FAAST - Fast Automated Angle Scan Technique

Philippe COPERET, Socomate International, Crécy la Chapelle, France

Abstract. Since "Phased Array" systems appeared in the field of industrial testing, this technique only reproduced an ultrasonic beam equivalent to that of a single element transducer, offering however, in addition, the possibility of an electronic control of the ultrasonic beam direction and shape.
These systems thus offer an increased flexibility of use, higher linear or angular scanning speed, together with a considerable advantage in terms of the volume of the probe-holder mechanics.
However, this technique did not bring any improvement in terms of defect detection and characterization, as the reflected energy is still depending, like with single element probes, on the position of the transducer to the part and on the actual orientation of the defects.
This paper describes a new method for processing the acoustic field received by a multi-element probe, which, at last, brings a solution to this endemic problem and the associated electronic device suitable for industrial applications.
This method and system enable the detection and characterization, from a single ultrasonic pulse, of all types of defects, plane or spherical, situated in the acoustic field of the probe, whatever their orientation and allows, in addition, tolerance of guiding precision.
As an example, the first industrial application being built by SOCOMATE using this method is an ultrasonic rail testing car providing in-track inspection at a speed of 100km/h.

Introduction

The goal of this research was the development of Ultrasonic Industrial equipment able of processing, in real time, data coming from a multi-element probe, in order to detect and characterise, in one shot, all reflectors inside the acoustic sound field of this probe.
Studies have been realized in this way by different Labs and Universities, but never developed into an industrial product, because algorithms, generally used for image processing, request too much important calculation resources to be, either implemented into cost effective equipment, or developed under software basis with a processing speed compatible with requested in-line testing requirements.
At the moment, current equipments on the market are all based on the Beam forming principle using the Sum technique of phased signals.
The new concept Socomate International has developed can be applied to any type of materials, and particularly, as we will see it later on, to tube, bar, composite……….and, in order to illustrate this new concept in both interest and principle sides, we will take as example an on-track Rail Testing, which has been the very first industrial application of our FAAST System, and for which the main goals were:

- Testing speed: 100km/h
- Control pitch: 4mm, that allows, at the testing speed, a max UT and processing time of 140µs per shot.

- Main Test Angles, in the rail longitudinal axis, as examples: -70°; -35°; 0°; +35°; +70°.
- Ability to detect and characterize flaws whose directions are not exactly normal to the five main Angles.
- The elapsed UT time for each of those angles according to wave type and scanning depth is 100µs. So total 500µs for the 5 angles.

