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Guided Wave Inspection of Railway Tracks: A Review of Electro Magnetic Acoustic Transducer Techniques

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Abstract: ***Indian Railway has expanded its track to approximately 115,000 km's reaching to every nook and corner of the country. Both the passenger and freight traffic are continuously increasing along withincrease in axle loads,warranting for more accurate and fastertracks inspection techniques. Present work is a review on Guided Wave Inspection Techniques using Electro-Magnetic Acoustic Transducer (EMAT) for railway track. Guided wave inspection potentially enables a large area of structure to be tested from a single transducer position, so avoiding the time-consuming scanning required by conventional ultrasonic or eddy current methods. However, full utilization of EMAT techniques warrants tackling of the issues like difficulty of controlling the different possible modes and propagation directions. It is therefore important for research in this field to counterbalance the benefits offered by the multiple possible modes, with the complexities that the presence of so many modes can produce.***

Keywords: Freight Traffic, Electro-Magnetic Acoustic Transducer, Ultrasonic Testing, Tracks, Magnetic Fields

1. Introduction

The usefulness of ultrasonic techniques is well established in the literature of nondestructive examination. The generation of ultrasonic waves is achieved primarily by means of some form of electromechanical conversion, usually the piezoelectric effect. This highly efficient method of generating ultrasonic waves has a disadvantage in that a fluid is generally required for mechanical coupling of the sound into the material being examined. The use of a couplant generally requires that the material being examined be either immersed in a fluid or covered with a thin layer of fluid.

This paper will highlight the drawbacks of conventional piezoelectric ultrasonic wave crack detection techniques. Need for advanced crack detection techniques and use of guided wave technique for crack detection will be explored. The appropriate frequency range and appropriate wave type/wave mode will be selected. Role of EMAT in producing those waves will be discussed. Advantages, features and characteristics of EMAT technique will be discussed. Its limitations will also be discussed. A brief introduction to Indian railway Scenario will also be delved into.

2. Rail Defects and issues with Ultrasonic testing

Various types of rail defects that are encountered in common are as following:

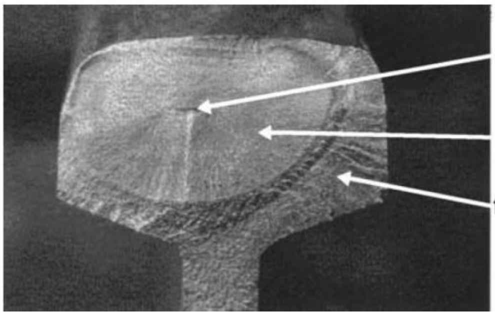


Figure 1: Courtesy- Cannon, D.F., Edel, K.Grassie, S.L. & Sawley, K. Rail defects: an overview. Fatigue & Fracture of Engineering Materials & Structures 26, 865-886 (2003)

Figure 2: Surface gauge corner head checks

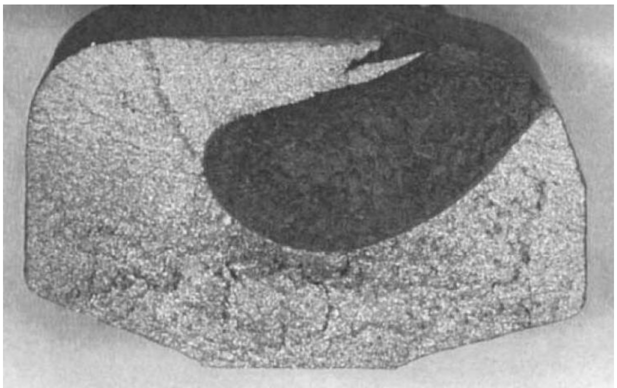


Figure 3: Transverse cracks originating from head checks

Figure 4: Transverse Defect in UIC 60, 880 Grade Rail covering 30% of railhead arealeading to derailment at New Faridabad Station in April 09. Nucleus of fracture initiationcorresponds to landing of shear crack present on gauge side of rail table. Adjoining photoshows extant of Head Checks at the location. (Courtesy: Ref- 7)

Figure 5: Rail pieces in juxtaposition exhibiting angle of inclination (Approximately 6degree from vertical) of Transverse Defect. Ultrasonic test report of the rail less than 15days prior to failure did not indicate any defect. (Courtesy: Ref- 7)

Rolling Contact Fatigue (RCF) defects are indicative of most of the railroads carrying heavy axle loads and intensive passenger traffic. RCF defects of nearly vertical orientation are one of the most lethal types of rail defects on account of their low chances of detection in rail testing regimes prevailing on rail networks. Detection of defects with favorable orientation under adverse rail surface condition also becomes sometimes very difficult. Funkwal [7] highlights Indian Railways experience in dealing with these defects and R&D efforts made to develop potential technology for their detection.

The paper argues that one of the most significant fallout of sub optimal rail-wheel interaction on today‗s rail steels is development of Rolling Contact Fatigue (RCF) defects in rail head due to which transverse defects of various orientations in rail head are common on rail networks carrying heavy axle loads. Generally, railroads adopt detection strategies based on their past experience of service failures on account of transverse defects in railhead. On Indian Railways (IR) the most commonly found orientation of transverse defects is approximately 20 degree from vertical. This has led to deployment of 70 degree probes for detection of these defects. However, there are distinct issues related with the non- detection of transverse defects in rail head.

- Compromised rail surface condition (scabs, wheel burns) inhibiting proper coupling
- Heavier trains especially those operating without right powering are causing rail scabbing/wheel burns at several locations which inhibits unhindered passage of ultrasonic energy to/from defects.
- Presence of head checks masking transverse defect beneath. Rail profile grinding is not being practiced on IR.
- Adverse orientation of defects leading to very poor reflection of ultrasonic energy.
- RCF defects of orientation flatter than 20 degree from vertical are also being encountered increasingly. These types of defects are also very difficult to be detected.

The paper [7] states that in the prevailing scenario, present ultrasonic testing protocols are not capable of detecting all types of RCF defects. Considering that such undetected defects can potentially be dangerous for a safety sensitive network like IR, it is imperative that more advanced technologies should be looked into for crack detection of rails.

3. Use of Guided waves for detecting rail defects

Various researchers have given valuable thoughts for using guided waves for inspecting the rails. Extracts from two relevant papers are given below:

Since continuously welded railway lines may be thought of as one-dimensional elastic waveguides, they are natural candidates for guided wave ultrasound, which offers the potential to interrogate a large length of rail from a single position. Apart from the increased propagation range, a strong motivation for the use of guided waves (as opposed to conventional high frequency ultrasound) is that these waves can detect smooth vertical-transverse defects even if they occur under surface cracks or shelling. A further motivation is that the lower frequency used is not strongly scattered by the large material grain size in alumino-thermic welds making it possible to detect defects within the weld. Surface or subsurface defects may prevent traditional ultrasonic wheel probes from detecting more serious deeper defects. The ability of guided waves to detect transverse defects under shelling has motivated extensive research at the Pennsylvania State University. This work led to the development of a ―Portable Rail Inspection for Strategic

Maintenance" inspection system by Waves in Solids (www.wins-ndt.com). The system is fitted to a Hy-Rail vehicle for scanning the rail and uses electromagnetic acoustic transducers (EMATs) to transmit and receive the guided waves.

Guided wave inspection potentially enables a large area of structure to be tested from a single transducer position, so avoiding the time-consuming scanning required by conventional ultrasonic or eddy current methods. However, until recently, this potential has only been realised in a small number of practical applications. This is largely due to the difficulty of controlling the different possible modes and propagation directions so that the signal-to-coherent noise ratio is satisfactory and simple, easily interpretable signals are obtained. It is therefore important for research in this field to concentrate both on exploring the opportunities offered by the multiple possible modes, and on managing the complexity that the presence of so many modes can produce. It has been shown that an array of transducers acting as point sources provides a basis from which these problems can be overcome and examples of pipe, rail and plate testing have been presented. To date, most applications have been on simple structures with a low density of joints, stiffeners etc. Future research directions include the inspection of more complex structures and developing techniques to test systems where the attenuation is very high.

