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Published in:
Physical Review Letters

DOI:
10.1103/PhysRevLett.112.174302

Publication date:
2014

Document Version
Peer reviewed version

Link to publication in Discovery Research Portal

Citation for published version (APA):
https://doi.org/10.1103/PhysRevLett.112.174302

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AN ACOUSTIC TRACTOR BEAM

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PACS:
43.25.Qp, Radiation pressure - acoustical
42.50.Wk, Light - Mechanical effects on atoms and molecules
43.20.El, Sound - reflection, refraction, and diffraction of
43.20.Fn, Scattering – acoustical

Negative radiation forces act opposite to the direction of propagation, or net momentum, of a beam but have previously been challenging to definitively demonstrate. We report an experimental acoustic tractor beam generated by an ultrasonic array operating on macroscopic targets (> 1 cm) to demonstrate the negative radiation forces, and to map out regimes over which they dominate, which we compare to simulations. The result and the geometrically simple configuration show that the effect is due to non-conservative forces, produced by redirection of a momentum flux from the angled sides of a target, and not by conservative forces from a potential energy gradient. Use of a simple acoustic setup provides an easily understood illustration of the negative radiation pressure concept for tractor beams, and demonstrates continuous attraction towards the source, against a net momentum flux in the system.

The momentum carried by fields and propagating waves has played a central role in the development of physics, impacting early discussions on the nature of light, the Second Law of Thermodynamics, the Stefan-Boltzmann law, and the development of Quantum Mechanics [1]. The association of this momentum with "action at a distance" has intrigued humankind for centuries, yielding science fiction concepts such as the “tractor beam,” in which an outflow of energy results, somewhat counterintuitively, in an influx of matter. Considering a general form of a tractor beam, theorists have recently proposed that attractive, or negative, forces can result from interactions of objects with directed optical and acoustic beams [2]–[11].

Some of the earliest experimental examples of remote manipulation with optical and acoustic fields took the form of levitation traps [12], [13], using positive, non-conservative, radiation pressure from a beam to push objects away from the source and balance against gravity. A positive radiation force ($F_+$) is relatively intuitive and is in reaction to either backscattering or absorption of the forward-directed momentum of a beam, and was famously reported in 1903 [14]. In contrast, most current optical and acoustic tweezing systems [15]–[18] are examples of conservative gradient force traps in which particles are drawn towards potential energy minima. However, tweezing systems that make use of potential energy wells do not provide the conceptual tractor beam defined in the theoretical literature, which is concerned with the role of (a negative) non-conservative radiation pressure, distinct from that of a gradient force, and directed towards the source. Time-evolving potential energy wells such as rotating anisotropic traps [19], or optical conveyors that move trapped particles by continuously sweeping potential energy minima [20], [21] are also not examples of non-conservative forces and hence do not constitute a tractor beam under this definition. Examples of (positive) non-conservative forces in

Accepted for publication in Physical Review Letters, February 2014
optics and acoustics include the transfer of orbital angular momentum [22]–[25] or guided transport along Bessel beams [26]. Specifically, it has been proposed that a tractor beam involves an attractive (negative) non-conservative force upon a target; that is, a continuous redirection of momentum flux is required [4]–[8].

![Diagram](image)

**Fig. 1.** Forward scattering of an acoustic or optical beam producing a net attraction force on a target. The change in momentum due to the axial redirection of a beam with locally off-axis components \((k_{i1}, k_{i2})\) by reflection or scattering \((k_{r1}, k_{r2})\) from the forward facing surfaces of an object results in a radiation force, \(F_{\text{rad}}\), with negative axial components and a resultant negative radiation force, \(F_–\), towards the source and opposite to the net momentum flux of the beam.