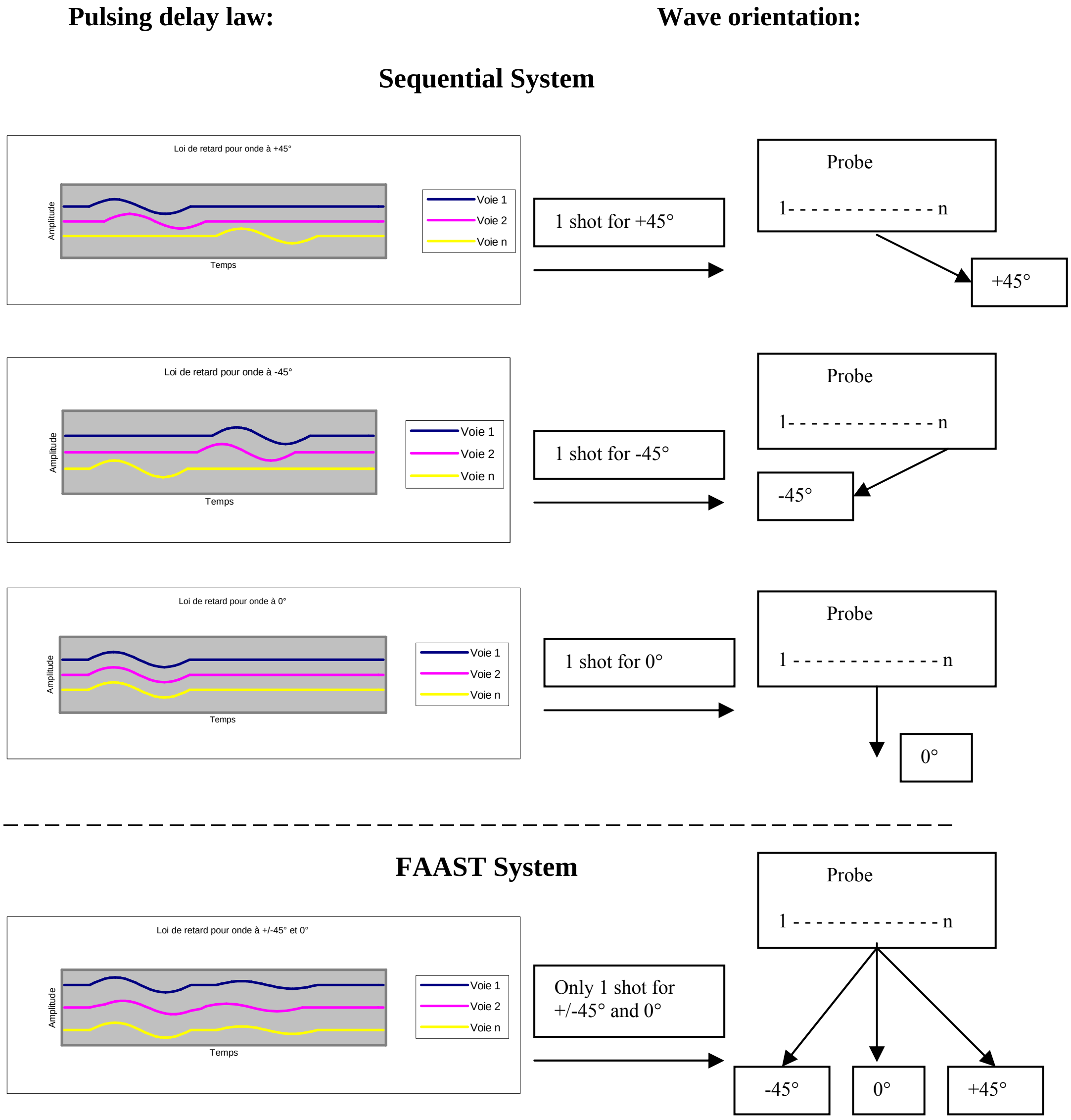
We instantaneously see that with conventional technologies, 5 multi-elements in parallel are needed to achieve such a performance, which would lead, with a "Phased Array" system, to a very high cost solution. The "Phased Array" solution ceases to be of interest as we would need as many multi-element probes and electronics as we have main angles, without, for all that, achieving the detection of flaws with different orientations.

Description of Completed Work

The two main areas of this study have been first to develop a Transmitter able to generate a multi-directional wave in one shot, and then, a real time processing method of data coming from a multi-element probe in order that they can be easily used in industrial environment.

Transmitter

We can easily prove that for generating a one-shot multi-directional wave, it is just enough to add, for each of the elements of the probe, the Pulsing Signals calculated for each of the wanted beam orientations.
As there is naturally inter-modulation of those signals according to calculated delay laws, this operation is only possible with a linear system. See the here below scheme as an example with 3 orientations.



Example of Ultrasonic Beam deviation

We have then developed a Linear Transmitter, which is in fact a Tone Burst Generator. This type of transmitter, although more expensive than conventional ones, has a huge advantage:

-Ability to combine several delay laws (deviation and/or focusing) at the same time.
With the above Rail Testing example, the energy is spread out simultaneously within the 5 directions.

- Ability of Pulsing in different directions at different frequencies, (within the band pass of the Probe).
Indeed, we can adjust the Central frequency as well as the band-pass of each signal transmitted into each direction, by setting, fully independently per direction:

- The basic sine wave frequency
- The number of cycles
- The amplitude modulation by Hanning, Hamming, or other filtering methods…..

