REFLECTORS FOR THERAPEUTIC VORTEX BEAM GENERATION

Noé Jiménez, Enrique González-Mateo, José M. Benlloch, Francisco Camarena

Instituto de Instrumentación para Imagen Molecular, CSIC- Universitat Politècnica de València, 46022 València, Spain

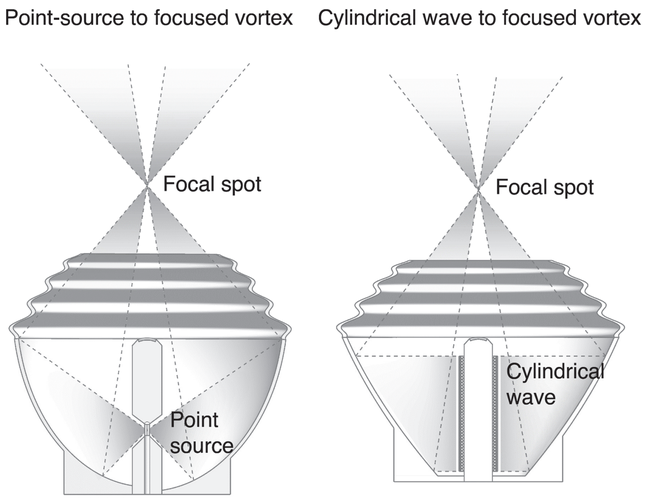
INTRODUCTION

Background

Vortex beams are currently used in many emerging imaging and therapeutical ultrasound applications. These include particle trapping, elastography imaging, bubble manipulation and payload release.

Our proposal

In this work, we present several reflectors to synthesize focused vortex beams for therapeutical ultrasound. We present the design equations of several topologies of reflectors to generate focused vortex beams. By using geometrical methods, we derived the parametric surfaces for helicoidal ellipsoid vortex reflectors using electrohydraulic sources, and helicoidal parabolic vortex reflectors using electromagnetic sources.



Helicoidal ellipsoidal vortex reflectors transform a point source into a focused vortex, while the helicoidal paraboloid transform a cylindrical wavefront into a focused vortex.

METHODS

Vortex generation by reflectors

Reflectors should introduce phase dislocation at the focal spot. This can be done introducing a temporal delay

$$\Delta t(\theta) = \frac{M\theta}{\omega_0},$$

where ω_0 is the frequency, M is the topological charge and θ is the polar angle.

Such delays are generated when the difference of acoustic paths is equal to

$$\Delta L(\theta) = \frac{M\lambda_0\theta}{2\pi},$$

where $\lambda_0 = 2\pi c_0/\omega_0$ is the wavelength at the design frequency and c_0 is the sound speed.

Theory

To describe acoustic propagation in water we make use of the Rayleigh-Sommerfeld integral:

$$p(\mathbf{r},\omega) = \frac{i\omega\rho_0}{2\pi}\int_S \frac{v_0(\mathbf{r}_0)\exp\left(-ik_0\left|\mathbf{r}-\mathbf{r}_0\right|\right)}{\left|\mathbf{r}-\mathbf{r}_0\right|}dS,$$

This expression is used to project reflected fields on the target space.

HELICOIDAL ELLIPSOID

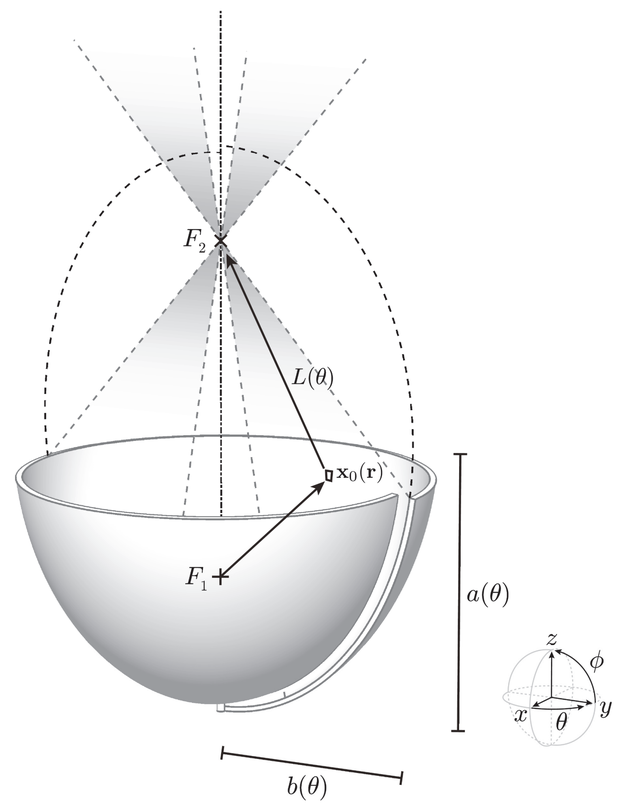
Surface design

Defining an elliptic curve with foci F_1 and F_2 , and defining the constant of the ellipse as

$$a_p(\theta) = \frac{2a - \Delta L(\theta)}{2},$$

where a is the largest of the minor axis of the helicoidal ellipsoidal reflector. The semiaxis of the reflector surface as a function of the azimuthal coordinate is