With complex beams, including those with conical or helical phase fronts [2], [8], [27]–[30], there can be a substantial reduction of the axial component of the local Poynting vector. It is the forward redirection of this locally off-axis “skew” momentum by a scattering object that leads to a negative radiation force, \(F_–\), on the object, even as the net momentum flux, or net Poynting vector, of the beam remains directed away from the source. Fig. 1 illustrates such an arrangement and the concept of a tractor beam in its simplest form. Optical trapping systems demonstrating these principles have recently been reported, manipulating particles in the presence of a surface. In one approach, a tailored optical beam incident on microscopic particles in the presence of a reflecting surface produces both gradient and radiation forces; the targeted particles reach an equilibrium position where gradient forces balance a radiation pressure that is towards the virtual source [31]. In another approach, optical radiation forces opposing the projected axial momentum of an incident optical beam are exerted on particles situated at the interface between two different dielectric media when the beam is refracted towards the plane of the interface [32]. The experiment presented here demonstrates an acoustic negative radiation pressure directed towards the source, without the need for an additional reflecting surface or refractive interface. Moreover, since the region of \(F_–\) extends from the source, providing a continuous attraction against a net momentum flux in the system, it is compatible with bringing samples in, from a distance, to docking contact with a source. The acoustic tractor beam is demonstrated with macroscopic samples (here > 1 cm) since acoustic devices can generate significantly larger forces (mN) than optical tweezers (pN) over larger length scales [25].

The present setup [33], illustrated in Fig. 2(a), uses a planar, 76-mm square aperture, ultrasonic matrix array operating at 550 kHz to form a directed acoustic field in a water-filled chamber. The ultrasound system and matrix transducer array used for the experiments (ExAblate 2100, InSightec, Tirat Carmel, Israel) is a clinically-approved ultrasonic array system for MRI-guided focused ultrasound surgery [34], [35] with individually controllable transducer elements. The authors have previously demonstrated, with this system, that complex pressure fields such as high order helical beams [25] can be sculpted with appropriate control of the source aperture and phase profile. See Supplementary Material for more information on the array control. Using the matrix array system, we steer locally planar wavefronts towards the axis of symmetry to produce an acoustic field with a sinc-like cross-sectional profile in the absence of a target (Fig. 2(b-d)). That is, we have produced rectilinear analogs of the cylindrically symmetric conical wavefronts associated with the Bessel-like beams discussed in much of the literature on negative radiation forces [2]–[8], [28]–[30]. This symmetric, rectilinear geometry simplifies implementation and characterization of the acoustic fields and the associated target design, and further demonstrates the ease with which negative radiation forces can be applied.

The phase profiles applied to the source array are designed to produce locally planar wavefronts steered at 50.6° from rectangular source apertures, symmetric about the array centerline. By activating only a peripheral subset of the source array elements, we generate hollow-core beams with initial internal core size \(\Delta x\). Simulated and measured maps of the pressure field transmitted from one side of the array (Fig. 2(b,d)) correspond well, showing

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Accepted for publication in Physical Review Letters, February 2014
the wavefronts steered at $\theta = 50.6^\circ$ towards the centerline, and the grating lobe at $27^\circ$ away from the centerline, which does not interfere with the radiation force measurement. The simulated and measured interference patterns for the tractor beam in the absence of a target (Fig. 2(c,e)) show the expected distribution. As the pair of active apertures are stepped towards the centerline, reducing $\Delta x$, the $50.6^\circ$ steering angle and relative phases remain the same, and the region over which the wavefronts intersect moves closer to the source, as visualized in Movie S1 with Schlieren imaging [36].

In the presence of an appropriate target, scattering leads to redirection of the incoming wave, resulting in a continuous attractive force ($-\mathbf{z}\mathbf{z}$) towards the source when the beam intersects forward-facing sides of the target. Each target demonstrated here is a hollow isosceles triangular prism, extending the full length of the array, with an acoustic absorber on the base and thin metal sides to give large acoustic reflection coefficients. The targets were designed to demonstrate $F_-$ and for mapping the force profile along the $z$-axis shown in Fig. 2. Target A has an apex angle of $50^\circ$, approximately matching the steering angle to maximize the $+\mathbf{z}$ change in momentum of the beam, while Target B has an apex angle of $38.2^\circ$, demonstrating that precise target geometry is not critical to the realization of $F_-$, and is smaller, allowing more localized force measurement and profile mapping (see Supplementary Material).