For instance, in the Rail testing example, we transmit simultaneously a 0° wave at 4MHz, and two 70° waves (±) at 2.5MHz.

- Possibility of coding Pulsing Signals, which makes received signal recognition by the Probe very simple, and opens signal processing ways, not yet running at this day, into the field of Ultrasonic Industrial Control.

FAAST Process

Having, in one shot, properly filled the part under test with sound in the zones of interest, the second step consists in processing, within the appropriate acoustic time, all data received back by the Probe, that can come simultaneously from all the different zones.
Our study had moreover the aim at solving major issues of Ultrasonic control, irrespective of their origin, either with single crystal or even more with multi-element Probes due to their spatial sampling. That is to say:

- The tolerance on mechanical guiding accuracy of the test piece relative to the Probe.
- The tolerance on the absolute value and the non homogeneity of Ultrasound Velocity in the materials.
- The tolerance on direction and shape of real defects related to reference ones

In order to make this possible, the FAAST concept is based on a radically different approach of what is being used in the Ultrasonic testing field.
Indeed, signal processing, according to delay &/or focal laws pre-calculated from theoretical data on positioning and Velocities, requests, to say the least, as many laws as sought defect types. This increases systems costs when parallel processing, or drops down the testing speed when sequentially processing, without for all that solving the tolerance issue described above.

The FAAST concept then consists of processing signals coming to each element of the Probe, without presuming a defect response, but instead by looking for coherence between those signals.

Thus, it is not any more a beam forming system from a multi-element Probe, but an image analysis process for signals received by this Probe.

All the difficulty remains in this image real time processing at over 10 kHz PRF with a data capacity per image of about several Mb, that is to say a data flow of several GB/s to process.

As far as Rail testing, as described before, is concerned, we have for instance 7 kHz PRF with 3.84Mb per image (this for a testing depth of 100µs, a sampling frequency of 50MHz, a conversion on 16bits and a 48 element Probe), then a data flow of 26.88Gb/s.

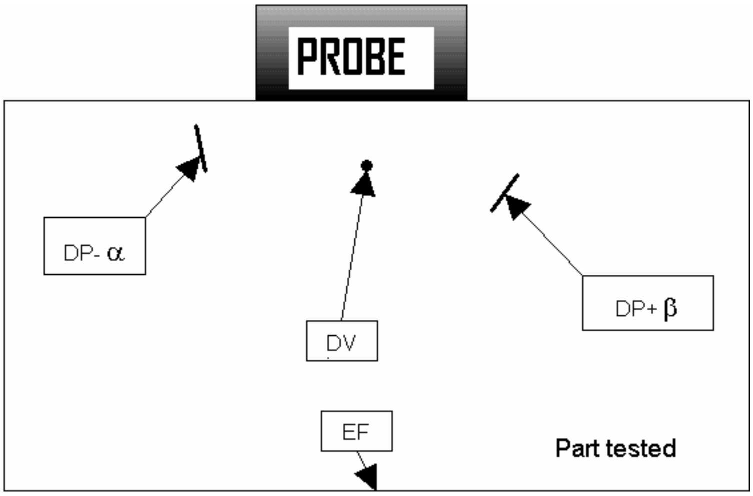
In this application as for many others for NDT, the goal is to get the Amplitude and the Position of only a few echoes that allow Alarm triggering for in-line control, as well as C-Scan mapping with immersion tanks.

