Acoustic diffraction-resistant adaptive profile technology for elasticity imaging

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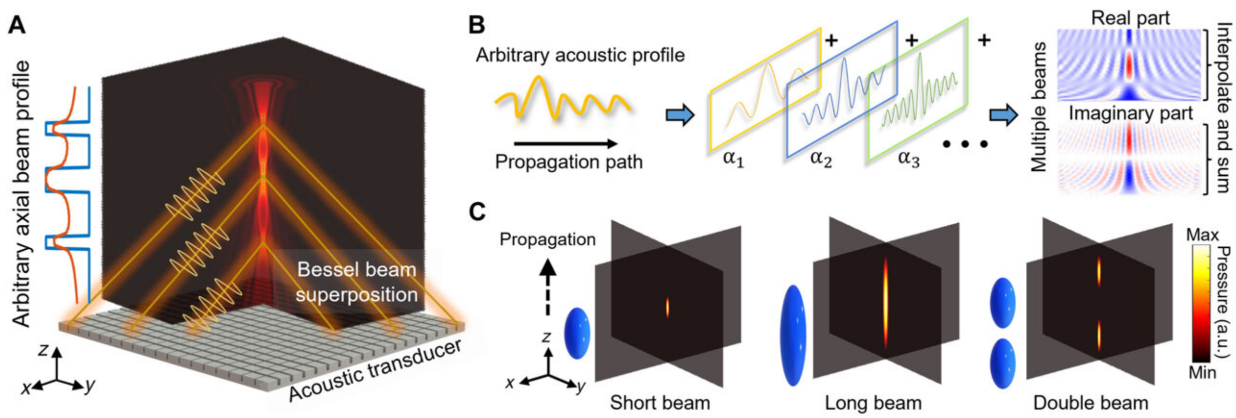


Beam-shaping mechanism of the acoustic diffraction–resistant adaptive profile technology (ADAPT). (A) Illustration of the propagation-invariant acoustic beam generated using ADAPT. An arbitrary axial acoustic beam profile can be defined and realized via weighted Bessel beam superposition. (B) A schematic of the beam-shaping procedures. An arbitrary axial acoustic profile can be expanded as a superposition of various aligned Bessel beams with corresponding weights. The ADAPT-based beam can be generated by beam multiplexing. (C) The orthoslice of the acoustic field of three generated ADAPT-based beams with different profiles. The ADAPT-based beams can be compressed, stretched, and divided into different shapes. a.u., arbitrary units. Credit: Science Advances, doi; 10.1126/sciadv.adi6129

Acoustic beam shaping with high degrees of freedom is critical for ultrasound imaging, acoustic regulation, and stimulation. The ability to fully regulate the acoustic pressure profile relative to its propagation path remains to be achieved.

In a new report published in *Science Advances*, Yuyang Gu, and a team of scientists in radiology at the Massachusetts General Hospital, U.S., describe an acoustic diffraction-resistant adaptive profile technology to generate a propagation invariant beam with a desired profile.

To accomplish this, they leveraged the wave number and beam multiplexing to develop a general framework and create a highly flexible beam with a linear array ultrasound transducer. The designed acoustic beam maintained a beam profile in the material by compensating attenuation.

The scientists showed shear wave elasticity imaging as an important modality to benefit from the method to evaluate tissue mechanical properties. Together, the technology overcame existing limits of acoustic beam shaping suited for a variety of applications including medicine, biology, and materials science.

Acoustic beams

The interest in shaping a desired acoustic beam has broad applications across biomedical imaging, sensing, and particle manipulation. Such acoustic beam methods are inspired by the fundamental physics governing wave propagation to benefit multidisciplinary fields including biology, and biomedical engineering.

