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Special linear phased array probes used for ultrasonic examination of complex turbine components

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Abstract

A large variety of linear phased array probes (LPAP) [size, frequency, bandwidth, multi-heads, pitch size] were designed and manufactured for examination of complex-shape turbine components, such as blade roots, rotor steeples, narrow-gap welds, disk blade rim attachment. The probes were designed and characterised for the following features: geometric dimensions, centre frequency, pulse duration, beam features (focal depth, beam spread in both directions, signal-to-noise ratio). Multi-head LPAP were manufactured to optimise detection and sizing for limited accesses contact areas. Examples of probe characterisation, detection and sizing of artificial and natural defects are given for the following applications: blade roots, rotor steeple, and disk rims. Examples of probe beam features are also presented. Some aspects of Imasonic and OPG QA program for phased array probe characterisation will be illustrated

Introduction

OPG has to run several inspections of complex-shape turbine components, such as blade roots, rotor steeples, narrow-gap welds or disk blade rim attachment. Specific aspects of this project were published in [1 – 3] . An update of field trial nr. 3 was presented in [4].
Taking into account the requirements for minimum target size, the geometry of the parts to be inspected and the productivity constraints, it was decided to use phased array technology with an improved probe design and reliability.
In this framework, collaboration was settled with Imasonic for the development of an advanced phased array probes concept dedicated to these applications.

Probes considered

About 32 phased array probes have been specifically developed during the last 4 years.

Among these probes we could mention:

- Hard-face multi-head L-waves probes in a single Hypertronix connector
- Hard-face custom-built probe for top inspection on L-1 steeple
- Soft-face T-waves probes for Parson-type blades/steeples
- Large soft-face probes for longer UT path (120-300 mm) to inspect GE turbine components

Phased array technology

Phased array technology has been selected for the beam steering and focusing flexibility and also for the possibility to angle the beam without wedge that would require too much space for some inspections.

Piezocomposite technology was preferred for the phased array technology and also to optimise the electroacoustical performances like sensitivity, signal to noise ratio, bandwidth and pulse length.

High frequency miniature probes

All probes are high frequency probes (from 5 MHz to 17 MHz) for high-resolution inspection.
Miniature probes were necessary to inspect the complex geometry and limited access components.

High quality

Further to the electroacoustical performances, OPG and Imasonic put emphasis on the reliability of the probes for their use in the industrial field

Probe design

Beam Modelling

The modelling of the probe is done by O.P.G., with PASS software.
The target parameters of this modelling are inspection depth, lateral and axial resolution, according to various inspections angles.
This modelling work allows the definition of the phased array probes, and particularly
Frequency, bandwidth, pulse length specification
Number, size and geometry of the elements
Probes are also designed to avoid grating lobes or secondary lobes that may generate unexpected parasitic echoes.

Imasonic checks this design with in-house software QuickSonic that allows a very quick check of the basic parameters of a linear phased array probe
If necessary, Imasonic may also confirm the design with CIVA software, developed by CEA (France). This very complete software allows accurate beam simulation and interaction with defined defects.

Electroacoustical design

Based on OPG specifications, the electroacoustical design of the probe is done by Imasonic. This design particularly concerns:
The piezo-composite material
A specially designed piezocomposite material 1-3 structure (see Figure 1) is implemented in each type of probe. Details could be found in [5] .
The composite components and geometry are defined according to the temporal and frequency response specifications, while keeping high sensitivity and signal to noise ratio level.
The piezocomposite material is also designed to lower the cross coupling between neighbour elements, which is necessary to properly steer the beam with electronic delay laws. Typical cross coupling is lower than –40dB.

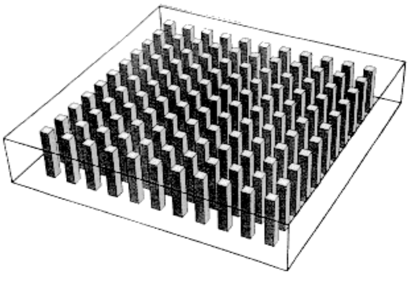


Figure 1: Schematic representation of a piezo-composite plate with a 1-3 structure - W.A. SMITH

The matching layer

Taking into account the using conditions of the probe (manual, automated, direct contact, contact with a wedge), the matching layer is designed to optimise the energy transfer, to shorten the pulse length and to be wear resistant.

