Integrated Mechanism based Multiplane/3D Ultrasonic Imaging Probes.

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ABSTRACT: Implementation of 3D capabilities on ultrasonic imaging systems tantalizingly proves the high interest for this diagnosing modality. However, to become a clinical tool, 3D ultrasound has to spend further technological efforts in acquisition performance and probe size to deliver on the fly, quality volumetric images as well as current functionalities.
Nowadays, numerous 3D designs have been reported such as: hand-moving imaging probes equipped with position sensors, rotating/sweeping probe including array transducer or more complex 2D array transducer. The first type of device reveals to be inaccurate in position, the second is often heavy and exhibits excessive volume while, although of compact size, the third type is unreliable and excessive in manufacturing cost that limits commercial widespread.
In this paper, the simultaneous use of slim-line high density phased array transducer and multilayer actuator based USM (Ultrasonic Motor) devices enables imaging probes to exhibit both Multiplane capability and high frame rate 3D rendering. The high level of integration allows the probe volume to be comparable to conventional 1D apparatus. Moreover, this concept when implemented in Transesophageal devices, further provides the probe with better acceleration rate, reduced backlash and transducer tip changeability. Probe internal structure is detailed and performances analysed.
Phased-array fabrication and interconnect problems have been addressed during this study as well as sub-system integration concerns.
***Key words*: Three-Dimensional, Multiplane, Ultrasound, USM devices, Optical encoder.**

INTRODUCTION

Moving the scanning plane with immobile probe is a must have characteristic for many ultrasound diagnostic imaging devices, particularly when applied to echocardiography and volumetric (3D) rendering of organs. Important diagnostic improvement may be expected from heart 3D ultrasound images, where the volume fraction of cavities is required. In parallel, Multiplane capabilities are mandatory in Transesophageal or catheter imaging probes which have got limited degrees of freedom.
Multiplane techniques can be exploited either for 3D rendering or for changing the scanning plane of organ. Two main methods are currently known as matrix (2D) array and mechanical moving phased-array. The first group of probes includes array transducers that exhibit elements aligned in the crossed directions of the emitting surface, elements are independently addressed to enable steering and focusing of the acoustic beam. However, with regard to this element density, the driving electronic is complex to design and the transducer fabrication is difficult and unreliable. In the second group, conventional phased-array is used to perform a 2D scanning and motorization means is additionally provided for moving this image (rotation or translation) so Multiplane or 3D acquisition functionalities are allowable. In spite of complicated additional moving mechanism, development of mechanically driving Multiplane and 3D probes remains sustained because their compatibility with existing systems, this feature enables user to access to these advanced modalities without important investment in equipment.
However, current moving phased-array probes that usually employ DC or steeper motors are too large, heavy and not compatible with required size and ergonomics for clinical use. Furthermore, electrical noise, generated by the motor brush-collectors dramatically impacts the image quality of systems.
Therefore, to overcome these limitations, the following design is proposed wherein ultra-compact transducer is moved by miniaturized piezoelectric motor and controlled by customized position encoder. Conventional probe volume is preserved, electrical noise is reduced and more integration of components is enabled.

DESIGN CONSIDERATIONS

Unlike other 3D products (i.e. continuous rotation via slip-ring device, motorized anti-torsion shaft or add-on motor probe), the present work involves alternate rotating imaging probes wherein the transducer is alternately rotated clockwise and counter clockwise to gather the volume image. The absolute amplitude of rotation may be hereby as much as several turns and the transducer is designed with optimized interconnect means to support severe rolling condition. Two designs of rotating probes were developed respectively for Transthoracic and