4. Efforts to use of EMAT for detecting rail defects

Certain efforts have been made internationally to use Electromagnetic Acoustic Transducer technique or detecting rail defects.

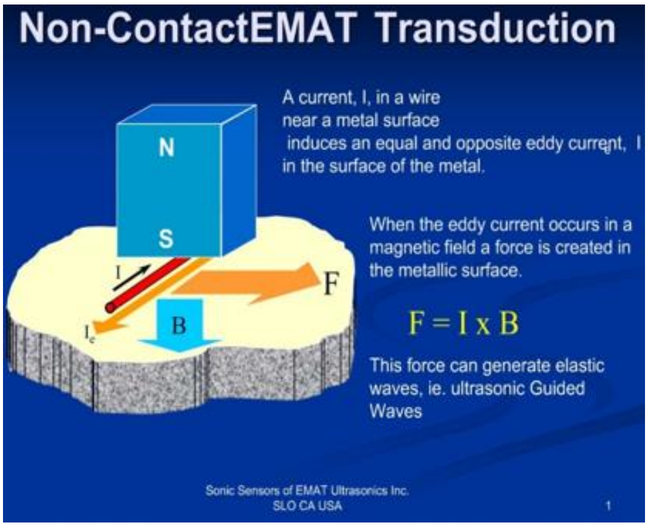
- Tektrend International, a Canadian company, undertook development of a mobile inspection system for rail integrity assessment for Transportation Development Center of Transport Canada in year 2000. The RailPro system developed for real time testing of rails using electromagnetic acoustic transducers (EMAT) technology could detect and locate rail defects. The detection capabilities were assessed over an evaluation track in Taschereau Yard in Montreal on Canadian National (CN) Railway. It was concluded that system along with procedures developed is an efficient and reliable inspection approach.
- Researchers in the University of Warwick developed a non-contact method of using ultrasound to detect and measure cracks and flaws in rail track – particularly gauge corner cracking. The technique makes use of low frequency Rayleigh waves generated using EMATs to interrogate top 15mm depth of rail.
- Chong Myoung Lee of Pennsylvania State University produced an extensive research on capability of EMAT system in detecting railhead defects under shelling in year 2006.

4.1 Principle of EMAT

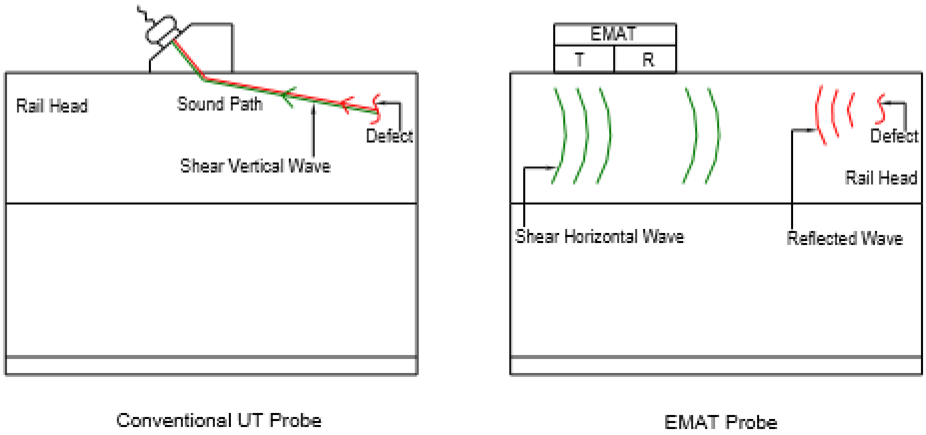
An electromagnetic acoustic transducer (EMAT) generates and receives ultrasonic waves without the need to contact the material in which the acoustic waves are traveling. The use of an EMAT requires that the material to be examined be electrically conductive or ferromagnetic, or both.

- The EMAT as a generator of ultrasonic waves is basically a coil of wire, excited by an alternating electric current, placed in a uniform magnetic field near the surface of an electrically conductive or ferromagnetic material.
- A surface current is induced in the material by transformer action. This surface current in the presence of a magnetic field experiences Lorentz forces that produce oscillating stress waves.
- Upon reception of an ultrasonic wave, the surface of the conductor oscillates in the presence of a magnetic field, thus inducing a voltage in the coil. The transduction process occurs within an electromagnetic skin depth.
- An EMAT forms the basis for a very reproducible noncontact system for generating and detecting ultrasonic waves.

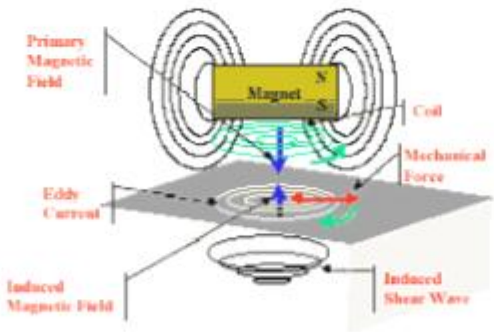
Some figures explaining the principle of EMAT have been taken from various sources as indicated below.



(a)



(b)



(c)

Figure 6: Principle of EMAT [Courtesy: (a)Ref- 10, (b) &(c) Ref.-7]

4.2 Advantages of EMAT

Since the EMAT technique is non contacting, it requires no fluid couplant. Important consequences of this include

- Applications to moving objects, in remote or hazardous locations, to objects at elevated temperatures, or to objects with rough surfaces.
- The technique is environmentally safe since it does not use potentially polluting or hazardous chemicals.
- The technique facilitates the rapid scanning of components having complex geometries.
- EMAT signals are highly reproducible as a consequence of the manner in which the acoustic waves are generated.
- Unique wave modes. Because they do not depend on liquid to transmit the sound, EMATs can generate any type of wave mode including horizontally polarized shear energy (SH). Shear horizontal energy does not mode convert when striking surfaces that are parallel to the direction of polarization. This is key to inspecting austenitic welds and other materials with dendritic grain structures (e.g., some stainless steels). Other types of waves that can be easily generated with EMATs are guided or plate waves (Lamb or SH at 90 deg), available on materials up to 0.5 in. (13 mm) in thickness.
- EMATs can produce horizontally polarized shear (SH) waves without mode conversion and can accommodate scanning while using SH waves.
- EMATs provide for the capability to steer shear waves electronically.
- High inspection speeds and the ability to inspect materials up to 1200°F Insensitive to surface conditions.
- EMATs are not sensitive to oxides, oil, water, or uneven surfaces and can inspect through thin coatings of material. Easier probe deployment.
- EMATs are not affected by the angle of incidence of the probe, and they can be made flexible to adapt to undulations and different contours.

4.3 Production of various types of Waves by EMAT

With the proper combination of magnet and coil design, EMATs can produce Longitudinal, Shear, Rayleigh, and Lamb wave modes. ***The direction of the applied magnetic field, geometry of the coil, and frequency of the electromagnetic field*** will determine the type of wave mode generated with EMATs.

Longitudinal Wave Mode—Fig. 7 illustrates how the direction of the applied static magnetic field in a conductor and the resultant direction of the Lorentz force can produce longitudinal elastic waves. For longitudinal wave generation, the Lorentz force and thus ion displacement is perpendicular to the surface of the conductor. The efficiency of longitudinal wave generation, as compared with other modes excited in ferromagnetic materials, is very low, and has no practical relevance.