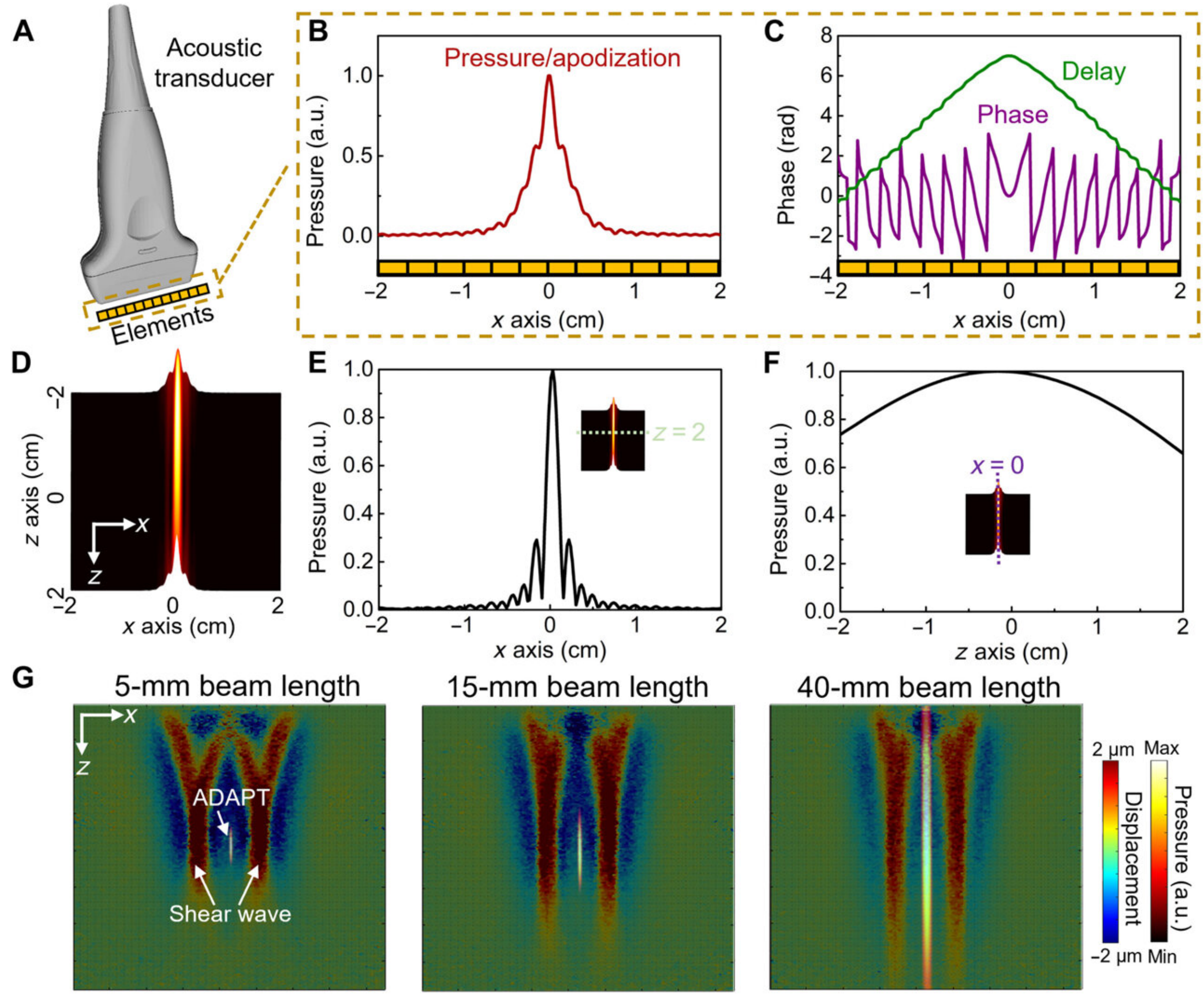
Researchers have hitherto considered a class of acoustic beams known as propagation-invariant or nondiffracting beams. The classic propagation-invariant beams include the Bessel beam, airy beam, Mathieu, and Weber beam; each with unique features for wide-ranging applications in optical research.

Examples include optical tweezers, ultra-resolution imaging, and nanoscale material processing. The acoustic beam Bessel is suited for telecommunication, and acoustic tweezers, where the acoustic airy beam can efficiently bypass any obstacle in the wave propagation path.

Generating the acoustic diffraction–resistant adaptive profile technology (ADAPT)

In this work, Gu and colleagues described a generalized framework to generate propagation-invariant acoustic beams known as acoustic diffraction-resistant adaptive profile technology (ADAPT) to realize arbitrary longitudinal pressure distributions. The scientists first introduced the basic concept with superimposed Bessel beams to realize beam shaping with a linear array transducer.

While the conventional focused beam only provided a limited effective imaging area at the beam focal depth, the method produced a beam with a user-defined region of interest to obtain an extended imaging area with higher accuracy.