Transesophageal application, however, many characteristics remain common for the two.
Since the moving contact between transducer and patient is undesired, the transducer is rotated in sealing cavity, under an acoustically transparent shell. The sealed volume corresponding to the transducer surface and the shell is filled by a coupling fluid to allow acoustic energy transmission.
Internally, probe structure is shared in wet and dry chambers. Preferably, wet chamber which comprises the transducer front-face, is designed as small as possible to limit liquid thermal expansion effect. The dry chamber lodges all other components of probe and is inherently much larger. The essential condition of reliability in rotating probes is the “sealing line” separating wet and dry volumes so this region is subject to particular attention. Different sealing configurations have been evaluated . Shrinking contact seals such as O-ring seals are obviously straightforward but the lip-stick effect, often reported makes their use unsuitable with rapid alternated rotating mechanism. With regard to bushing lip seals such as those supplied by Bal Seal®, their low friction coefficient allows high acceleration rate and speed.
<u>*Transthoracic design*</u>: the complete probe include a cardiac phased-array transducer with a circular foot print. Internal structure carries all mechanical parts including reference guide for probe housing assembly. This structure comprises a front cavity where are mounted an ultrasonic phased-array transducer and its front shell, the transducer is provided with a metal case equipped with central shaft which passes through the structure and coupled to this one via a bushing seal and ball bearing set. This shaft passes through an optical encoder and is interfaced with the motor output. Electrical interconnect of the transducer and encoder are performed by flex circuits. All flexes are in turn connected to a coaxial bundle finally plugged in the system. <u>*Transesophageal design*</u>: Efforts are here focused on the transducer tip design that is part of the endoscope probe and is located beyond the flexible coupler. Improvements and new functionalities issued from the integration study has enabled motor and encoder to be mounted into the tip. Assembly to endoscope instrument is greatly simplified. With regard to the required dimension of the transducer tip, internal components had to be redesigned. Manufacturing cost and assembly process objectives have been considered by designers during the project. Finally, an integrated assembly concept has been set up in which the main structure simultaneously acts as transducer case, motor housing and encoder assembly platform. This concept allows high component integration and efficient manufacturing cycle.

PHASED-ARRAY TRANSDUCERS

Transthoracic and transesophageal scanning are the two most common practices in cardiac application so dedicated phased-array designs have been considered and developed. Both designs exhibit circular foot print to reduce fluid resistance during operation. The transducers operate at 3.25 and 5MHz frequencies according to current specifications, however, higher frequency transducer can be set up for paediatric application for example. Because of the limitation in probe volume, sustained miniaturization efforts have been spent on mechanical and acoustic design of transducer. Particularly, development of new backing compound having sound attenuation ranged within 10-15dB/mm/MHz, has enabled the achievement of slim-line transducer which does not exceed 3mm thick for transesophageal and 5mm for transthoracic use. Design optimization of transducers has been performed based on in-house KLM model software that takes into account piezoelectric lateral behavior to provide realistic transducer responses. On the examination of modeling results, a new 1-3 structure PZT-Polymer composite is required to fit the desired transducer performance. Transducer surface is hard-focused in elevation plane to allow adjunction of a flat silicon lens, this method reveals to be beneficial for reducing the liquid volume between shell and transducer surfaces. The main characteristics of the transducers are summarized in the table below:

	TE	TT
Frequency	5.00MHz	3.25MHz
Diameter	9.3mm	16.0mm
Thickness	1.8mm	5.0mm
Nb of Elts	64	64
Pitch	145µ	220µ
Prim. Interconnect	Flex	Flex
Max. Ang. Ampl.	720deg	720deg
Piezoelectric	customized 1-3 composite	customized 1-3 composite

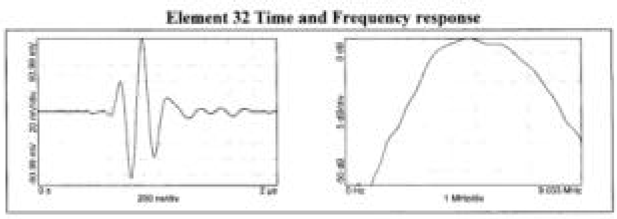

Figure 1: Transesophageal phased-array responses.

