through most incidence angles [11]. In the case of a cladded inside wall, this range of angles permits the testing from the outside, of the outer surface zones and of the cladding and the base metal above (*Figs.* 4.3, 4.4).

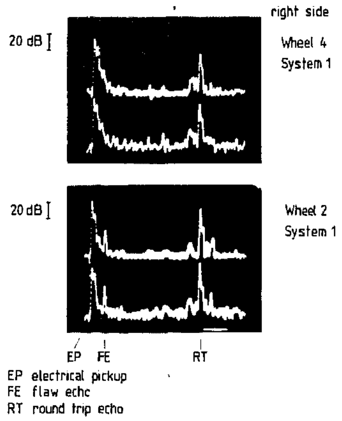
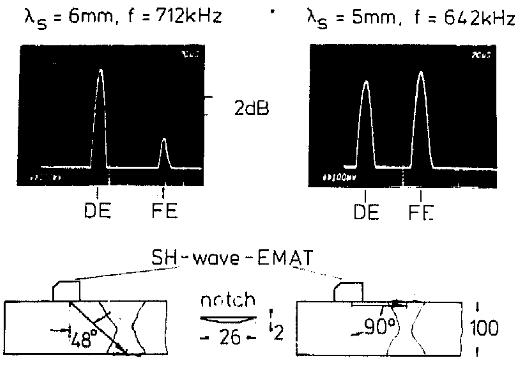


Fig. 4.2. — Field testing result from an engine.



signal to noise ratios

SH - wave	conventional
90°, 642kHz: 20dB	Rayleigh-w., 1MHz: ≤6dB
48°, 712kHz: 18dB	creeping-w., 2MHz: <6dB
	SV-w., 45°, 2MHz: <6dB
DE: defect echo	long.-w., 45°, 2MHz: <6dB
FE: form echo	long.-w., 60°, 2MHz: 8dB

Fig. 4.3. — Detection of a notch in an austentic weld by electromagnetically excited SH waves.

Since SH waves propagate also at grazing incidence along a surface, unconventional testing geometry can be used, for example when testing the inner surface of a nozzle in a PV wall (*Fig.* 4.5). For this purpose the transducer is positioned on the PV wall, inclined at a certain angle relative to the radial direction at the nozzle center, and moved along a circle or an ellipse around the nozzle. Figure 4.6 shows a resultant echo from a crack at the inner surface of a nozzle.

Shear waves with normal incidence polarized at right angles to each other permit the determination of structural or stress-induced anisotropy by relative time-of-

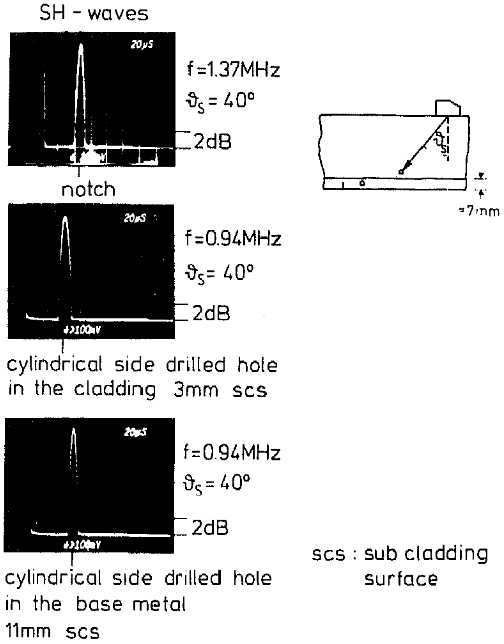


Fig. 4.4. — Testing the inner near surface zone of the RPV with SH waves.

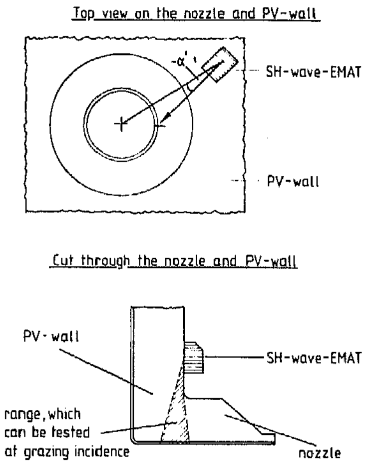


Fig. 4.5. — Testing the inner surface zone of a nozzle with SH waves.

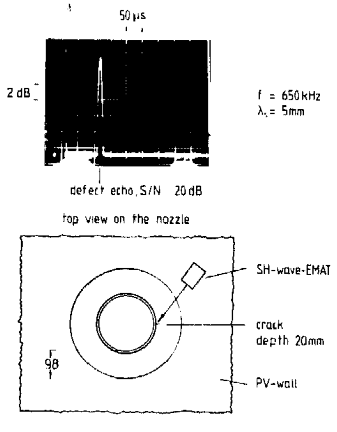


Fig. 4.6. — Detection of a crack at the inner surface of a nozzle.

flight measurements. Figure 4.7 shows the influence of external stress on the backwall echo sequence of radially polarized shear waves [12]. Due to acoustic birefringence beats occur in the amplitude of the backwall echoes, which allows the quantitative determination of shear-wave-velocities polarized "in" and "perpendicular" to the plane of incidence and therefore enable stress analysis without knowing or measuring sound paths.

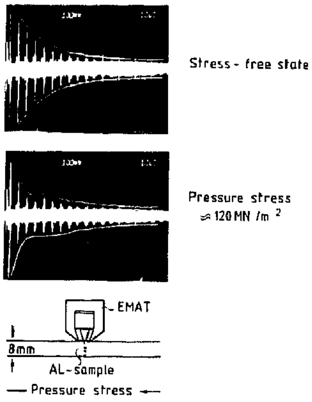


Fig. 4.7. — Backwall echo sequence in an A 1 sample under stress.

5. Transducer performance

Table 5.1 gives a comparison of the performance of piezoelectric and EMUS transducers. EMUS transducers have higher insertion loss than piezoelectric ones. The dead zone of normal probes can be minimized to a practicable value whereas the dead zone of EMUS angle probes is large compared to conventional ones. Any drawbacks which result from the use of a couplant are eliminated with EMUS transducers, however an EMUS transducer has to be close to the surface: the loss due to lift-off amounts to 80-100 dB per transducer period. The scanning speed achievable with EMUS transducers is limited only by mechanical conditions. These advantages are the basis to the requirement to overcome the drawbacks of high insertion loss and large dead zone.

6. Conclusion

This paper described the amount of constructional variety that is accessible in the desing of EMUS transducers. Several examples were given where ultrasonic testing with EMUS transducers can be performed in an unconventional manner. The capabilities and engineering requirements of EMUS transducers have been discussed. Future work has to bring even more of these capabilities into practical use.

TABLE 5.1

Comparison of transducer performance

	Piezoelectric transducers	EMUS transducers	In relation to piezo electric transducers
Insertion loss.	10-20 dB	40-50 dB	—
Gain in reserve.	50-70 dB	$\leqq \left\{ \begin{array}{l} 55 \text{ dB, ferritic steel} \\ 45 \text{ dB, austenitic steel} \end{array} \right\}$	—
Dead zone.	0	3 mm (normal probe) 15 mm (angle probe) 35 mm (segmented probe)	— —
Acoustic coupling			
Longitudinal, SV.	BBy liquids (normal forces)	Not necessary bu narrow gap, (lift off loss, 80-100 dB/λ_S)	+ + +
SH (normal and oblique incidence).	Practically impossible (only, by high-viscous, paste or pressure)		
Scanning speed.	limited due to wetting and cavitation	Limited only mechanically	+ +

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