Design Of An Airborne Ultrasonic System For High SPL, Large Focusing Range Applications

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Introduction

This work reports the FEM design of a high-power ultrasound system, capable of emitting acoustic radiation at 20kHz with SPL (Sound Pressure Level) peaks up to 160dB at a distance of 1m.
Such pressure level can be found as a requirement for the system in some works and industrial applications ([1],[3]), like foam reduction or gas special processing and particle agglomeration.
An important design issue for high power airborne ultrasonic systems lies in the air low acoustic impedance, resulting in poor power transfer.
Generally there are some ways to overcome the problem , such as :

- increase the electrical generator power
- exploit an acoustic impedance matching horn (as it is done in audio systems)
- enlarge the radiator surface area as much as possible
- design an array of radiators

It will be discussed that the first and second solution listed above are not viable for high power ultrasound systems operating in the kHz range, while the third and fourth are both effective. Furthermore, the solution based on an array of radiators is the only way to achieve a large focal distance for the ultrasonic airborne system.
The complete design of the ultrasonic system was developed with COMSOL FEM modules, namely: Multiphysics, Structural and Acoustics, with active link to SolidWorks CAD.

High power ultrasonic airborne systems and specific impedance mismatch

Generally, high power ultrasonic systems (from 1 to 4kW and more) are used for processing of fluid products, exploiting the phenomenon of cavitation. Coupling to fluid can be quite efficient, thanks to good acoustic impedance matching, so very high-power transfer efficiency is possible.
As regard an ultrasonic airborne system, operating in air, the radiating sonotrode is made of metal (generally titanium alloy) that has a very high specific acoustic impedance (28 Mrayls) while air specific impedance is very low (400 Rayls), resulting in generally poor power transfer.
As anticipated, such issue can be generally addressed following the next possible ways:

- increase the generator power
- exploit an acoustic impedance matching horn
- enlarge the radiator surface area as much as possible
- design an array of radiators

All these possible solutions will be analyzed in the following paragraphs.
A few studies are present in current literature ([1],[2]), reporting airborne ultrasonic systems capable of high pressure in air, mainly aimed at 'foam reduction' or gas processing applications ([1], [3]). Above all solutions, the one of the 'stepped radiating disk' is very interesting ([1], fig.1), as well as functional, as will be seen from simulation results.

Figure 1: stepped disc radiator [1]

Generator power

Similarly to audio speaker technology, one way to overcome the low power transfer efficiency is simply to increase the electrical generator power that drives the ultrasound transducer, but that have many drawbacks.
Above all, even if the ultrasonic transducer is designed and manufactured to operate with very high electro-mechanical efficiency, a minimum (2-5%) of the electrical power will dissipate in thermal energy, that is generally not easy to draw for such devices. Indeed, the cooling system will eventually set the limit to the maximum operating power. High power ultrasonic transducers (or so called 'converters') are special devices where not all types of cooling are applicable directly on the active part; generally only air cooling is easy to implement.
In short, it is not realistic to build a single ultrasonic airborne system with power ranging in tens of kW unless special, cumbersome and expensive cooling techniques are used.

Horn

Even if a horn (fig.2) is the best impedance adapter for mid/high audio frequency devices (tweeter), it's not viable for high power ultrasound systems operating in the kHz range.

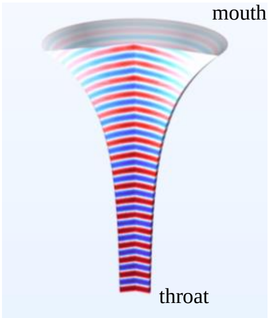


Figure 2: Horn

Indeed, horns have specific dimensional requirements for best operation, that cannot always be met in practice. The horn 'throat' and 'mouth' are related to the maximum and minimum wavelenght of the signal, thus it's not always possible to design a realistic horn for certain frequency range (for example, low audio frequency).
Some horn design basic rules are listed, as follow:
- throat dimensions: the shortest wavelength reproduced (in air) is twice the diameter of the throat. So, for high frequency response, the throat needs to be as small as possible.
- mouth dimensions: the mouth needs to be half the size of the wavelength of the lowest frequency to reproduce. So, for good bass response the mouth needs to be as big as possible.
- lenght of the horn: It depends on mouth and throat areas of the horn, many equations are available.