Generation of an acoustic diffraction–resistant adaptive profile technology (ADAPT)-based beam with a single multielement acoustic transducer via beam multiplexing. (A) A schematic of a linear-array transducer consists of multiple elements with controllable pressure and phase. (B) The superposed pressure/apodization function assigned to the acoustic transducer. (C) The superposed phase and corresponding delay function assigned to the acoustic transducer. (D) The acoustic field of one example ADAPT-based beam with a localized pressure distribution along the axial center line. (E) The simulated acoustic pressure distribution along the horizontal middle line. (F) The simulated acoustic pressure distribution along the axial center line. (G) The ADAPT is able to induce the shear wave in an elastic medium through acoustic radiation force. With various beam lengths of ADAPT-based beams, shear waves with different wave profiles are produced. a.u., arbitrary units. Credit: Science Advances, doi;

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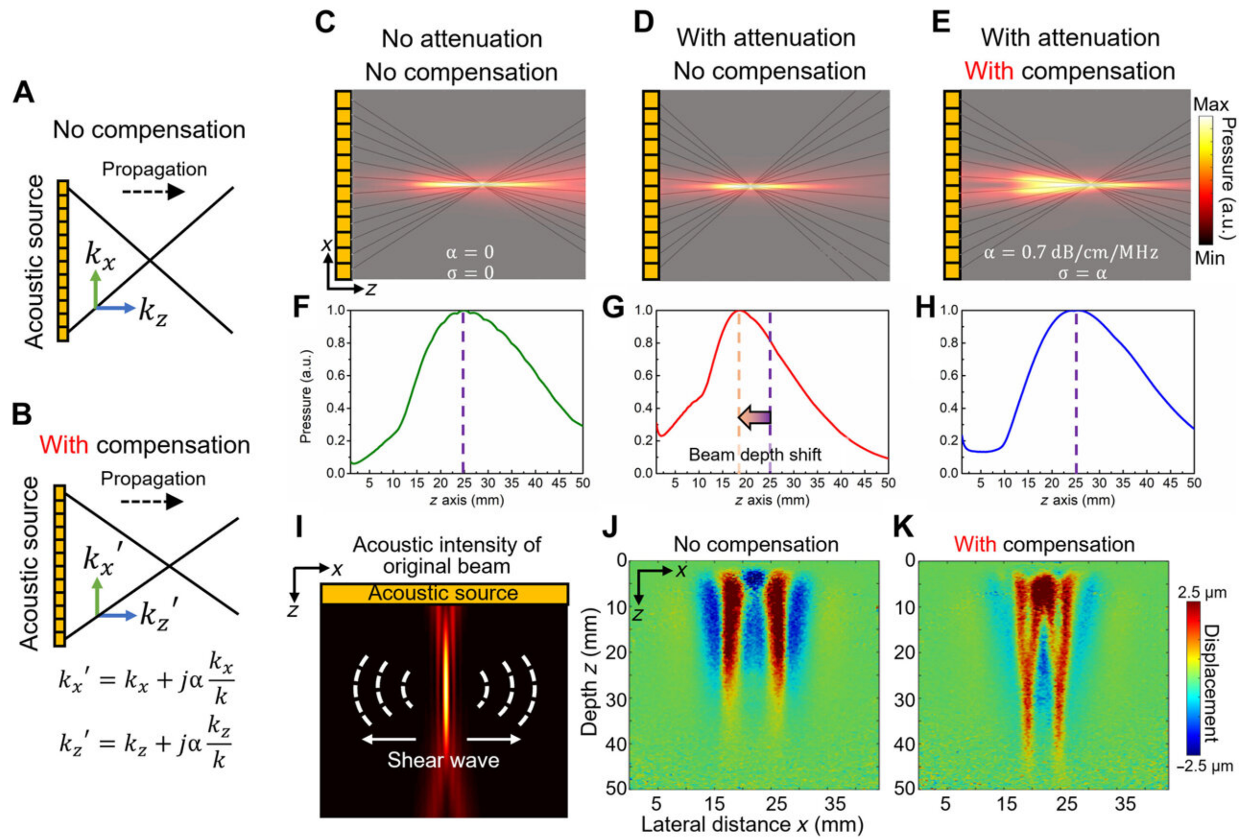
Shaping propagation-invariant acoustic beams

There are two well-established methods to shape an acoustic beam. One method aims to classically shape focused beams by combining a predefined single focal position and the information of the acoustic source. The other method aims to directly map the known pressure or phase distribution function including the Bessel function to each pixel in the acoustic source. Both methods are suited to regulate the longitudinal acoustic profile of the beam.

The ADAPT method (acoustic diffraction-resistant adaptive profile technology) introduced in this work combined both methods by separating a predefined acoustic beam into multiple Bessel beams with different wave numbers and coefficients. The schematic of the ADAPT-based beam with an example predefined pressure profile includes a random, three-section high-pressure region defined as an 'isolated' and propagation-invariant pattern.