$$b_x(\theta) = \sqrt{a_p(\theta)^2 - F_2^2}.$$



HELICO-PARABOLOID

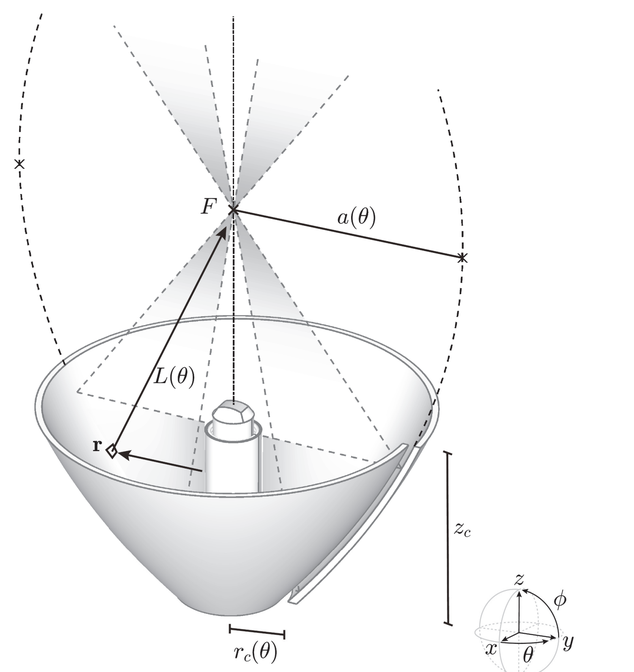
Surface design

reflector is defined by a helicoidal parabolic surface, consisting of a parabolic profile whose focus is fixed. In cylindrical coordinates, this surface is defined as

$$r_c(\theta) = R_m - m'\frac{M\lambda_0\theta}{2\pi},$$

where m' is a constant. The surface has its vertex at the point $\mathbf{r}(\theta, r, z) = (0, -1/4a(\theta), F)$, where the geometrical parameter a is given by

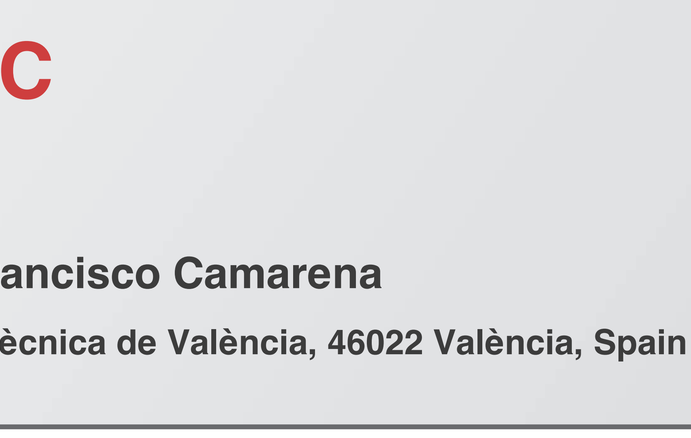
$$a(\theta) = \frac{r_c(\theta) - \sqrt{F^2 - 2Fz_c + r_c(\theta)^2 + z_c^2}}{2\left(F^2 - 2Fz_c + z_c^2\right)}.$$



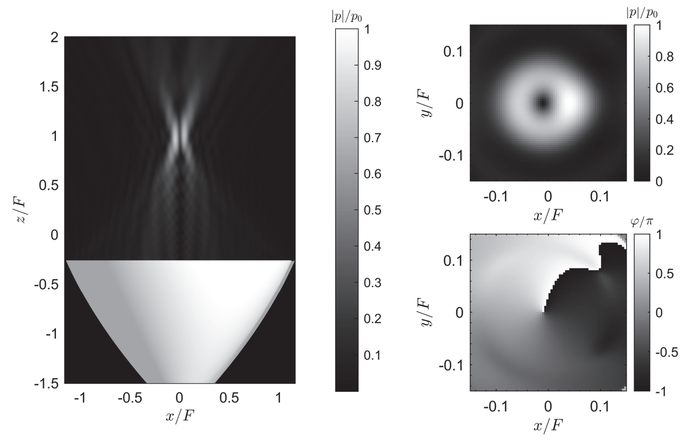
FOCUSING VORTICES

Vortex generation

Acoustic vortices are generated by the reflected field of a point source on the helicoidal ellipsoidal surface. A surface waves designed for a single topological charge, and a field containing a phased dislocation is observed at the geometrical focus of the reflector.



When a cylindrical wavefront is reflected by the helico-parabolic surface, designed for a single topological charge, a single vortex is focused.



CONCLUSIONS

Summary

By using geometrical methods, we derived the parametric surfaces for helico-ellipsoidal, and helico-parabolical vortex reflectors. The topological charge of the vortices at the design frequency can be tuned by the design equations. Vortices with integer topological charge emerge at the design frequency, while vortices of fractional topological charge are observed at other frequencies.

Conclusion

While these complex wavefronts can be generated by phased arrays or lenses, the proposed mirrors do not introduce remarkable attenuation and, therefore, they can be used when a large mechanical amplitude is needed, such as in using electrohydraulic (point) sources or electromagnetic (cylindrical) sources for lithotripsy, histotripsy, or particle and tissue manipulation applications.

A **patent** of invention has been approved.

Next steps

Experimental validation using reflectors of several geometries.

AKNOWLEDGMENTS

Research supported by the Spanish Ministry of Science, Innovation and Universities through grants PID2019-111436RB-C22, and “Juan de la Cierva – Incorporación” grant IJC2018-037897-I. Action cofunded by European Union grant IDIFEDER/2021/004.