For the present ultrasonic system the first rule for the throat is quite limiting: in fact the throat needs to have a diameter of only 9mm (at 20kHz). Such value would lead to a very small sonotrode, resulting in a system with a low SPL and low focusing.
Moreover, from calculation using equations for the third rule, it's possible to see that, for the specific system, a very long horn would be needed too.
In general, focus range cannot be easily controlled and maximum sound pressure level (SPL) is however limited, as confirmed by FEM simulation results, not reported here for brevity’s sake.

Radiating surface area and arrays

Getting to the third and fourth solutions, enlarging radiating area and making use of arrays are both effective for increasing the efficiency and focusing performances of the radiating system (similarly to antennas).
Enlarging the radiating surface leads to a better loading of the sonotrode (even if it doesn’t solve the specific impedance mismatch) and allow to get a better focusing of radiation on the system axis, thus resulting in higher SPL.
As regard arrays, arranging more than one ultrasonic radiator it’s possible to control the resulting radiation beam shape and focusing, increasing all performances.
Implementation of these two solutions will be reported in next paragraphs, describing the ultrasonic system design and FEM simulation results.

Ultrasonic system description

The 3D rendering of the ultrasonic system is reported in figure 3.

Figure 3: Ultrasonic Airborne System

The system consists of three parts:
- Transducer or ‘Converter’
- ‘Booster’
- Disc sonotrode

The ultrasonic Converter is a special device designed to operate with very sharp resonance and high power in the low ultrasound range (20kHz). A deep *know-how* on high power ultrasound is essential to develop such device, as maximum efficiency is crucial for both performances and reliability.

The core of the transducer is a stack of piezoelectric rings, made of PZT hard ceramic material, arranged in a *Langevin* structure, preloaded by tuned acoustic metal parts, which complete the assembly.
A simple sketch follows :

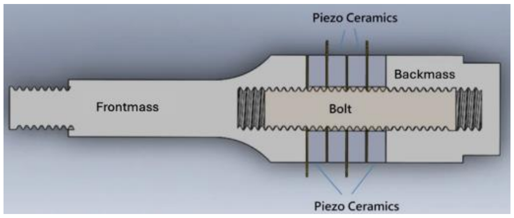


Figure 4: Converter structure

The system developed for the present work exploits special radial vibration decoupling features, that are not reported here as they're classified.
Of course FEM is the best tool to build such structure, performing an optimization process to get perfect tuning to the desired resonance frequency, maximum efficieny and maximum vibration amplitude of the front mass, that is transfered to the sonotrode.
The booster (see fig.3) is a device that ‘boosts’ the amplitude of vibration on the thinner side with respect to the thicker one (with nodal region in the middle). Such device is important to limit the required electrical current to drive the sonotrode vibration and reduce the piezo-rings fatigue, thus resulting in the higher possible operating power.
As regard the special sonotrode, it is a radiating disk made of Ti-6Al-4V titanium alloy, with special stepped ring shape that will be described in the following.
Such sonotrode is a very complicated part to design because its geometry must be studied carefully to guarantee the best acoustic beam focusing and vibration shape, limiting spurious undesired resonances.
The electro-mechanical system is thus critical to design and optimize, to yield very high acoustic pressure levels, as required for the industrial applications. If a deep modeling and optimization procedure is performed, the final result is a very efficient system that dissipates the minimum amount of energy.

Comsol Model description

A detailed FEM for the ultrasonic system was built using COMSOL Multiphysics® 6.1, making use of Solid Mechanics, Piezoelectric, Acoustics and Solidworks link modules.
The design of ultrasonic system and surrounding acoustic domain are developed in the frequency domain, in 2D and 3D space, making use of symmetries and approximations, when possible, in order to keep the required CPU load and required memory to acceptable levels. Indeed, such acoustic FEM can be quite heavy in term of computation load and time, as large acoustic domain and minimum mesh size can lead to models that may be almost impossible to solve. To overcome such issue, the acoustic domain is always limited and calculation of the pressure in the surroundings of source boundaries is performed with the Helmholtz-Kirchhoff integral [5]. Such tool allows to get an exact solution for the pressure generated in the domain where the ultrasonic airborne system is destined to operate, without a complete FEM for it.
PML (Perfectly Mtched Layers) are used on boundaries, to avoid reflection of outgoing pressure waves. Finally, a ‘step approach’ was followed : first the piezo-mechanics model was developed and optimized to design the ultrasonic device, then the disc sonotrode only was considered for the Structural-Acoustic model, with proper boundary load to make it vibrates at resonance.
Next a description of the Structural and Acoustic models is reported.