A set of Bessel beams formed the final beam, therefore the non-diffractive beam markedly decreased pressure outside the desired high-pressure region via wave-interference. By separating the beam into multiple weighted Bessel beams, Gu and team interpolated the amplitude and phase distribution of each pixel or element to coherently sum up the final amplitude and phase applied to the acoustic transducer.

The team showed how the ADAPT-based beam profiles can be stretched flexibly, compressed, or divided, to generate acoustic beams at different axial locations.



Attenuation-compensated acoustic diffraction–resistant adaptive profile technology (ADAPT)-based beams. (A) A schematic of an ADAPT-based beam without attenuation. (B) A schematic showing a complex wave number can be assigned during the ADAPT calculation that incorporates the attenuation coefficient to compensate for attenuation. (C) The simulated acoustic pressure in the absence of attenuation and compensation. It indicates the originally designed beam profile at the desired location. (D) The simulated acoustic pressure when attenuation is included without compensation. The beam profile and location are distorted. (E) The simulated acoustic pressure when medium attenuation and compensation are included. The beam distortion from attenuation is minimized. (F to H) Plots of the axial center-line pressure distribution correspond to three scenarios in (C) to (E), respectively. (I) The simulated acoustic intensity of the originally designed ADAPT-based beam. (J) The experimental generated shear wave without compensation. The acoustic transducer is located at z = 0 with the center aligned with the shear wave field center. (K) The experimental generated shear wave when attenuation is compensated. The shear wave profile matches the designed ADAPT-based beam profile. a.u., arbitrary units. Credit: Science Advances, doi; 10.1126/sciadv.adi6129

Beam multiplexing

The team found that simultaneously generating the requisite Bessel beams by using a single multielement acoustic wave was challenging. Unlike propagation-invariant laser beams that are generated by using a combination of multiple lenses and photomasks, the acoustic propagation invariant wave maintained a narrower spatial frequency bandwidth that corresponded to limited spatial modulation capabilities. As a result, Gu and team used a multiplexing method to generate the ADAPT-based beam with the desired features.

In its mechanism-of-action, the scientists aligned the beam with the highest transverse spatial frequency requirement to the array element size by using the total spectral bandwidth of the transducer to simultaneously produce multiple acoustic beams with different wave numbers.

The variables of frequency, pitch and element size affected the transverse and axial wave numbers to influence the spatial bandwidth of the acoustic beam. While higher frequencies yielded narrower beams with increased resolution and limited penetration depth, lower frequencies resulted in wider beams with increased penetration but lower resolution. Gu and colleagues adjusted the pitch and element size to regulate spatial resolution, to enable a wider range of beam generating possibilities.

Adaptive shear wave generation via ADAPT

When an acoustic wave is propagating inside a material, this will generate an acoustic radiation force. Such radiation forces are proportional to the rate of change of momentum of an acoustic wave propagating in a medium.

Gu and team showed how the impulsive excitation of an acoustic beam can induce the transient laterally propagating shear wave with a shape that depends on the geometry of the beam. This shear wave speed is directly proportional to the elastic properties of the medium, allowing the researchers to conduct experiments inside a tissue-mimicking phantom with the Verasonics research scanner. The team regulated the specific input parameters, including beam center location and length to achieve the desired line-shape profile.