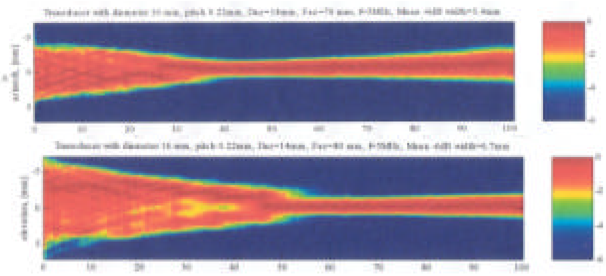

Figure 2: Schlieren beam-profile plot of 64-element azimuth and elevation focused aperture at 3MHz.

The electrical interconnect of transducer elements is performed via flex circuits that are specially designed having high density trace pattern. Traces are afterward gold plated to improve conductivity of contacts. However, prototypes equipped with coaxial bundle are also attempted, and improvement on signal quality is reported as well as inherent higher manufacturing cost.

UPD MOTOR

The UPD (Ultrasonic Piezoelectric Drive) is a globally circular metallic shell based stator. It is actuated by one internal axis comprising two opposite piezoelectric elements and a central counter mass. Under excitation of the flexure and translation modes, each contact surface located on the UPD shell tips performs an elliptical vibration that can induce the relative motion of a driven part using a stick-slip phenomenon. This UPD uses multilayer-piezo ceramics at resonance mode for producing a 5µm elliptical vibration at only 10Volts. UPD motor is a patented technology from Cedrat Technologies (France).
Rotating piezo-motors (RPM) based on roller UPD driving technique have been built. To achieve desired specifications on speed and torque, only rotor diameter and UPD dimension are to be considered so that leads to a low cost approach for providing customised precision motors. At the beginning, a UPD20 based motor along with a 23mm roller has been built for simulation assessment needs.
A first usable UPD based motor has been developed for transthoracic probe that withstands speed and torque requirements of the project. Coupled with optimized gearbox, the related motor has 20mm of diameter and 11mm thickness and exhibits a speed of 600 rpm and a blocked torque of 8mN.m at the resonance frequency of 60kHz. On completion of the transthoracic motor design, another UPD device (8x17x3 mm) operating at 100kHz is being developed for transesophageal use. The most advanced feature of this motor is its direct integration in the transducer tip.
The choice of UPD motors for moving the transducer is essentially motivated by the lower driving voltage provided by this type of device that has been achieved with multilayer piezoelectric actuators. The Figure 3 shows the flexural modes being exploited in the motor principle and the 3D view of the complete gearbox motor build.

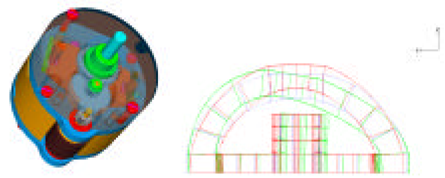

Figure 3: Translation and flexure modes in the UPD (right), and gearbox motor (left).

OPTICAL ENCODER

Optical encoding technique has been chosen for monitoring the rotation of transducer. In order to allow the integration of the encoder within current probe volume, miniaturized encoder design is required that can not be found in commercial product list. A specific encoding device has then been developed, which comprises a micro incremental disk provided with increments corresponding to the specifications of final product and a detection module that carries optical detectors as well as associated electronic circuits. Overall specifications for Transthoracic and Transesophageal encoders are depicted as follows:

	TT	TE
Counts/turn	1440	720
Max. Rot. Speed	600rpm	800rpm
Nominal voltage	5Vrms	5Vrms
Maxi. Diameter	19mm	6.5mm
Disc Material	glass	glass

Prototypes of encoder for Transthoracic probes have been carried out for performance assessment and first results show encouraging characteristics that let expect good detection performance. The whole thickness of encoding device (< 3mm) will not critically impact the probe volume.
The signal processing circuit for optical detection system is located away from the encoder in order to improve reliability and to lower the manufacturing cost. This electronic circuit includes different functionalities such as filtering, trigger and amplification, necessary for signal processing operation. The Figure 4 shows expanded views of incremented disk and the detection module circuit.