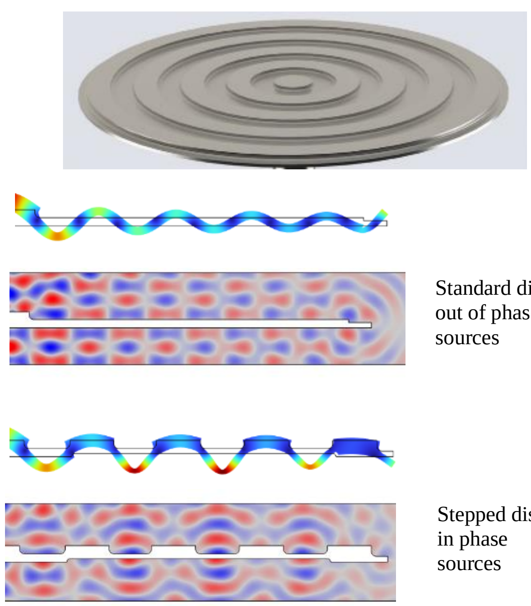
Structural Mechanics

As already mentioned, the electro-mechanical converter is based on a prestressed stack of four hard-PZT-8 piezoelectric rings, that work electrically parallel and mechanically series. As regard the piezo material, hard PZT-8 type ceramic is chosen as active medium, due to its exceptionally high efficiency and *Q* factor. In the Structural Mechanics module, a piezoelectric material special domain is available, that takes into account the anisotropy, piezoelctricity and electro-mechanical connections of the PZT materials, to solve the constiutive equations that rule them [4], in *stress-charge* form:

$$\begin{cases} \mathbf{T} = \left[\mathbf{c}^{\mathbf{E}}\right] \mathbf{S} - \left[\mathbf{e}^{t}\right] \mathbf{E} \\ \mathbf{D} = \left[\mathbf{e}\right] \mathbf{S} + \left[\boldsymbol{\varepsilon}^{\mathbf{S}}\right] \mathbf{E} \end{cases} \qquad \text{Eq.1}$$

where **T** is the stress vector, **c** is the elasticity matrix, **S** is the strain vector, **e** is the piezoelectric matrix, **E** is the electric field vector, **D** is the electric displacement vector, **ε** is the dielectric permittivity matrix.
Piezoelectric and Electrostatics domain were selected for the four piezoceramic rings inside the transducer and ground and electric potential were set alternately on the ring faces to get electrical parallel connection.
As regard the two metal parts that enclose the piezo-stack in the converter, it’s to be noted that their design is critical, since they are responsible for: tuning, efficiency and vibration amplitude of operation.
In the standard Langevin structure they are generally called ‘backmass’ and ‘frontmass’ (see fig.4).

The backmass is generally made of steel and the frontmass is made of Aluminum or Titanium alloy.
In the present work, the converter was designed to operate with a resonance frequency of 20kHz with operating power up to 2kW.
Next, the Booster and special sonotrode were designed and optimized.
The Booster must be designed to match the operating resonance frequency (its lenght must be approximately half wavelenght) and amplify vibration amplitude on its thinner side. It must also include a mechanical suspension system, in order to decouple radial undesired vibration modes from the system mounting flange.
As regard the disc sonotrode, it was mentioned that one way to overcome the problem of acoustic impedance mismatch between radiator and air is to increase the radiating surface. That is only possible to some extent, as spurious vibrations increase in number and intensity as the radiator dimensions increase. In the present work a 500mm diameter disc was designed. Very fine tuning of the FEM allows to get a 'good' resonance at 20kHz, but a 'wave-like' deformation of the disk is unavoidable (same circular wave shape as the one generated by a stone falling in water). Such wave shape leads to different phase of the acoustic wave departing from the disc from different radial position (see fig.5 below). Through simulation it can be seen that the resulting radiation from a simple flat disk is a non-constructive interference pattern, that is of course undesirable. A way to correct that is a 'stepped' shape for the disk surface [1], as follows :