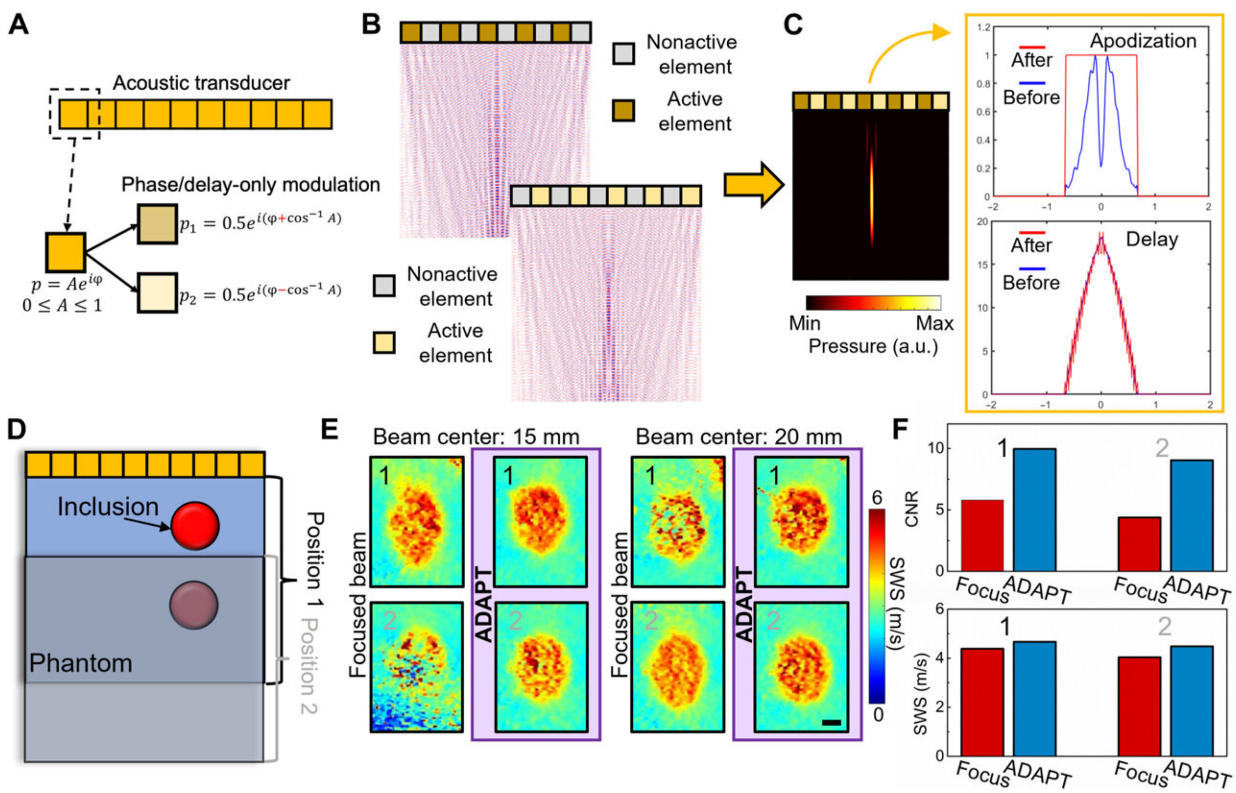


Illustration of phase-only acoustic diffraction–resistant adaptive profile technology (ADAPT) on a linear-array transducer and application of shear wave elasticity imaging. (A) Schematic of the phase-only ADAPT-based beam-shaping mechanism. Each element with specific pressure and phase is divided into two subelements with uniform pressure and different phases. (B) Schematic of the element dividing for phase-only ADAPT and corresponding acoustic pressure of each part of the aperture. The entire aperture is divided into two parts with interleaved elements. Each portion of the aperture can form part of the ADAPT-based beam, and then the set is superposed to shape the final beam. (C) The simulated acoustic field through phase-only modulation. Inset: The comparison of apodization and delay before and after the phase modulation. The information of apodization is encoded into the delay function with a sawtooth distribution. (D) Schematic of the experimental configuration applying phase-only ADAPT for shear wave elasticity imaging. An inclusion is embedded in the phantom. The distance between the phantom and transducer is varied to show inclusions at different depths. A water dam is used when the distance between the phantom and the transducer is too short. (E) Inclusion delineation performance is compared between the focused beam and the ADAPT-based beam. For each beam, two different beam depths are configured at 15 and 20 mm. Scale bar, 2 mm. (F) The contrast-to-noise ratio (CNR) and average shear wave speed (SWS) inside the inclusion are calculated and compared between the cases using the focused beam and the ADAPT-based beam. The ADAPT-based beam produces two times better CNR and more accurate shear wave speed estimate than the focused beam. a.u., arbitrary units. Credit: Science Advances, doi; 10.1126/sciadv.adi6129

Outlook

In this way, Yuyang Gu and colleagues describe a method known as acoustic diffraction–resistant adaptive profile technology (ADAPT), to generate propagation-invariant acoustic beams. Such beams can be generated with a single, linear-array transducer using Bessel beam multiplexing.

This method offered a high degree of freedom to regulate the longitudinal acoustic energy, and optimize the method across a variety of applications. The non-diffracting nature of the ADAPT-based beams allowed acoustic attenuation and diffraction in the material for the acoustic beam to maintain the desired profile effectively during propagation.

Gu and colleagues suggest the introduction of a variety of add-on features, to increase its applications, including shear wave elasticity suited for medical imaging, sonar, and acoustic tweezers.

More information: Yuyang Gu et al, Acoustic diffraction–resistant adaptive profile technology (ADAPT) for elasticity imaging, *Science Advances* (2023). DOI: 10.1126/sciadv.adi6129