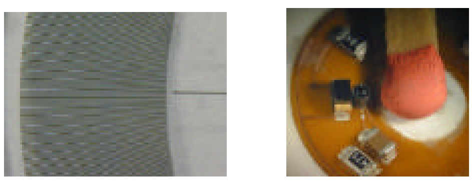

Figure 4: Optical disk and detector circuit.

MTE, Austrian SME specialised in optical instrument is in charge of the development of the encoding devices based on specifications from Vermon and GE Vingmed.

PROBE INTEGRATION ASPECT

Integration of components in preserving external volume is one of the best challenges of the present work. Unlike conventional rotating probes which are built by adding motorization means on an existing product, this work focuses on the simultaneous integration of all the components for the purpose of optimization of available space. Inter-linking design of components belonging to a same probe has permitted a gain of around 30% in volume which benefits to probe dimension or integration density. The imaging transducer is directly mounted into the moving shaft which in turn carries the position encoder prior to coupling to a gearbox motor. Dynamic aspect of the probe has been one of the strongest difficulty to be solved, in spite of use of bushing seal, tolerances of shaft should be tight enough to ensure adequate reliability. Moreover, mounting of precision ball bearing to perfectly control the rotation of shaft is mandatory. As the rotating shaft is located at the centre of the structure, interconnect means for transducer is placed at the vicinity of the shaft and around Encoding optical disk is designed based on the shaft diameter and the structure body, this is carried by a plastic receptacle. For detecting the disk increments, detection electronic circuit is mounted in front of the disk. Once the encoding system is mounted, the pre-assembled UPD motor is then coupled to the rotating shaft through a Holdam coupler to avoid misalignment problem. Behind the motor are jumbled interconnection means between coaxial bundle and flex, encoder signal processing electronic and optionally thermal probe for internal temperature monitoring. The list below summarizes composition materials of the Transthoracic probe:

?? Shell material: TPX® (Mitsui)
?? Coupling fluid: Silicon grease
?? Probe structure: Titanium Alloy
?? Probe housing: Noryl®

At current stage, Transesophageal general design is being studied mechanically and definition of dedicated UPD motor and encoder prototypes has been completed. Laboratory prototype of Transesophageal motorized ultrasonic head will be started within the next three months period at the completion of technical validation on motor and encoder breadboards.

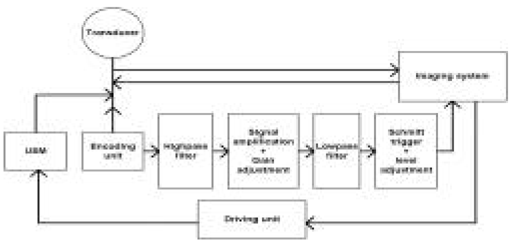

Figure 5: Probe functional synoptique.

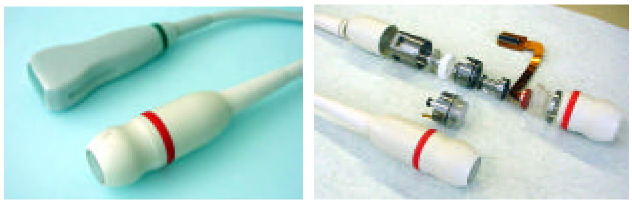

Figure 6: Comparison with standard phased-array.

CONCLUSION AND ACKNOWLEDGEMENTS

This work, EUREKA* labelled and supported by European grants, is currently at its middle term and aims at achieving technical breakthrough in integration and miniaturization of diagnosing instrument and particularly ultrasonic imaging probes. The project has involved three parallel developments including several technical domains as different as: ultrasonic transducers and probes, piezoelectric motors and customized miniature optical encoder. The synergy of these actions will with no doubt contribute to the development of advanced diagnostic tools where 3D capability and moving scan are omnipresent and will make ultrasound multiplane scanning a widespread technique .

At the final stage of the project, integration and reliability tests of complete probe are planned, so functional prototypes are expected for the next period and probes will be supplied to GE Vingmed for acoustic and clinical tests.

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