The backing material

The backing material is designed to shorten the pulse length and attenuate the back echo. Specially designed backing materials allow interesting compromise with high damping and high attenuation in reduced dimension

The cable

The cable performances are also a key parameter for the overall performances of the probe. Its attenuation must be as low as possible, mainly for high frequency probes. Its electrical impedance is matched to probe and electronic characteristics.
The bending capability is optimised to access small areas, while keeping high mechanical resistance and constant electrical properties.

KLM Model

The electro-acoustical influence of all these components is simulated with software based on KLM model. The target parameters are temporal and spectral response, sensitivity and electrical impedance (see Figure 2).
Combined with this software, Imasonic databases on piezocomposite material allow precise simulation and very predictable electroacoustical performances.

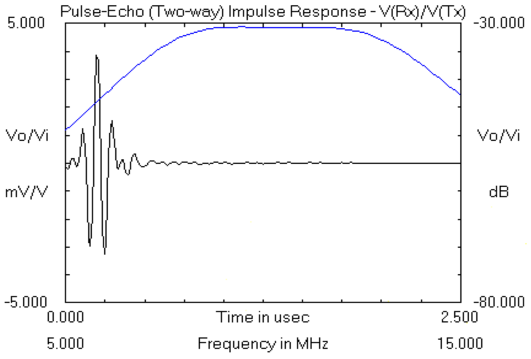


Figure 2: Electro-acoustical design with KLM Model

Mechanical design

OPG issued mechanical specifications for each probe based on part geometry and manipulator holding device.

These specifications include overall dimensions, particular geometry requirements, and cable output position.

Imasonic validate this design or propose modifications to OPG to guarantee a high mechanical resistance and watertightness under 50cm of water.

New challenges

OPG challenged Imasonic with new features for its phased array probes

Hard face

Several probes are used manually or automatically in direct contact, which is very aggressive for the front face. The wear of the front face may have unexpected consequences on the probes like water penetration in the probe or modification of electroacoustical properties.
In the meantime, the implementation of a protective layer on the front face may alter the pulse length and sensitivity due to the additional interface.

For this reason, Imasonic implemented a new hard face material $\lambda/4$ material that combines an appropriate acoustical impedance for high energy transfer. OPG tested wear resistance which was 10 times higher than conventional front face.

Miniaturisation & Geometry

The restricted space available for inspection and limited access for contact area required miniaturised probes with particular front face geometry.

Imasonic manufactured small probes down to 8 x 8 x 17 mm for 6 x 6mm active area with 20 elements.

Multiple head / custom-built

Inspection speed required parallel inspection of neighbour blade roots or rotor steeple, or parallel inspection of different area of the same part.
For this purpose, OPG designed and Imasonic manufactured up to 4 head probes connected in a single connector (see Figure 3).

The ends of L-1 steeple may be inspected for crack confirmation with a custom-built hard-face probe capable to fire positive and negative angled beam from the top of the steeple, under the blades (see Figure 4).

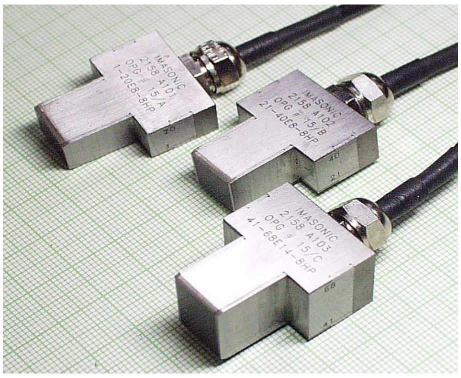


Figure 3: Probe 15A & 15 B: 1-20E8-8HP 20 elements / Pitch: 0.4 mm / 10 MHz Probe 15C: 41-68E14-8HP 28 elements / Pitch: 0.5 mm / 7 MHz Automatic inspection of L-0 rotor steeple grooves.