Standard disc : out of phase sources

Stepped disc : in phase sources

Figure 5: stepped disc concept

Acoustics

The acoustic domain surrounds the ultrasonic disc radiator and the acoustic-structure interaction is automatically set on the boundaries.
Comsol solves the wave equation (see eq.2) for in the acoustic domain, to give final results for the pressure:

$$\nabla^2 p - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = 0, \qquad \text{Eq.2}$$

As anticipated, the system was analyzed in the frequency domain, making use of both 2D-axialsymmetric and 3D geometries, along with special features such as PMB (Perfectly Matched Boundaries) and external pressure calculation based and Helmholtz-Kirchhoff integral [5], in order to limit the acoustic domain dimensions and computational load.
In the Acoustic module postprocessing section it is possible to study the pressure field generated by the disc, with special interest in 2D SPL map, pressure plot along the system axis and polar radiation directivity plot.

Simulation Results

The most important results of simulations are reported in the following. Such data are the result of the complete design and optimization process, which is not entirely described for the sake of briefness.

Structural Mechanics

As a first step of the ultrasonic system design, the main results from the electro-mechanical study and optimization will be reported for the Converter-Booster-Stepped Disc (500mm diameter) assembly.
Let it be clear that the electro-mechanical optimization of a high-power ultrasound device is essential, as it will be driven with very high electrical power that needs to be converted to mechanical one with maximum possible efficiency in order to keep dissipation and heating as low as possible. Indeed, as in many other high power electrical device, overheating is often the limiting factor for possible maximum power , not the generator's capabilities.
For the mechanical optimization it is possible to use a 2D-axialsymmetric or 3D model ‘slice’ of the system, exploiting symmetries. A mesh of the 3D model follows (fig.6).
The following results shows that the optimization procedure has led to a clean , strong resonance without unwanted spurious vibrations that would cause overheating (fig.7).

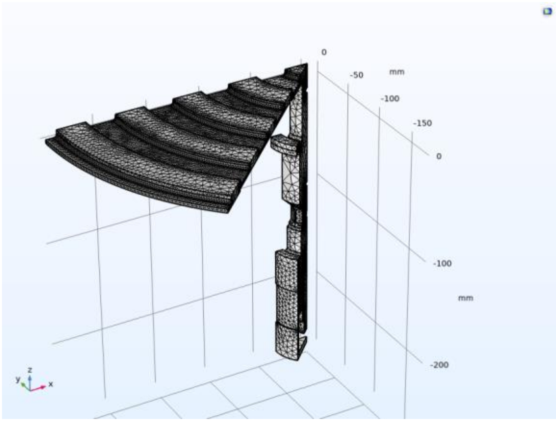


Figure 6: mesh of the mechanical model (slice)

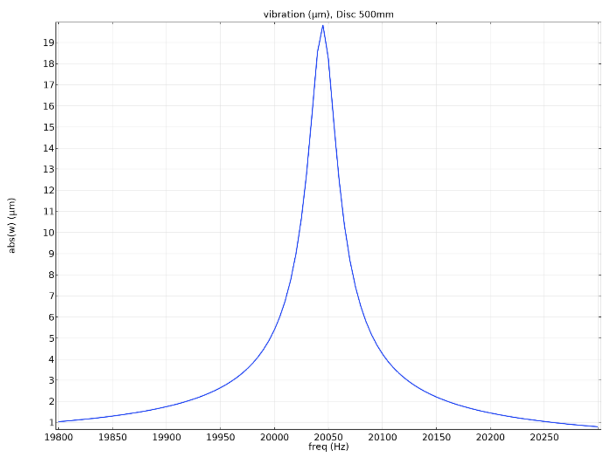


Figure 7: vibration vs.frequency (center of disc)

Next , the 3D vibration amplitude and deformed shape, along with the mechanical stress map :