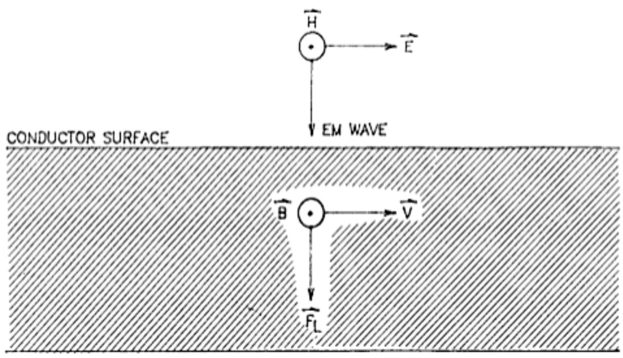


Figure 7: Generation of longitudinal stress waves (Courtesy- Ref: 1)

Shear Wave Modes—Fig. 8 shows how the direction of the applied static magnetic field in a conductor and the resultant direction of the Lorentz force can produce shear elastic waves. For shear wave generation, the Lorentz force and thus ion displacement is parallel to the surface of the conductor. EMATs are also capable of producing shear wave modes with both vertical and horizontal polarizations. The distinction between these two shear wave polarization modes is illustrated.

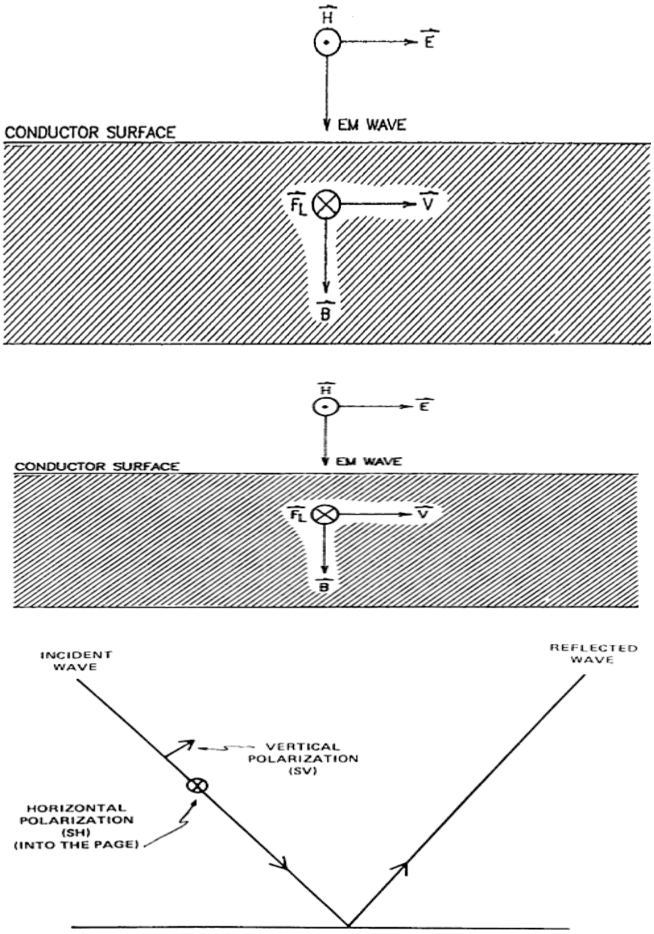


Figure 8: Generation of shear waves (Courtesy: Ref- 1)

Rayleigh Wave Mode— For Rayleigh or surface wave generation, the applied static magnetic field will be oriented perpendicular to the surface of the conductor in the same manner used for shear wave propagation. A meander line or serpentine-type coil is used to provide a tuned frequency EMAT. The frequency of the EMAT is determined by the geometry (that is, line spacing) of the meander lines in the coil. By proper selection of frequency, it is possible to propagate only Rayleigh or surface waves. If the thickness of the material is at least five times the acoustic wavelength that is determined by the frequency and wave velocity, then Rayleigh wave generation is essentially ensured.

Lamb Wave Modes—The various Lamb wave modes (symmetric and anti symmetric) can be generated in a manner similar to Rayleigh wave propagation. For Lamb wave production, the tuned frequency of the meander line coil is chosen to give the desired Lamb wave mode and is dependent on the material thickness.

Versatility of EMAT waves is illustrated in the following figure taken from Ref [10]

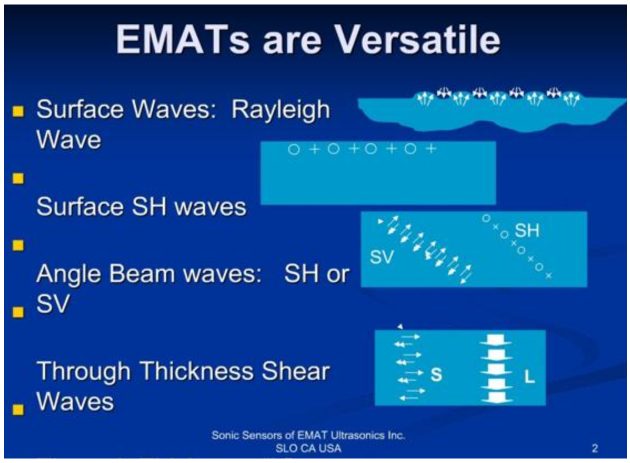


Figure 9: (Courtesy: Ref- 10)

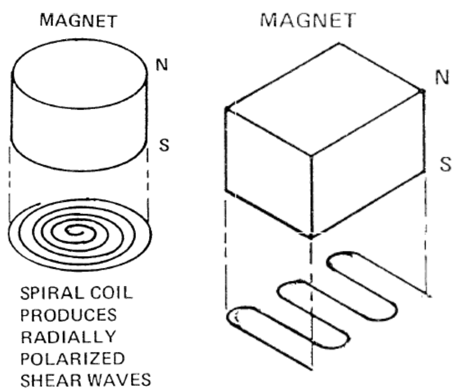
4.4 Features of EMAT

Following are some important features of an EMAT set up:

Transducers— As in conventional piezoelectric-type ultrasonic testing, there are basically two types of EMATs with respect to beam direction. EMATs can be designed for either straight or angle beam inspection

Straight Beam— The spiral or pancake coil design is one of the most efficient EMATs for producing a straight ultrasonic beam. The direction of the applied magnetic field is perpendicular to the plane of the spiral coil, as shown in Fig. 10. The magnetic field can be produced by a permanent magnet, an electromagnet, or a pulsed magnet. Assuming that there is no fringing of the magnetic field parallel to the coil, a radially polarized shear wave is produced. Since there is always a small gradient of the field lines parallel to the coil, a small amplitude longitudinal wave will also be present. However, the longitudinal wave component can be held to a minimum by the proper design of the EMAT. The same holds for butterfly coils, placed in a perpendicular magnetic field with spatially alternating magnetic direction for the excitation of linearly-polarized shear waves.

Angle Beam—The meander line or serpentine coil EMAT can be designed for angle beam ultrasonic inspection. The orientation of the applied magnetic field is perpendicular to the plane of the meander coil, as shown in Fig. 10.



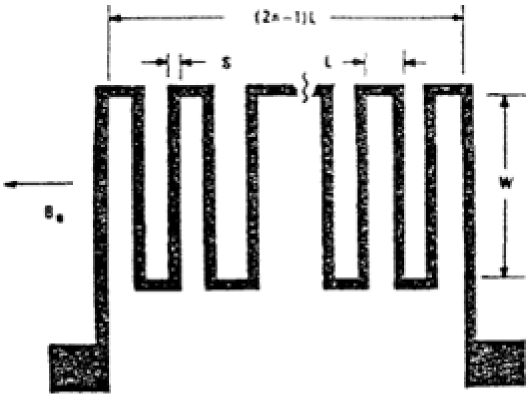


Figure 10: Geometry of Meander Coil (Courtesy: Ref-1)

Due to the geometry of the meander lines, periodic surface stresses are generated in the test specimen. The meander EMAT can be used to generate either shear or longitudinal angle beams where the beam angle is controlled by the frequency of the electromagnetic field. Because of differences in the velocities of longitudinal and shear waves, there will be a low frequency cutoff for these two wave modes. By proper selection of frequency, it is possible to propagate only a Rayleigh or shear wave, whereas longitudinal waves must be accompanied by shear waves.