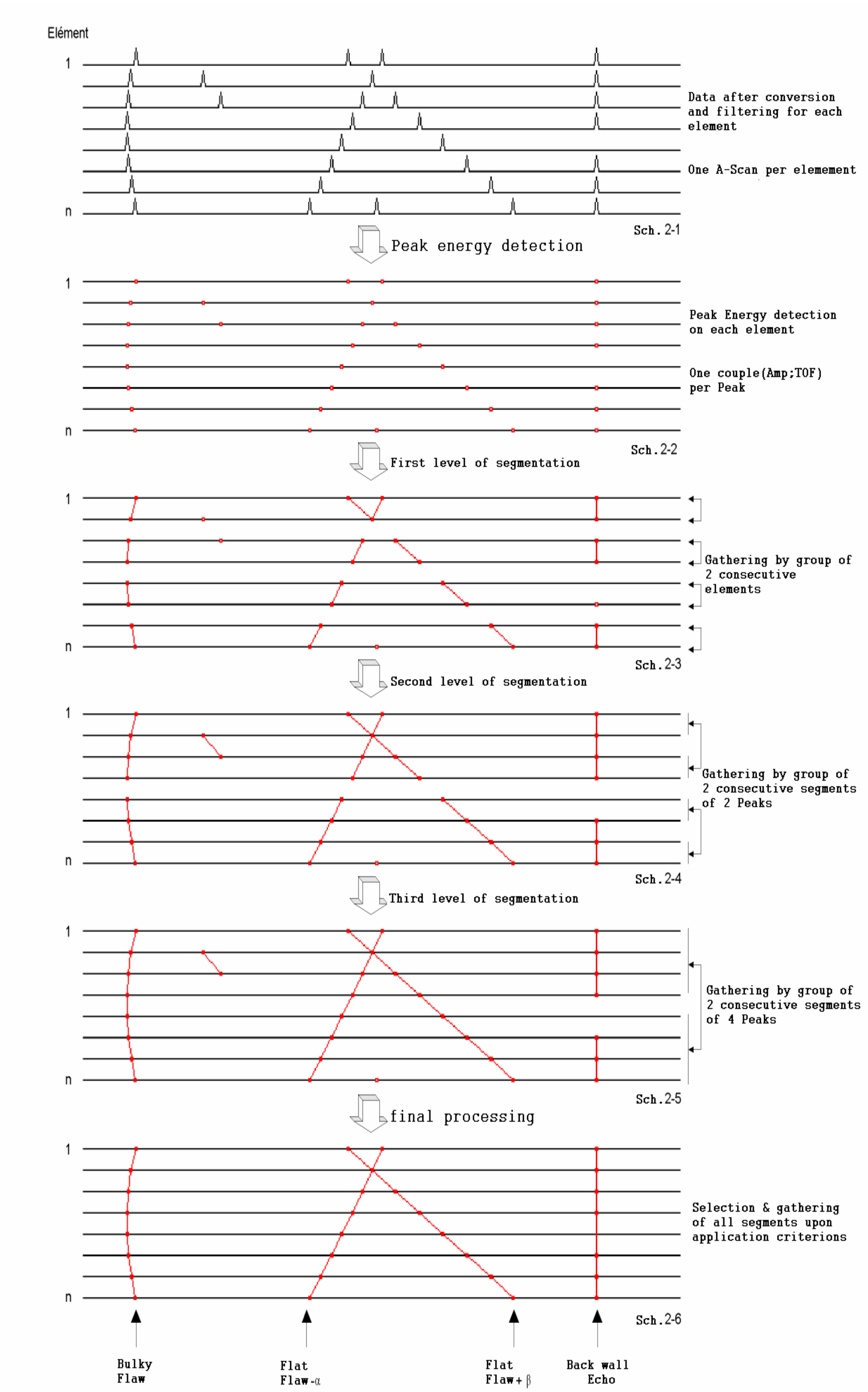
With rail testing, every 4mm pitch we process Amplitude & Distance data coming from 6 echoes such as 70° both side, 35° both side, 0° flaw & Back wall.

Each echo is being processed on 40 bits (16 bits for Amplitude and 24 bits for Distance), the really used data volume goes now from 3.84Mb to only 240 bits, which means an incredibly huge data compression.