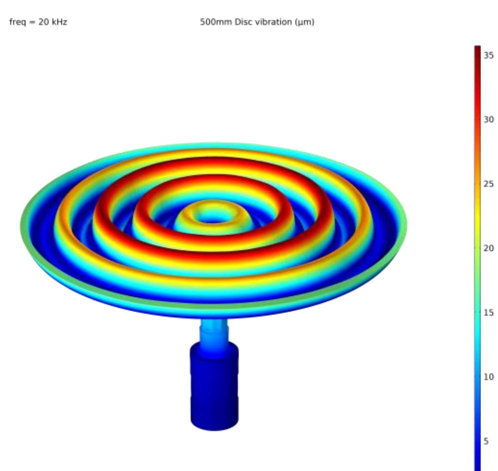


Figure 8: 3D amplitude of vibration

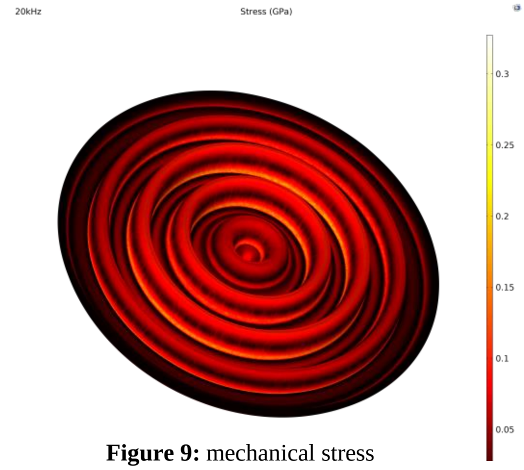


Figure 9: mechanical stress

From the figures reported above, it's clear that :
- deformation at resonance is high (up to 35 microns) and 'well-shaped' across the disk while being low on the converter (as desired)
- stress on the titanium alloy disk (Ti-6Al-4V) is 0.3 GPa max., so safely lower than the material tensile strenght, equivalent to approx. 1GPa, so there shouldn't be any disc breaking during operation

Acoustics – single disc

As the electromechanical efficiency is optimized, it is possible to analyze the acoustic performances of the large disk system, to check if it fulfils the requirement of SPL = 160dB.
A 3D FEM model is used, making use of symmetries, with mesh as flollow.

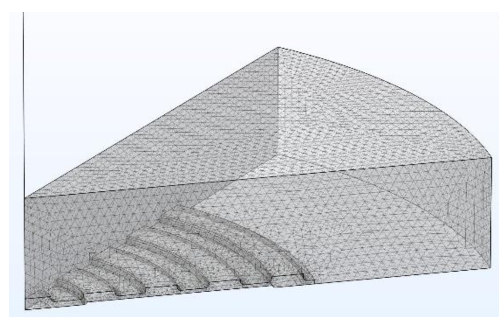


Figure 10: 3D model and mesh, single disc

Pressure was calculated outside the acoustic domain with ‘exterior field calculation’ feature (Helmholtz-Kirchhoff integral). Moreover, to cut calculation time further, only the disc sonotrode is modeled as structural mechanics part and it’s excited at the resonant frequency found in previous step to replicate the same vibration, thus generating the corresponding acoustic field.

Starting with a single ultrasonic disc system, some results follow, namely the SPL (dB) map on a section plane, the pressure level vs. depth on axis and finally a polar directivity plot.