While EMAT transducers do not require physical contact with the material to be examined, the proximity of the coil to the material does have a major effect on signal strength. It is therefore important to maintain a minimum liftoff to ensure maximum signal strength. Also, in addition to maintaining a minimum liftoff, it is important to maintain a constant liftoff to ensure the reproducibility of signals and to aid in signal analysis.

Pulser/Receiver: The electrical characteristics of EMATs are considerably different from piezoelectric transducers used in conventional ultrasonic testing. EMATs generally behave as inductive loads, whereas piezoelectric transducers act as capacitive loads. As a result, it is obvious that the design of the EMAT pulser driver must be different from that of conventional ultrasonic pulsers, albeit some manufacturers are offering pulser boards compatible with and applicable to EMAT applications. Another consideration in the design of EMAT pulsers and receivers is that the insertion loss of EMATs can be as much as 40 dB or more when compared to piezoelectric search units. Noise level and overload recovery time are very important in the design of EMAT receivers because of the high gains required in the preamplifier. For example, in an EMAT pulse-echo system, the preamplifier must be able to withstand the full voltage connected to the EMAT and then recover rapidly enough so that flaw signals can be measured.

Following figures show the specific characteristics of EMAT taken from Ref[10].

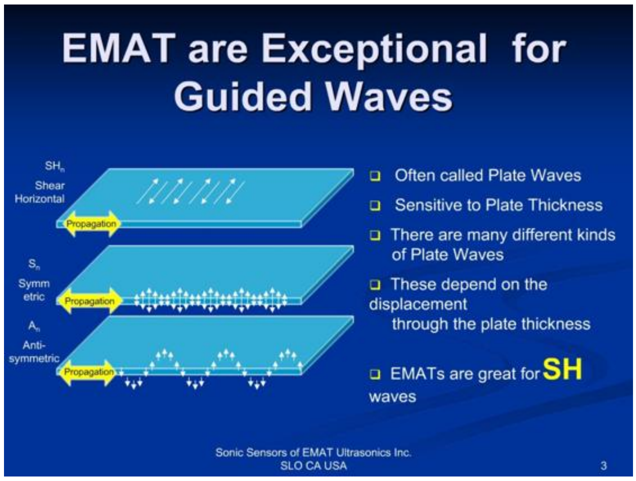


Figure 11: Characteristics of EMAT (Source: Ref-10)

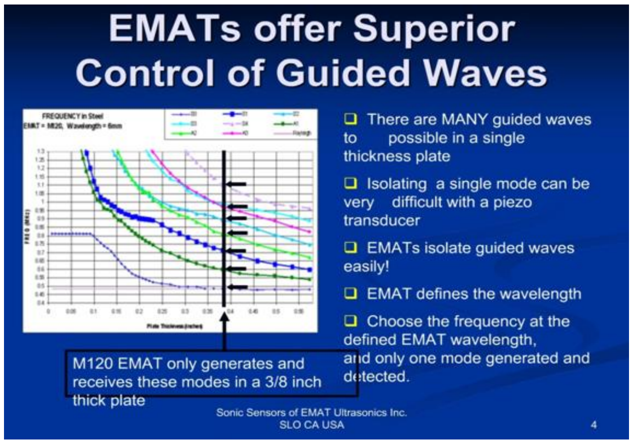


Figure 12: Characteristics of EMAT (Courtesy: Ref-10)

Frequency Region to be selected

In the paper presented by Ryuea J et al. [9], wave propagation along the railway track was examined in the frequency region up to 80 kHz by means of Wavenumber Finite Element (WFE) analysis. The simulations were validated experimentally on the basis of decay rates, obtained on an operational track. Excellent agreement between predicted and measured decay rates was obtained. Finally, the question of how far along a rail can vibration travel could be answered clearly from the simulated and experimental results.

The paper states that a localized head bending wave in the vertical direction travels efficiently through the rail head. For this wave, the minimum decay rate of about 0.04 dB/m occurs between 22 and 40 kHz. At the side of the rail head, the primary propagating wave is a lateral bending wave which has global deformation including the web and rail head. The minimum decay rate of this wave is about 0.04 dB/m and occurs between 22 and 35 kHz. .The 1st order web bending wave propagates dominantly through the web, having the minimum decay rate of about 0.05 dB/m between 20 and 40 kHz.

Conclusively the paper states, if a 50 dB level reduction is assumed detectable in the rail vibration, the maximum propagating distances will be about 1.2 km at the rail head and about 1.0 km at the web. It has to be noted that these results may depend on the track structures and their material properties, although rail geometry does not vary greatly in many situations.

4.5 Selection of Waves/Wave Modes

Rose J.L et al. [8] have given a valuable insight in applying EMAT method for detecting cracks in rails. The authors have provided the results of experiments they have conducted on rail at test tracks and on an operating railroad. Results are presented that suggest that the frequency range [40-80 kHz] readily supports guided waves. Theoretical results including roots of the dispersion relations for rail and a sample of wave displacement within a railhead are presented. Non-contact air-coupled and electromagnetic acoustic transducers (EMATs) are discussed as receivers of sound energy emanating from rail. The results of an experiment that used air-coupled transducers to profile the radiation pattern of a rail are presented. A rail cutting experiment with EMATs that simulated a transverse rail defect is discussed.

Guided wave methods provide wave modes that can travel great distances in rail, e.g. 2130 m, and that can insonify the entire volume of a rail. In this paper, findings based on guided wave experiments on rail that were performed at test track facilities and on an operating railroad.

Rail mounted accelerometers were used as sensors early on and it was the analysis of their data that uncovered the preference for rail to ultrasonic energy in the [40-80] kHz: Fig. 1 shows a mounted accelerometer. The analysis included data from rails having sound energy introduced into them by a moving trains (40–97 km h–1), a hand held 1.36 kg sledge, and a pneumatic impactor.

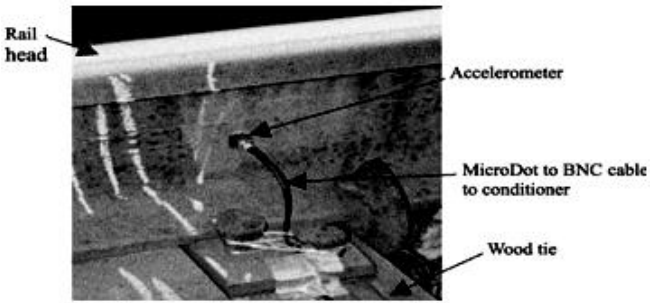


Figure 13: Accelerometer mounting configuration (Courtesy: Ref-8)

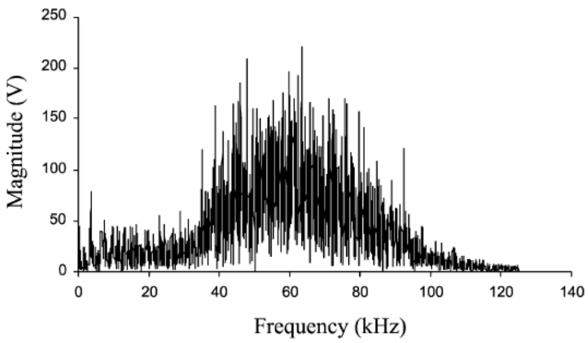


Figure 14: Train Noise and spectra as detected by an accelerometer as a train approached it travelling 40Kmph (Courtesy: Ref-8)

Analysis of the RF waveform data we obtained from alltest track and operating sites showed that mostly all sonic and ultrasonic energy resided in roughly three frequency ranges: [0-20], [20-40] and [40-80] KHz. Their analysis also indicated that the attenuation of sound in rail was frequency-dependent with higher frequencies attenuating less over distance than lower ones. Fig. 14 depicts this relationship.