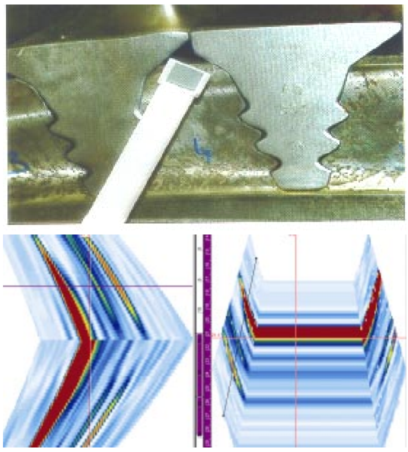


Fig. 4: Probe 19 and S-scan (VC-S-scan) display of 2 targets on CCV and CVX-Hook 1

Imasonic QA system

The probes are designed and manufactured according to Quality Assurance system of Imasonic, which is ISO 9001 certified since January 1998.

Characterisation process

All probes are checked according to internal procedures and periodically calibrated equipment linked to traceable standards. The goal of these procedures is to test during the manufacturing and the final control the performances of the probe that can guarantee the specified performances in the specified using configuration.

Checked parameters

The main parameters checked during the final control are
Frequency (typically ±10%)
Bandwidth (typically 60 to 100%) & pulse length
Sensitivity homogeneity (typically <3dB)
Cross coupling (typically <-40dB)
Electrical impedance

An example of probe performances (nr. 9) is presented in Table 1 and Figure 5.

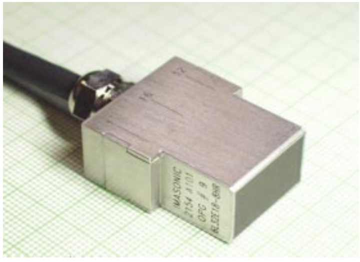
Electroacoustic measurement for the XCR n° 2154 A101 :
(Acoustic load: 1.5MR. IMASONIC procedure: INP 410.)

#	Vpp (mV)	Fc (MHz)	Bw (%)	Lg p. (-20dB) (µs)	#	Vpp (mV)	Fc (MHz)	Bw (%)	Lg p. (-20dB) (µs)
1	694	6.53	69	336	**17**	631	6.34	64	348
2	669	6.46	67	580	**18**	600	6.33	63	408
3	644	6.52	71	492	**19**	587	6.36	66	348
4	619	6.31	64	672	**20**	606	6.33	65	356
5	619	6.39	65	596	**21**	600	6.35	65	596
6	562	6.59	72	600	**22**	594	6.33	66	352
7	587	6.44	68	604	**23**	587	6.31	64	592
8	600	6.49	69	344	**24**	600	6.30	64	592
9	613	6.52	70	492	**25**	594	6.39	66	592
10	587	6.39	66	348	**26**	575	6.37	66	596
11	631	6.46	68	348	**27**	556	6.48	70	604
12	637	6.42	68	596	**28**	562	6.39	66	488
13	613	6.39	68	344	**29**	581	6.39	64	584
14	600	6.32	66	496	**30**	581	6.50	69	344
15	613	6.38	67	344	**31**	587	6.50	66	336
16	631	6.34	66	352	**32**	606	6.44	65	340

	Vpp (mV)	Fc (MHz)	Bw (%)	Lg p.(-20dB) (µs)
Minimum :	556.0	6.3	63.0	336.0
Maximum :	694.0	6.6	72.0	672.0
Standard deviation :	29.68	0.08	2.25	120.40
Average values :	605.2	6.4	66.7	469.4

Homogeneity in sensitivity (dB) : **-1.93**

Table 1: Electro-acoustic measurement for probe nr. 9.