Consequently to this establishment, the FAAST process is configured to realize this compression at the early stage of the measuring process, just after the A/D conversion, in order to allow a real time processing at high speed with hardware and software resources compatible with the multi-elements market price.

So, the FAAST system proceeds as follows (see schemes below):





Detection of the maximum energy peaks received on each element of the Probe (See scheme 2-2).

To do this, several methods are possible, from which one very simple, but nevertheless more than enough for most of applications, which consists in deriving the signal envelope. We can also use the transmitter ability to generate coded signals in order to make this detection by auto-correlation, this method being much more sensitive if it was necessary.

Gathering in one segment ℓ (see scheme 2-3) of two max energy peaks detected by two consecutive elements j & j+1 if: $\left| TOF(j)_{i=1 \text{ à } k} - TOF(j+1)_{i'=1 \text{ à } k'} \right| \leq \Delta T$
Where,

- $TOF(j)_{i=1 \text{ à } k}$ is the temporal position of the maximum i, with i = 1 to k, in the signal of response generated by the element j
- $TOF(j+1)_{i'=1 \text{ à } k'}$ is the temporal position of the maximum i', with i' = 1 to k', in the signal of response generated by the element j+1
- T = t + ε, with t = (p.sinx)/V, where p is the distance from element j to j+1, x is the max wanted deflecting Angle, and ε is representing the tolerance of the processing operation due to calculation errors and mechanical deviation.

Segments ℓ that were generated, made with 2 maxima coming from 2 consecutive elements, are then gathered into segments L made with 4 maxima from 4 consecutive elements (see scheme 2-4).
This gathering is made according to the same temporal criterion as the operation before, to which has been added a slope criterion such as $\left| \text{slope}(\ell) - \text{slope}(\ell+1) \right| \leq \Delta P$, where slope
(ℓ) and slope (ℓ+1) are respectively from segment ℓ & ℓ+1 and where ΔP is a predetermined value of the accepted difference between the slopes of two consecutive segments.

This operation is repeated upon all the elements making up the Probe Reception aperture, in order to gather the whole max energy peaks coming from one reflector (see scheme 2-6).

The final segments that were created contain all the necessary information to characterize all the reflectors located in the acoustic sound field of the Probe, whatever they are planar or volumetric (see scheme 2-6).

Flaw amplitude is indeed equal to the sum of peak energy max included in the segment, its distance is the segment position, and its angle is related to the Pulse direction as well as the segment angle.

We then can create one or several A-Scans, for instance 5 with the Rail testing application, each of them representing a main Angle such as 0°; +35°; -35°; +70°;-70°.

It is important to notice that, for each echo in the A-Scans, we have the real Angle value of the corresponding reflector, which moreover allows a bi-dimensional Amplitude correction according to the reflector position and real Angle.

Those echoes then can be monitored by conventional way in order to trigger Alarms and generate maps.

Results

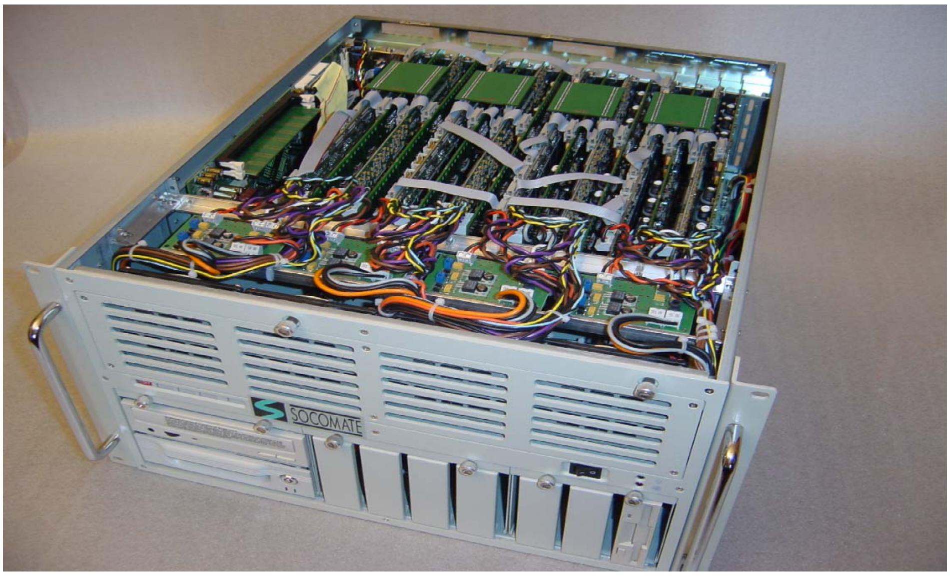
This new concept gives huge advantages over single or multi-element conventional Ultrasonic Testing Systems, that is to say:

- A greatly increased Testing Speed with flaws detected simultaneously into all directions. In Rail testing case, for instance, the Testing speed is 5 times faster than a Phased Array system.
- A high tolerance on mechanical location of the probe on the test piece in-line as well as on the flaw real Angle, which has an effect on the segment slope but not its resultant Energy, unlike conventional systems.
- A High tolerance on Ultrasonic Velocity variations in materials whatever they are global or localized. These cause segment distortion, but, once more, without any influence on the resultant Energy.
- The improvement of flaw characterisation thanks to the segment Angle detection in case of flat reflector, or to a curved segment in case of volumetric reflectors.
- As far as an acoustic Image analyses process is concerned, as opposed to a beam forming process, the Probe specifications criterions can be very different of those from conventional systems. It is in particular possible to widely reduce the number of elements for some applications.

Equipment

FAAST Hardware is Based on PCI Boards mounted into an Industrial PC Rack (see picture below).
Each rack is able to integrate up to 64 Channels in fully parallel mode. It is possible to drive and synchronize up to 32 racks simultaneously, which allows systems with up to 2,048 parallel channels.
Other FAAST main features are as follows:

- Software adjustable linear transmitters with 1 Watt average Power per channel.
- Analogue bandwidth: 20MHz
- Input digitising dynamic: 84dB
- Embedded Signal Processing with CPLDs & DSPs



FAAST PC RACK 64 CHANNEL

Conclusion

As previously described, this new concept allowed the realization of a Rail testing system on track that was unimaginable with a conventional Phased Array, at the requested testing speeds.

The FAAST Rail system has got 128 channels and is able to detect flaws in the longitudinal and transverse planes of the rail at a speed of 100km/h, whatever their orientations are.

We have also realized trial projects, with the prototype, into different industrial sectors, and have shown up that in addition to the speed advantage, the process ability in compensating automatically for the mechanical variations gives a huge improvement to the detection and characterization of defects.

For instance, we can give two significant examples as tube testing and Carbon Composite radius parts from aerospace:

- Tube testing: using both methods of a ring of probes or rotating the tubes, the FAAST System allows the detection of flaws at high speed while being very tolerant on mechanical guiding. The more significant example that we have realized on this field is about oblique longitudinal flaws on rotating tubes. We have proved that the FAAST is able, in one shot, to detect and characterize oblique defects with ± 25° variation. Amplitude variation of echoes in this angular range is less than 3dB, and can be easily corrected since the obliquity is recognized by the segment slope as previously described.
- Carbon Composite radius testing: The radius geometry not being constant, it is very difficult to obtain liable results with conventional methods because calculated focal laws are thereby arbitrary. The ability of the FAAST process to compensate mechanical inaccuracy has brought a solution to this difficult form of test. Indeed, we have proved that flaws were detected with a repeatability of 2dB with eccentricity of ± 1mm.

In conclusion, the brand new FAAST concept developed as part of this study and the industrial equipment based on this principle are today available on the market. This gives innovative solutions with outstanding performances, when high testing speed, quality of detection and characterization are concerned, and this has been proven in all the industrial fields.