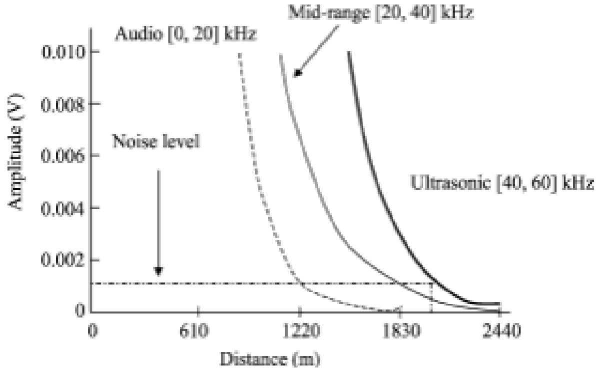


Figure 15: Frequency – dependent attenuation (Courtesy: Ref-8)

Finite-element modeling of guided wave propagation in a rail over the frequency range [0-80] kHz: Figs. 16 show results produced using the ABAQUS. In the modeling, the rail head was treated as a bar, to relate mode wave structure to its utility for penetration (effective distance traveled in rail) and for sensitivity (smallest defect detectable at a distance). Since wave structure is a function of phase velocity and frequency, penetration and sensitivity are also. Finite-element methods were also used to find standing wave solutions. Fig. 16 shows an example of a standing wave in a rail.

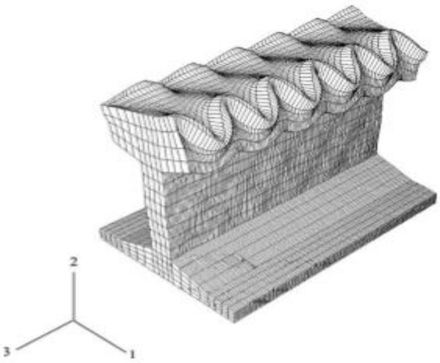


Figure 16: Finite element representation of a standing wave in a rail head (Courtesy: Ref-8)

Most of the energy is concentrated in the railheads only. This mode is having considerable displacements in directions 1 and 2 .i.e. good for measuring transverse and longitudinal cracks.

Further, by examining the shape of a standing wave in a prismatic structure, the wavelength of the wave can be determined. The phase velocity of the wave can be found by multiplying the wave‘s frequency with its wavelength. By this process, the (frequency, phase velocity) coordinates for all standing waves can be calculated. The ensemble of coordinates then represents the dispersion curves for the structure. Fig. 17 shows the frequency–phase velocity coordinates obtained.

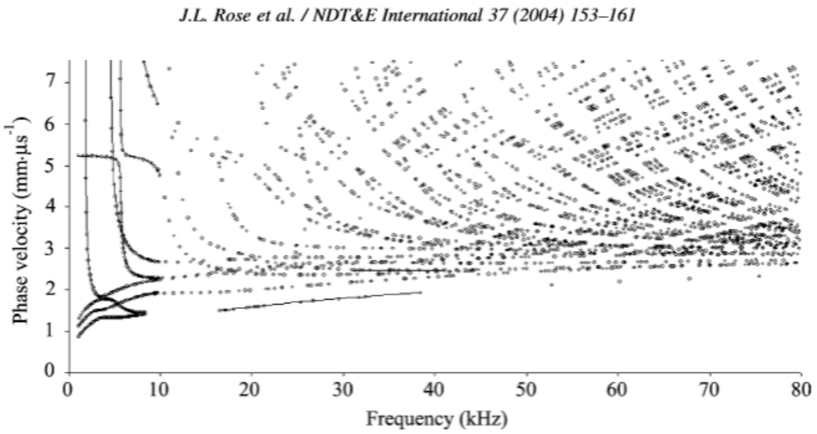


Figure 17: Dispersion curves for a rail over the frequency range [0-80] KHz and phase velocity range [0.5,7.5] mm per microsec(Courtesy: Ref-8)

As the frequency–phase velocity coordinates of Fig. 17 show, a multiplicity of modes are possible within the range [40; 80] kHz. This situation accents the possibility of the mode conversions that can occur upon wave interaction with a defect. These mode conversions may obscure the defect identifying characteristics of a received signal. On the other hand, mode conversion may enhance the detection of certain defects by their mere occurrence. Despite these complexities, implementation may not be so difficult since only those modes that have strong surface components on the surface where sensors are mounted would be in evidence. Since the rail base is constrained by sleepers (rail ties), mode conversion from modes existing in the railhead into vibrational modes in the rail base could be suppressed.

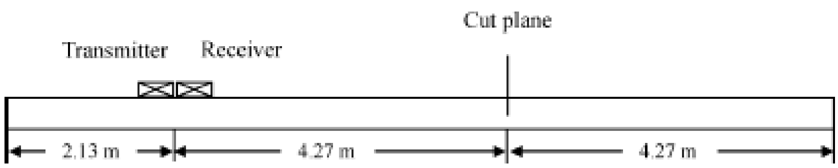
Along these lines, it may be that a collection of certain modes are less subject to mode conversion than others and may be the modes that are most effective for defect detection.

Various EMATs were also evaluated and among those were 60 kHz Lamb wave, 60 kHz Shear horizontal (SH), and 220 kHz SH EMATs. The 60 kHz Lamb wave EMATs were quite noisy, the _noise‘ likely being the multiplicity of modes present in the rail. The 60 kHz SH and 220 kHz EMATs both performed well with the 60 kHz far outperforming the 220 kHz probes. In sense, the 220 kHz test verified the statement about staying within the range [40; 80] kHz.

Using the 60 kHz SH EMATs, a rail cutting experiment was performed for identifying any correlation between EMAT response and cut depth. Fig. 11 shows some photographs of some of the rail cutting experiments.

The experimental arrangement for evaluating the pulse–echo response of the 60 kHz SH EMATs to rail cuts of varying depths is shown in Fig. 12. The pulse–echo response of the 60 kHz EMATs is shown in Fig. 19. The echoes from the various depths of cut are well defined up to 31%. Mode conversion then entered the picture making the distinction between the echo and the modes arising from mode conversion less obvious. The amplitude trend followed being weakly monotonic and increasing. This heuristic trend is expressed as the _expected result‘ curve in Fig. 13.The experimental arrangement for evaluating the through transmission response of 60 kHz SH EMATs to rail cuts of varying depths and results are shown in Fig. 19.An exponentially decaying trend was expected and is noted.

Figure 18: Rail cutting site. Bottom photograph shows the arrangement for the 60 KHz SH EMAT evaluation (Courtesy: Ref-8)