Probe 09: 6L32E18-8HR
32 elements / 0.55 mm / 6MHz

Manual PA L-0 blade/steeple H5
Automatic PA L-0 blade

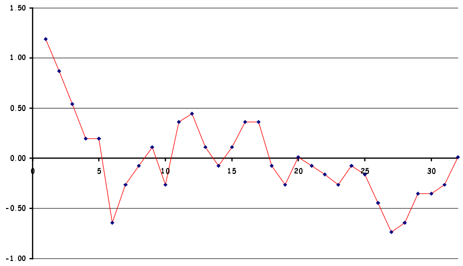


Figure 5: Probe #9 Sensitivity homogeneity

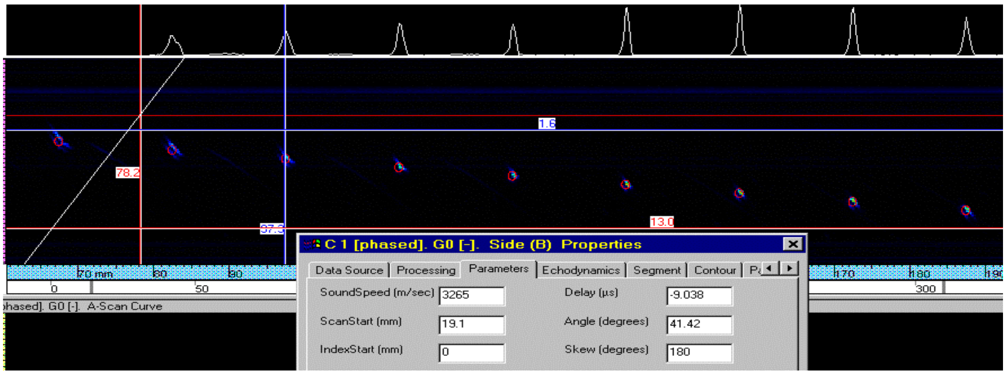
OPG checking procedure

OPG implemented a checking procedure for LPAP probes. Further to Imasonic tests, the goal is to test the beam characteristics with representative delay laws.
Automatic analysis procedure linked to excel sheets have been developed
Table 2 presents the main features to be certified. Index evaluation is presented in Figure 6.

Table 2: Phased array probe main features to be certified by OPG.

Feature	*Symbol*	*Value (example)*	*Remarks*
Centre frequency [MHz]	f_0	10.8	for one set-up
Peak frequency [MHz]	f_p	11.2	for one set-up
Pulse duration [µs]	Δt_{-20}	0.32	for one set-up
Relative bandwidth [%]	BW	78.5	for one set-up
Focal depth [mm]	F_0	50	for specific angles/focal laws
Depth of field [mm]	L_{-6}	14 –86	for specific angles
Wedge delay [µs]	TOF_{wedge}	3.5 – 6.4	for specific angles
Refracted angle [^{0}]	β	35 – 55 , step 5	for a specific focal law
Signal-to-noise ratio [dB]	S / N	> 30	for specific angles
Start Scan – Index [mm]	ΔX_β	14	for specific angles
Beam divergence [mm]	$\Delta X_{-6\,dB}$	3	for specific angles
Near-surface resolution [dB]	$A_{n\text{ “ h = mm “}}$	>2	for specific angles
Far-surface resolution [mm]	$A_{f\text{ “h” mm}}$	< 80	for specific angles
Skew angle [°]	θ_{skew}	N/A	for one refracted angle
Beam dimension on X [mm]	$X_{-3\,dB}$	1.8	for specific angles
Beam dimension on Y [mm]	Y_{-3dB}	8.5	for specific angles

Figure 7-9 illustrate evaluation of beam divergence, depth of field and S/N ratio on various probes. The Experimental parameters are very close to modelling.



SoundSpeed (m/sec) 3265
ScanStart (mm) 19.1
IndexStart (mm) 0
Delay (µs) -9.038
Angle (degrees) 41.42
Skew (degrees) 180

Figure 6: Example for evaluation of actual refracted angle, wedge delay, and exit point, using specimen features of reference block with side-drilled holes.