The net force on each target was measured directly as the excess or reduced weight on a balance from which the targets were suspended (see Supplementary Material). A force balance is the standard method for determining the power generated by clinical ultrasound equipment, measuring the positive radiation pressure on a target in the beam. For each active aperture with separation $\Delta x_n$, the force profile was measured as a function of the target position above the source, $z_T$. Finite element analysis [37] was used both to predict $F_{net}$, and to separate it into the component radiation forces on the target sides, $F_-$, and the base, $F_+$. Since acoustic velocity is not zero at all faces of the target, it is necessary to take this movement into account when calculating the mean force on the boundary. The net force on each surface was calculated via integration of the acoustic radiation stress tensor over the mean position of the surface of the target (see Supplementary Material). Measured and predicted force profiles are compared in Fig. 3, and a simulation of the interaction between the acoustic pressure field and Target B at different $z_T$ is visualized in Movie S2.

Fig. 2. Experimental configuration to demonstrate negative radiation forces with a planar ultrasonic array. (a) Scaled cross-sectional geometry of the 550 kHz planar matrix array source, and hollow, prism-shaped targets suspended above the array. Linear phase gradients applied to the array elements produce wavefronts steered at $\theta = 50.6^\circ$ towards the array centerline. Active sub-apertures, forming a hollow core with diameter $\Delta x_n$, are stepped towards the centerline by the array element pitch, with a corresponding lateral ($\pm x$) shift in the transmitted local wavefronts and an axial ($-z$), shift of the intersection with the axis. (b,c) Normalized maps of simulated instantaneous pressure field and (d,e) measured magnitude of the pressure field produced by the transmitting sub-apertures illustrated under the field maps.

The net steady state force depends simply on $z_T$ and the cross-section of the wavefronts incident
on the target. When the field is turned on, the net lateral forces on the sides of the target cause it to shift and rotate so its length is parallel with the centerline of the array, centering the target, no matter the initial lateral position. When the target is close to the array (small $z_T$), $F_{\text{net}}$ is indeed negative, pulling it towards the array because the steered wavefronts primarily interact with target side surfaces. As $z_T$ increases, the wavefronts begin to interact more with the absorbing base of the target and less with the sides, until $F_+$ and $F_-$ are balanced (Fig. 3A). When $z_T$ is big enough, the wavefronts are incident primarily on the base, so $F_{\text{net}}$ becomes positive, reaching a maximum upwards push when the base is at the highest intensity region of the field, before moving beyond the region of interference between the two crossing wavefronts. This same trend in forces is seen in both the simulation and experimental measurements, and for both targets.

The wavefronts intersect the broader base of Target A (Fig. 3(b,c)) at a lower $z$ than Target B (Fig. 3(b,d)), increasing the $F_+$ component, and consequently $F_{\text{net}}$ is negative over a shorter distance from the source. However, the pulling force on Target A is bigger, up to 1 mN, because of the larger surface area and optimized apex angle compared to Target B. The difference in the ratio of the maximum upward and downward forces between simulation and experiment can be attributed to a decrease in $F_-$ from the non-unitary reflection coefficient at the sides, and an increase in $F_+$ from reflections at the imperfectly absorbing base of the target. As expected, reducing $\Delta x$ (Fig. 2(a)) has a similar effect to increasing $z_T$, such that the region, measured from the source, over which $F_{\text{net}}$ is negative, is shorter. With larger $\Delta x$, the maximum of $|F_{\text{net}}|$ reduces because of diverging and lower intensity fields farther from the source, and the position of maximum negative radiation force is farther from the source. For both predicted and measured forces, the axial position, $z_{T0}$, at which $F_{\text{net}} = 0$ (Fig. 4) increases linearly with $\Delta x$, corresponding to an axial shift in the interference field of the tractor beam. Differences between simulation and experiment can again be attributed to imperfect reflection and absorption by the targets. Above this position, the target is pushed away from the source, while below $z_{T0}$, it is continuously pulled towards the source.

In this experiment, a phased array ultrasound source was used to apply a controllable negative radiation pressure that is continuous from the source until the directed beam diverges. The measured force profile confirms that the object is pulled towards the source even when the apex of the target intersects high intensity regions of the beam, demonstrating that the force is due to non-conservative radiation pressure, not a conservative force due to gradients in the field. These results also indicate that these methods, in addition to other techniques, extend the dexterity of an ultrasonic matrix array to the point of having the ability to
acoustically manipulate the position of matter in all
directions, given the proper phasing and drive. Using
the present 76-mm wide ultrasonic array, \( F \) has
been demonstrated for objects centered up to 29 mm
away. This suggests that a large aperture source is
required to manipulate distant objects but it will be
possible to increase the net \( F \) with more tightly
collimated beams, or more complex propagating
beam types, such as Airy beams [38].