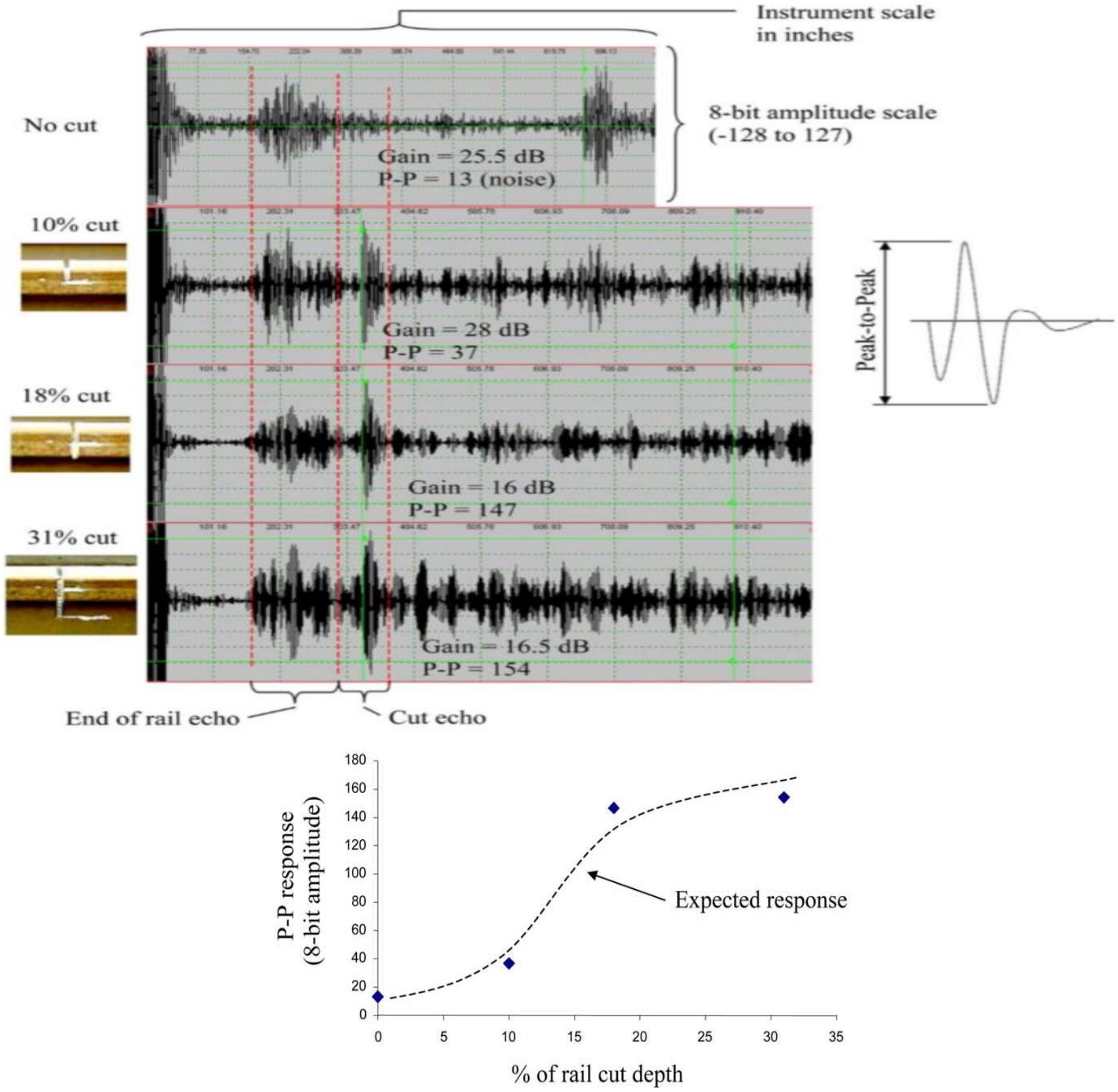
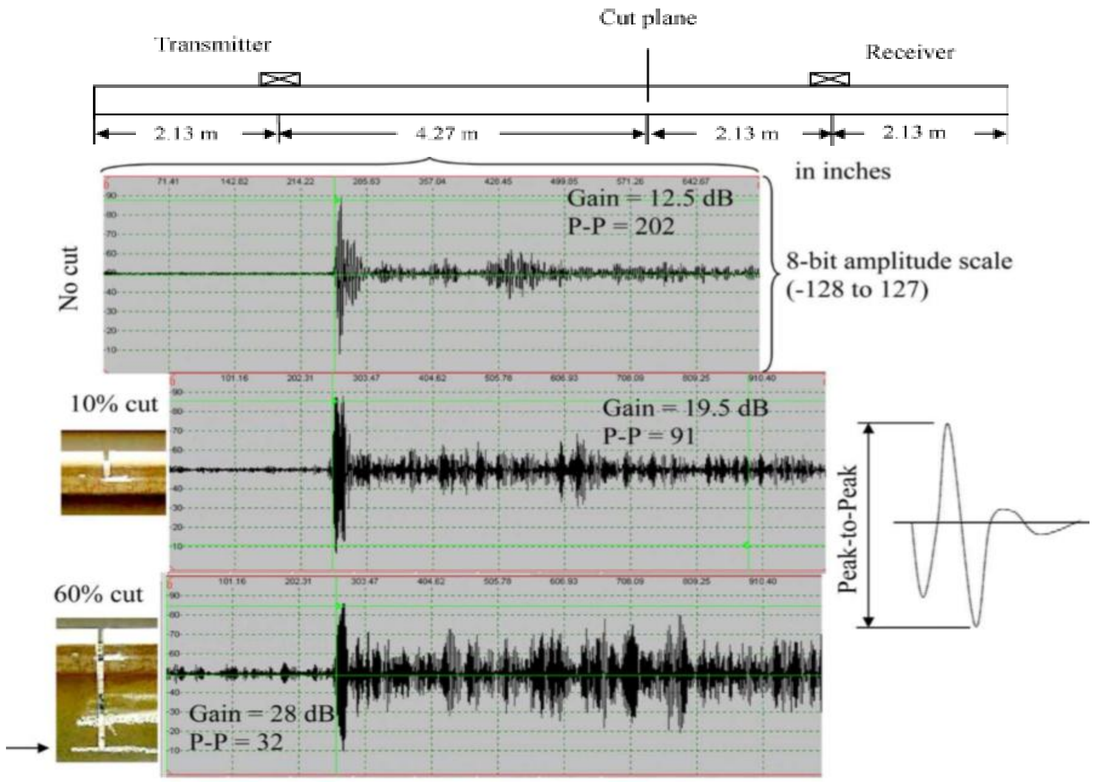


Figure 19: Experimental arrangement for pulse echo evaluation of 60 kHz EMATs and the selected pulse echo responses (Courtesy: Ref-8)



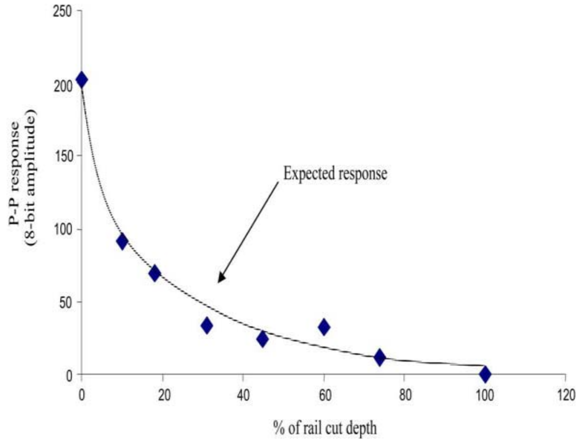


Figure 20: Experimental arrangement for through transmission evaluation of 60 kHz EMATs and the responses .The EMATs were separated by 6.4 m and the cut was 4.27 m from the transmitter. (Courtesy: Ref-8)

Over all, the 60 kHz SH EMATs demonstrated the best performance of the EMATs evaluated. An excitation frequency of 50 kHz was used as it provided the maximal response during calibration. This can be seen via the crispness of the RF waveforms excited at this frequency.

Using the distance between transducers and the arrival time of the transmitted pulse, a wave velocity of 3.02 mm/microseconds was calculated (λ = 6.05mm).A somewhat exponential amplitude decay response was anticipated as a function of cut depth. Fig. 20 shows waveforms for 0, 10, and 60% cuts. Note, at the60% depth, a multiplicity of modes is present as a result of mode conversion.

The paper concluded that the Rail can and does support guided wave propagation in the ultrasonic range [40-80]KHz and this frequency range will support modes that can travel appreciable distances (2134 km for example).Non-contact methods for receiving sound energy from rail like air coupled transducers and EMATs could be used. Air-coupled transducers can receive sound from rail at distances greater than 1.52 m from the railhead. On the other hand, EMATs are presently handicapped in the sense that lift-off distance greater,0.15 cm degrades rail signals substantially. ***Research is being done in EMAT design to improve signal quality at increased lift-off distances***.

The paper also suggested that the responses from ***shear horizontal wave*** EMATs corresponded in a weak monotonic (never decreasing) fashion to the vertical extent of transverse cuts in rail. Because of their signal-to-noise ratio and monotonic response trend with cut depth they should be considered as major candidates for the development of a transverse defect detection system.

Rose J.L. et al. [3] have also explored the possibility of using the Lamb type EMAT transducers for detecting transverse cracks and shelling.