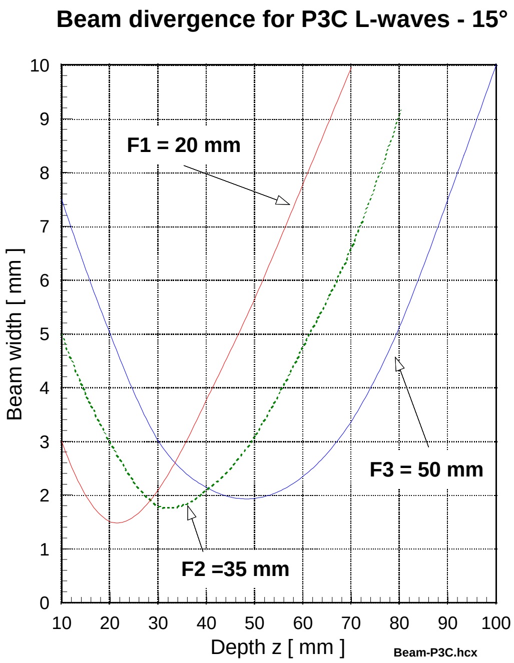


Figure 7: Beam divergence for P3C.

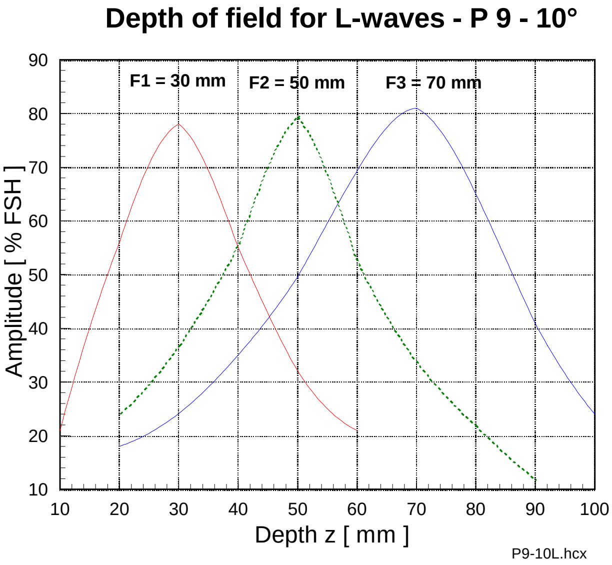


Figure 8: Depth of field for probe 9 (L-waves).

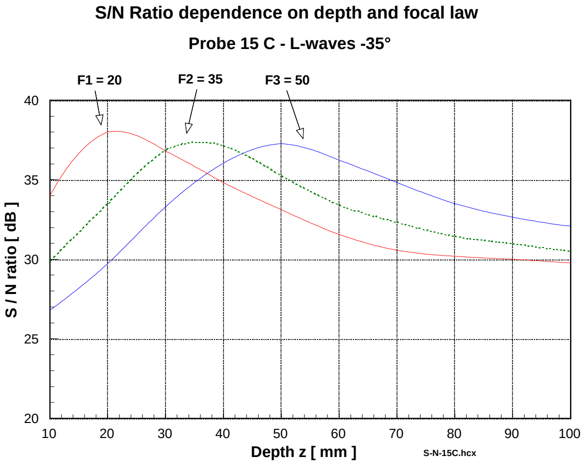


Figure 9: S/N ratio for probe 15C – L-waves at 15°.

Detection & sizing capabilities

Table 3 summarised the detection and sizing accuracy for in situ examination of turbine components of ABB low pressure turbine at Darlington NGS for field trial nr. 2 and nr. 3.