Negative radiation forces on objects, which arise
from the reflection or scattering of locally off-axis
wavefronts towards the beam axis, have been proposed
for a range of particle trapping and manipulation
applications using both optical and acoustic beams. We
have demonstrated experimentally negative acoustic
radiation forces on macroscopic objects. The use of
a clinically approved ultrasound system opens up a
range of potential medical and biosciences applications
that may exploit tailored and complex ultrasound
beams. By implementing the advanced control of
ultrasound fields developed in experiments such as
this, there is significant potential to improve the control
of energy deposition in focused ultrasound surgery
and targeted drug delivery, in which high intensity
beams are used to treat tumors noninvasively. Negative radiation forces might also be
used for \textit{in vivo} manipulation and stimulation of
objects, fluids or biological tissue, yielding novel
diagnostic techniques and treatment options. These,
and other potential applications beyond the biomedical
context in which the work was done, will benefit from
the large forces possible with ultrasound, due to the long
wavelength, and are not constrained to the simple
target geometry used here. The depth penetration up to
several centimeters we have achieved with the current
ultrasound system is limited primarily by the discrete
steering angles and the lateral extent of the current
array. The approach demonstrated here provides
additional incentives for developing tailored ultrasound
fields for generating conservative and non-conservative
forces, and adds to the set of techniques available for
contact-free, dexterous manipulation of objects.

Acknowledgments:
This work has been funded by: the Engineering and Physical Science Research Council,
UK, through the Electronic Sonotweezers research
project (EPSRC EP/G01213X/1); the European
Community’s Seventh Framework Programme
through the Nanoporation project (EU FP7 43915);
and the European Regional Development Fund. The
authors thank A. Volovick of InSightec Ltd., Y. Qiu
and Z. Qiu of the University of Dundee, and the
Sonotweezers project partners at the Universities
of Bristol and Glasgow for their support and assistance
in this research.

Author Contributions
GCS conceived the study, and with PMD, ZY,
CEMD, SC and MPM, designed the experiments and
analyzed the data. ZY and PMD performed the force
measurements and pressure field measurements.
PGJ, CEMD and PMD performed simulations. SC,
MPM, and AM supervised the study and contributed
experimental tools. PMD, CEMD, ZY, SC, MPM
and GCS wrote the manuscript.

Supplementary Movie Captions
Movie S1. Schlieren imaging of the acoustic pressure
fields generated with different active aperture separations,
\( \Delta x_n \), without a target in the water chamber.
https://discovery.dundee.ac.uk/admin/files/temp/perm-temp-
6ce2da82-d847-495e-80ae-
989b2866b81/MovieS1_Schlieren.avi?mimetype=video/msvid
go
Movie S2. Simulation of the interaction between the
acoustic pressure field and Target B at different
separations between source and target, \( z_T \) using finite
element analysis (PZFlex, Weidlinger Associates, Inc.,
CA, USA). The largest separation between the active
apertures, \( \Delta x_1 \), is used in the simulation of the transmitted
wavefronts.
https://discovery.dundee.ac.uk/admin/files/temp/perm-temp-
84a5be5-6fe4-4aed-8200-
8a8742fab07f/MovieS2_TargetinField.avi?mimetype=video/ms
video

References and Notes:
of radiant heat,” Ann. Sci., vol. 46, no. 2, pp. 183–194,
sphere and direction reversal of the force,” J. Acoust. Soc.
Am., vol. 120, no. 6, p. 3518, 2006.
radiation force exerted on a sphere by standing and

Fig. 4. (color online) Axial position of targets, \( z_{T0} \), at
which positive and negative radiation forces balance,
calculated from the zero crossings in Fig. 3 for both
simulation and experimental measurement of \( F_{\text{net}} \).

Accepted for publication in Physical Review Letters, February 2014