5. Tackling the practical problems of coherent noise and dispersion

Cawley Peter [2] has tackled the practical problems of coherent noise and dispersion. Ideally the signal should contain two distinct echoes from the two ends of the pipe rather than the very complicated trace seen in the results of Fig 21. The complication arises from the excitation of multiple modes which travel at different velocities in both directions, and these velocities being in general a function of frequency (i.e. the modes are dispersive). Fig 22(a) shows the dispersion curves for a 6 inch diameter, schedule 40 steel pipe. There are about 50 modes present at frequencies below 100 kHz and many of them are strongly dispersive.

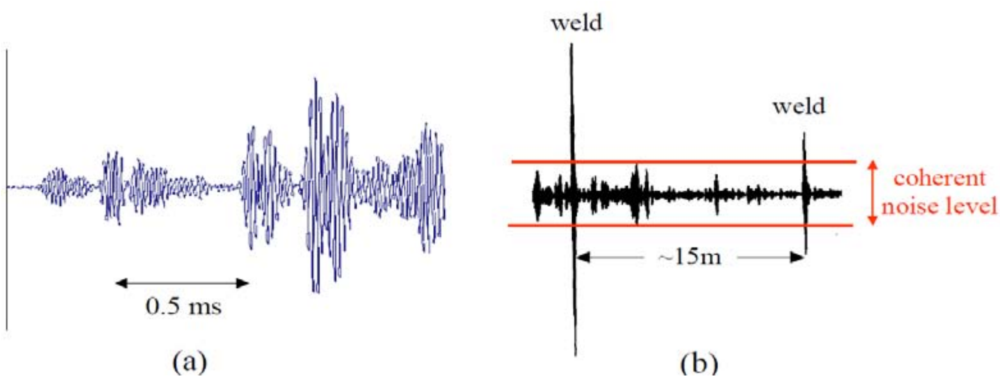


Figure 21: (a) Signal received on length of plain pipe using transducers over quarter of circumference; (b) signal received on welded pipe in early site test. (Courtesy: Ref-2)

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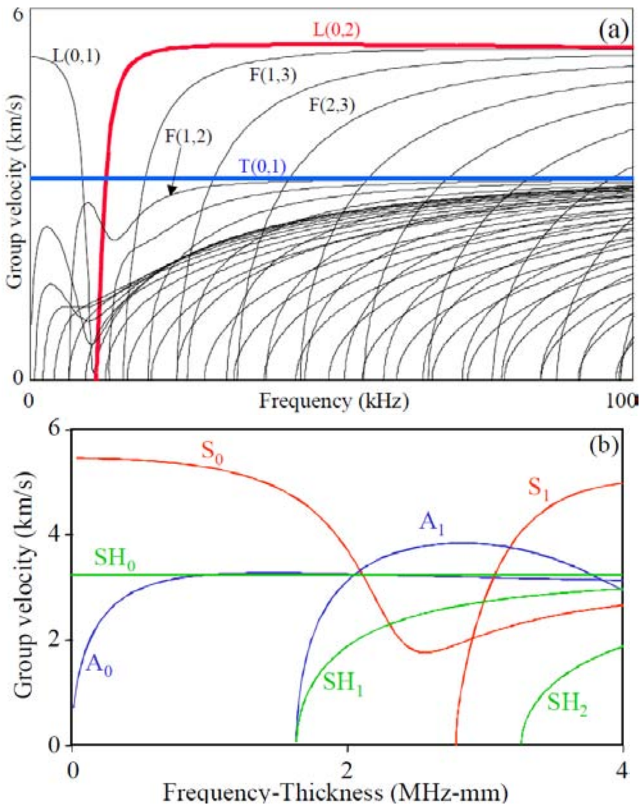

Figure 22: Dispersion curves for (a) 6 inch, schedule 40 steel pipe; (b) steel plate (Courtesy: Ref.-2)

Fig 21(b) shows the corresponding diagram for a plate. Here the group velocity is plotted as a function of frequency-thickness product and below about 1.6 MHz-mm only three modes are present (a0, s0 and SH0). Therefore in a 10 mm thick plate there are only 3 modes present below 160 kHz. Mode control is therefore easier in a plate than a pipe but other problems are more difficult, as will be discussed later.

Fig 21(b) shows a clearer signal obtained at an early stage in the development of the pipe screening system discussed later. Reflections from two welds approximately 15m apart in a long pipe can clearly be distinguished. However, there are many smaller signals between the two weld echoes which should not be present since this was a new pipe.

Averaging did not improve the signal, indicating that the problem is coherent, rather than random, noise. The welds are approximately -14 dB reflectors and the coherent noise level is about 10 dB below the weld echoes indicating that the signal to coherent noise ratio is between 20 and 25 dB. However, the target reflection size in this application was -26 dB so the system needed further refinement to reduce the noise. The coherent noise has two main sources:

- The excitation and reception of unwanted modes
- The transmission of waves in the opposite direction along the pipe and the reception of echoes from that direction.

The key to controlling coherent noise is therefore to excite and receive a single mode in one direction. The choice of mode will be influenced by the ease of exciting it while minimising the excitation of other modes, and by its sensitivity to the defect type(s) of interest. In addition to controlling coherent noise, it is also necessary to control dispersion. If the chosen mode is dispersive, the different frequency components in the signal travel at different velocities so the signal duration increases which compromises the spatial resolution (the ability to distinguish echoes from closely spaced reflectors). Dispersion is not very evident in Fig 21b since it was controlled by applying narrow band excitation centred on a region where the mode of interest is non-dispersive. The paper suggests that this strategy to overcome dispersion problems is often sufficient, though dispersion compensation can also be valuable.

In medium range testing, mode control is usually achieved by choosing an appropriate transducer and excitation signal. Fig 23 shows a schematic diagram of an EMAT (electro-magnetic acoustic transducer) which generates a wave in the structure via the Lorentz force and/or magnetostriction. A narrow band signal (typically a few cycletone burst) is applied to the meander coil and the current flows in opposite directions along successive limbs of the coil, so producing force in opposite directions. Therefore the spacing between the limbs of the coil controls the dominant wavelength of the excited wave. Hence a chosen mode can be excited by tuning the frequency, f, to the point on its dispersion diagram where the phase velocity is given by

$$c_p = f\lambda$$

Where λ is the wavelength imposed by the EMAT. Direction control can be achieved by employing a second coil overlapping the first but displaced from it along the structure by a quarter wave length. If the two coils are excited with the same signal, it may readily be shown that the waves generated in one direction interfere constructively, while in the other direction the interference is destructive.

It is important to use a transducer which forces the structure in the most appropriate direction. For example, at low frequency the s0 mode in a plate involves predominantly inplane motion, while the a0 mode is predominantly out-of-plane. It is therefore very difficult to obtain a satisfactory ratio of s0 to a0 signal by using a transducer such as a piezoelectric transducer on an angle wedge because it applies an out-of-plane force to the structure surface; if the s0 mode is to be used in this regime, an EMAT designed to apply an in-plane force is preferable.

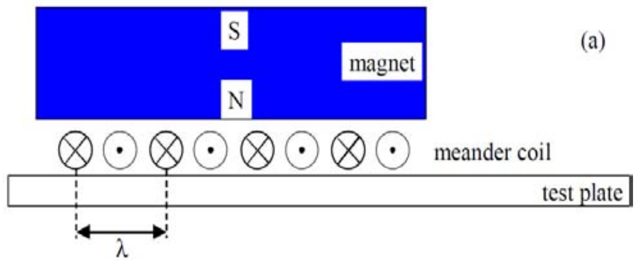

Figure 23: Schematic diagram of excitation of guided waves by EMAT (Courtesy: Ref-2)

The degree of modal selectivity obtained is governed by the size of the transducer and the excitation signal. The transducer size controls the effective wavelength bandwidth (with the EMAT) or the effective phase velocity bandwidth (with piezoelectric excitation),while the excitation signal governs the frequency bandwidth. This is discussed further in[21, 23-25]. In order to obtain satisfactory mode control, the transducer generally has to be a round 3-5 wavelengths long. For a mode with a phase velocity of 3 mm/microseconds, the wavelength is 6 mm at a frequency of 500 kHz so the required transducer size is modest.