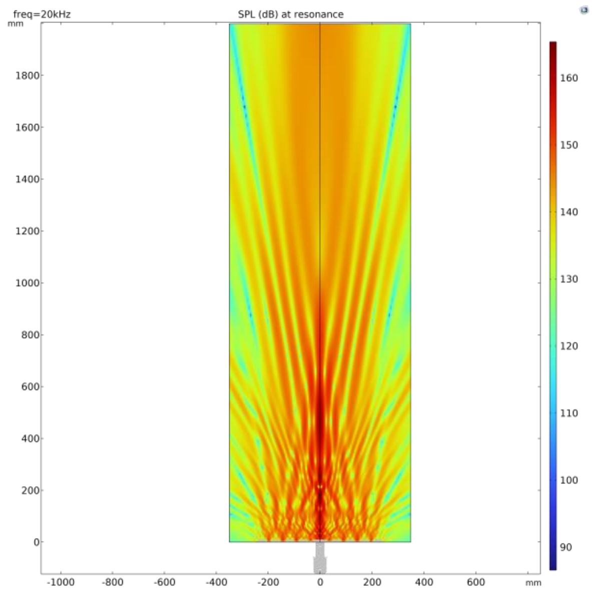


Figure 11: section plane SPL map, at 20kHz

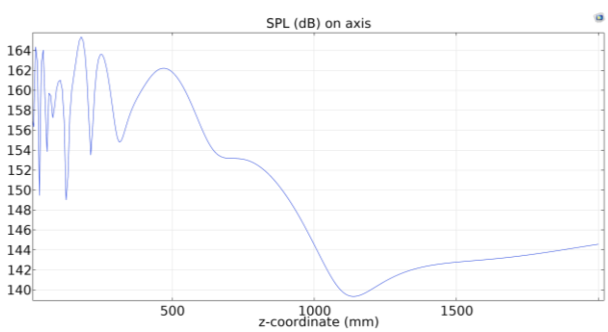


Figure 12: SPL on axis, at 20khz

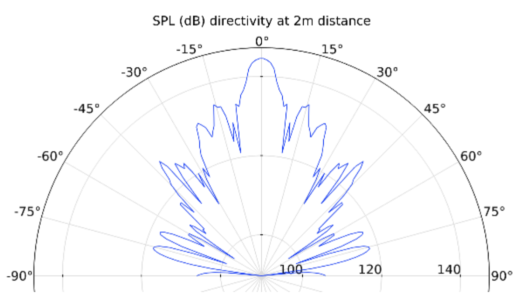


Figure 13: directivity plot, at 20khz

Conclusions on the single ultrasonic system (500mm diameter disc sonotrode) are the following:

- SPL on axis is 162dB at focus distance: enough for the system requirements (fig.12)
- The focus distance of the system is short, at approx. 0.5m (fig.12), while required value is 1m
- Beamwidth at -6dB from max. is approx. 20° aperture (fig.13)

Next an array of 5 units will be studied, mainly to increase the focus distance.

Acoustics - array of discs

Finally, the best solution is conceived: a circular array of 5 stepped disks (500mm diameter each). The main purpose of the array is to achieve a larger focus distance with respect to the single disk alone, as it will be shown in the following.

Basically, the idea is simple (see below): many radiating units lie on a spherical surface whose center is the focus of the system (in the shape of a surgical lamp), so that the focus of the system can be significantly increased compared to that of the single unit.

Figure 14: section plane SPL map, at 20kHz

The array arrangement (disc tilt and distances) was deveolped with a 3D Multiphysics FEM, to optimize the acoustic performances.

Many FEM features are employed to cut calculation load to an acceptable level, since the device is clearly quite complicated to model and simulate. First of all , a ‘slice’ of the system is modeled (as it was made in the structural model) and symmetries are set on boundaries. Then, Acoustic domain is limited to the surrounding of the discs, PMB (Perfectly Matched Boundaies) are set on borders and external pressure calculation is performed through external field calculation feature. Finally, as it was made for the single disc system, only the discs are modeled as structural mechanics parts and are excited at the resonant frequency found in previous step to replicate the same vibration, thus generating the corresponding acoustic field. The model and mesh follow.