Date	ABB item	Detection [L x h] mm	Accuracy [±mm]			remarks
			Length	Height	Location	
May 1999	L-0 Blade	5 x 1 – P, H1	1.5	0.7	3.5	Min detection 5x0.5mm
	L-0 Steeple	9 x 0.5 – H1 9 x 1 – H2, H5	1.5	0.5	4	Min. detection: 9 x 0.15mm Special plotting for location
	L-1 Blade	3 x 1 – H1	1.2	0.7	2	Manual Phased array
April 2000	L-0 Blade	5 x 1 – P, H1	1.5	0.7	3.5	Min. detection: 5 x 0.15 mm
	L-0 Steeple	9 x 0.5 – H1 9 x 1 – H2, H5	1.5	0.5	4	Min detection: 9 x 0.15 mm Special plotting for location
	L-1 Blade	3 x 1 – H1	1.2	0.7	2	Scan 4-blades same time manual scans in parallel
	L-1 Steeple	4 x 1.5 – H1	1.8	0.8	3	Automated scan 4 items simultaneously

Probes in the field

All probes withstood the field conditions with reliable performances for manual and automated inspections. A full-length inspection campaign demonstrated the reliability and high-performance of these probes. Examples are illustrated in Figure 10 and 11.

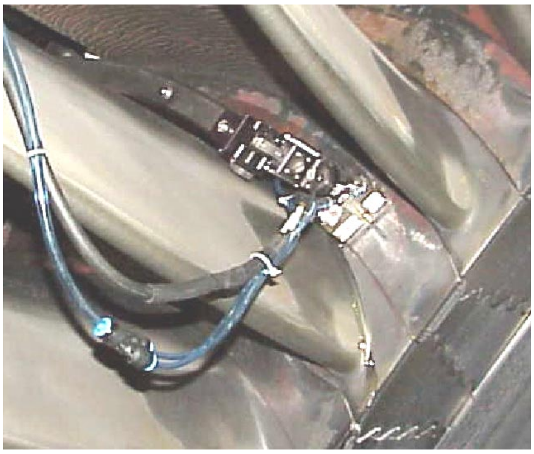


Fig. 10: L-0 steeple inspection with 3-heads probe

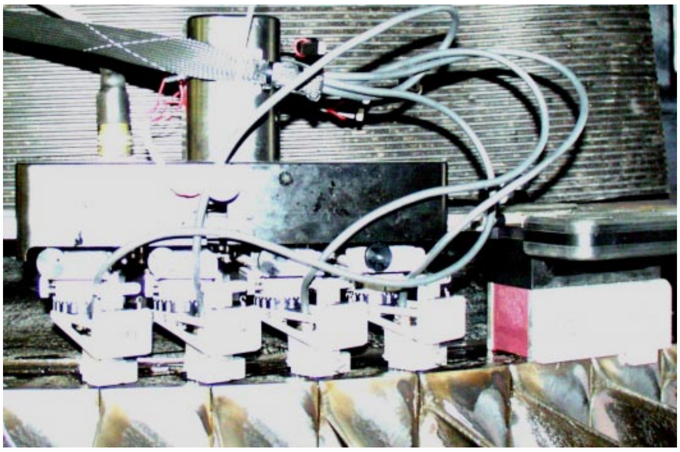


Figure 11: Inspection of L-1 blades with 4-head probe

Conclusions

Prototype probes passed the field test with reliable performances.
The design and manufacturing were satisfactory and an in-deep characterisation assured a high sensitivity in detection and accuracy in sizing
The improvements concerning design and manufacturing the probes for long-term inspection were implemented and contributed to a successful inspection campaign during 2001.

References

(1) P. Ciorau, OPGI, J.Poguet, IMASONIC "In-situ examination of turbine components (blade roots, rotor steeple grooves and disk-blades attachments) of low-pressure steam turbine, using phased array technology" – 3rd International conference on NDE in relation to Structural Integrity for Nuclear and pressurized components (Seville 2001)

(2) P.Ciorau, D.Macgillivray, T.Hazelton, L.Gilham, D.Craig, OPGI, J. Poguet, IMASONIC " In-situ examination of ABB L-0 / L-1 blade roots and rotor steeple of low-pressure steam turbine, using phased array technology". 15-th WCNDT (Rome 2000)

(3) G.Fleury, IMASONIC, C.Gondard, CEA CEREM "Improvements of Ultrasonic Inspections through the use of Piezo Composite Transducers" - 6th European Conference on non destructive testing (NICE 1994)