However, if the frequency is reduced to 50 kHz, the wavelength increases to 60 mm and the required transducer size becomes impractical. Therefore in long range testing an alternative to single, monolithic transducers must be sought and it has been found that an array of point sources is very attractive in several applications, as discussed below.

If an array is used, satisfactory mode control requires that the direction of the force applied by the individual elements is appropriate for the desired mode, and that the individual array elements have good gain and phase consistency. Signal processing makes an important contribution to extracting the desired input mode - received mode combination from the array and rejecting other combinations, so improving the signal to coherent noise ratio; this is discussed further in the examples below. It is also potentially possible to subtract a baseline signal obtained at an earlier stage in the life of a structure from the current signal in order to track changes. This is particularly applicable in 'smart structure' applications where the transducers are permanently attached, but the operation is not straightforward since, for example, temperature changes or small, unimportant changes in material properties with age will affect the dispersion relationships, and hence the received signals.

More sophisticated arrangements – EMAT pairs for different defect detection

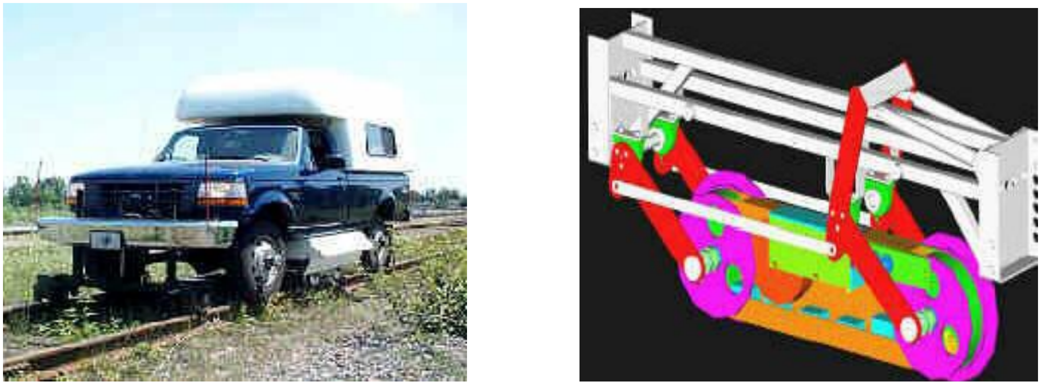

Figure 24: Integrated mobile inspection system. Designed transducer carriage and holder.(Courtesy: A.Chahbaz, M.Brassard and A. Pelletier, Mobile Inspection System for Rail Integrity Assessment. WCNDT 2000)

5.1 Limitations of EMAT

There are certain limitations of EMAT
- EMATs have very low efficiency.
- The insertion loss of EMATs can be as much as 40 dB or more when compared to conventional ultrasonic methods.
- The EMAT technique can be used only on materials that are electrical conductors or ferromagnetic.
- The design of EMAT probes is usually more complex than comparable piezoelectric search units.
- Due to their low efficiency, EMATs usually require more specialized instrumentation for the generation and detection of ultrasonic signals.
- High transmitting currents, low-noise receivers, and careful electrical matching is imperative in system design.

In general, EMAT probes are application-specific, in the same way as piezoelectric transducers. The main disadvantage of EMAT is the low efficiency of the transducer, which requires high power and very precise electronic designs to generate and detect the signals. This disadvantage has become less relevant with new hardware and software tools that permit complex signal processing in real time.

6. Indian Railway Scenario

Due to the specialty of EMAT of generation of Shear Horizontal (SH) wave mode it is being commonly used to detect and characterize defects in stainless steel plates and welds. In view of advantages of EMAT technology and non availability of rail testing systemscommercially, it was decided to explore the technology indigenously. This paved way forinitiation of a joint research on the subject with Indian Institute of Technology (IIT), Kanpur underTechnology Mission on Railway Safety (TMRS) in year 2005. Initially generic EMAT equipment along with normal and angle probes was procured fromInnerspec Technologies Inc. USA in order to obtain firsthand experience with EMATs [7].

Figure 25: Power Box Set up from Innerspec and Testing of Rail Containing Natural GFC defect (Courtesy: Ref-7)

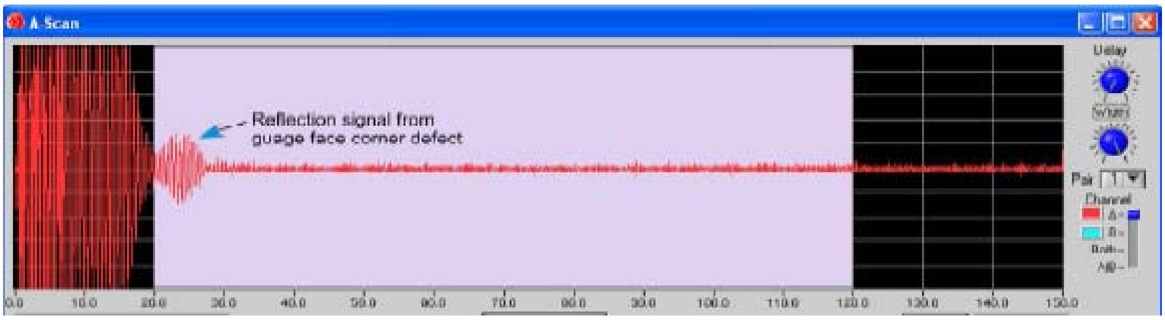

Figure 26: Screenshot Indicating Signal Obtained from GFC Defect in Rail Using Angle Probe (Courtesy: Ref-7)

Initial experiments with rails containing natural and artificial defects led to following conclusions:

- The EMAT technology is able to pick up transverse defects in rail head.
- The weight of the system and requirement for the power source for electromagnetsdictated that the rail testing system be essentially vehicle based.
- In order to make it suitable for rail testing considerable customization of user interfaceand probe parameters was considered necessary.

The focus of studies with guided wave EMAT probes were detection of vertical defects of varioussizes in rail head from distance. Another area of interest was detection through alumino thermicwelds in rails. Reference [7] shows that excellent detection levels were exhibited by the guided wave probes for gauge corner defects ofarea 4 mm^2 and higher from a distance of 36cm to 94cm.

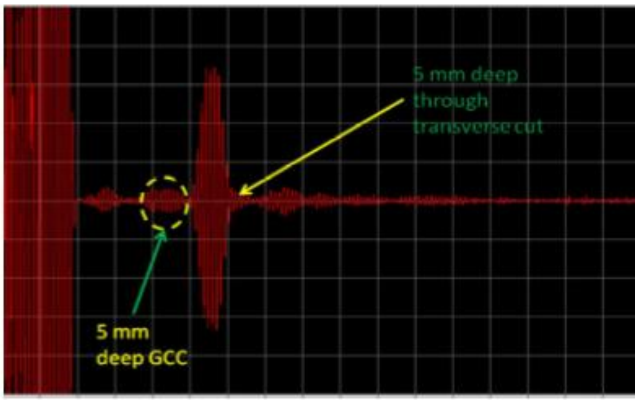

Figure 27: Defect Signals from 5mm deep Gauge Corner Defect and 5mm Deep Through Cut in the Railhead (Courtesy: Ref-7)

These experiments provided insight into the capabilities of EMAT guided wave technology fordetection of transverse defect under adverse surface condition. These included reasonableaccuracy in detection of target defects of very small size from a distance. It was also noted thatguided waves are able to penetrate through defect free welds, thus proving useful for detection ofdefects in welds and see through the welds for inspection of rail section behind welds.

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