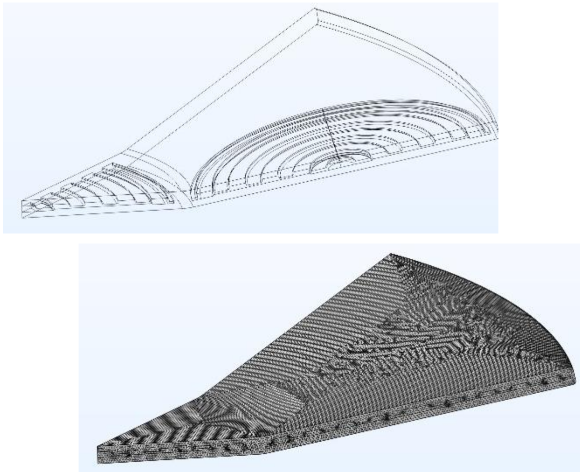


Figure 15: 3D model and mesh, array

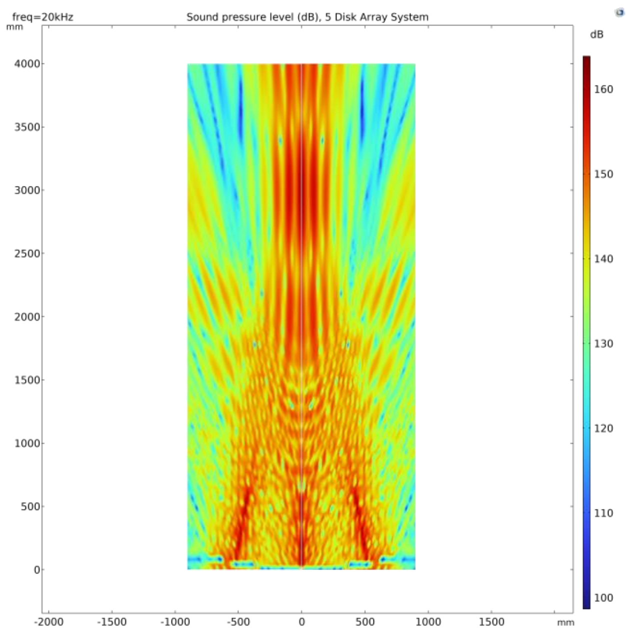


Figure 16: section plane SPL map, at 20kHz

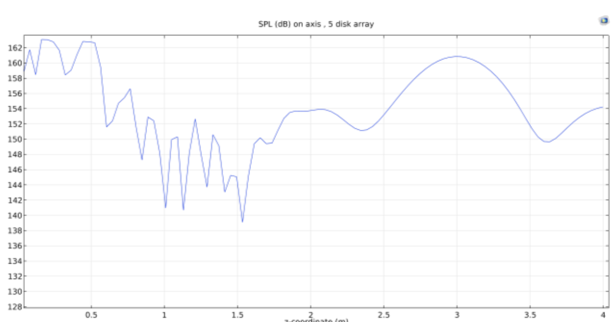


Figure 17: SPL on axis, at 20khz

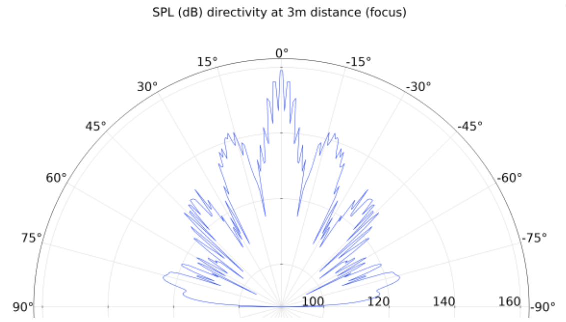


Figure 18: directivity plot, at 20khz

Concusions on the array system (5 disc, 500mm diameter each) are the following:
- SPL on axis is more than 160 dB at focus (fig.17)
- focus distance value is 3 meters (fig.17)
- Beam directivity is good, with a strong and narrow center lobe of radiation (Beamwidth at -6dB from max. is approx. 10° aperture, fig.18)

It must be noted that the focus distance can be easily modified simply adjusting the array configuration with a different spherical radius, so that all ranges from 1 to 3 meters may be accessible.

Conclusions

A high-power 'airborne' ultrasonic system was designed, to fulfil the requirement of high sound pressures levels (160dB) and large focus distances (1m). The design and optimization of the system was performed through multiphysics (Acoustical-Structural) FEM simulations and deep *know-how* on high power ultrasonic systems.

In the end, the best solution was found to be an array of special shape radiating units that lie on a spherical surface whose center is the required focus of the system. Such system is capable of:
- SPL of more than 160 dB on axis
- focus distance as high as 3 meters from the system
- good directivity with a strong and narrow center lobe of radiation

Finally, it must be noted that all performances reported here are achievable with acceptable electrical powers, that never exceeded 1kW for each ultrasonic unit in the set of FEM simulations.

References

1. Power ultrasonic transducers with vibrating plate radiators, *J.A Gallego-Juarez et al.*
2. Recent developments in vibrating-plate macrosonic transducers, *J.A Gallego-Juarez et al.*
3. Advanced technique to reduce emissions of fine particulate matter using ultrasounds, *B. Bergmans et al.*
4. COMSOL Multiphysics Module User Guide
5. COMSOL Acoustics Module User Guide