# Nonlinear Acoustics Today

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***Nonlinear acoustics can remove particulates from air, quiet sonic booms, create audio spotlights, and improve medical ultrasound imaging and therapy.***

## Introduction

The world around us is inherently nonlinear. Linearity of any process is an approximation for the case of small, possibly infinitesimal, motion. From this point of view, it would seem that it should be linearity rather than nonlinearity that is considered unusual. Linearity is commonly assumed in wave physics, which allows, for example, the principle of superposition, according to which two waves pass freely through each other, not interacting or influencing one another in any way.

Nonlinear waves that we have all seen many times are those on the surface of water. When such a wave approaches the shore, its profile begins to distort; the crest of the wave travels fastest, causing the wave to steepen and eventually overturn, ultimately breaking and creating a cloud of foam (**Figure 1, *top***). Unlike waves on a water surface, it is physically impossible for sound waves to become multivalued (e.g., possess three different sound pressures at one point in space) and subsequently break. However, exact formulations of the equations for ideal fluids by mathematicians in the eighteenth and nineteenth centuries (luminaries such as Euler, Riemann, Poisson, Earnshaw, and Airy) predicted multivalued solutions for sound waves that generated considerable controversy. The matter was ultimately resolved by Stokes, who explained that viscosity prevents nonlinear acoustic waves from overturning and, instead, discontinuities appear in their profiles, which are referred to as shocks (see Hamilton and Blackstock, 2008, Chap. 1).

As depicted in **Figure 1**, the frequency spectrum of a nonlinearly distorted sound wave contains, along with the initial frequency, many frequencies referred to as harmonics. The process of waveform distortion, especially shock formation, and the accompanying generation of higher frequencies are distinguishing features of nonlinear acoustic waves (Atchley, 2005). Several examples are considered below, first in the frequency domain and then in the time domain.

Nonlinear distortion results in energy being exchanged among different frequencies, not only frequencies that were present at the source but other frequencies too. For example, if a wave is radiated at a single frequency ($f_0$), it interacts with itself to transfer energy from the signal at $f_0$ to frequencies $2f_0$ (called the second harmonic), $3f_0$, $4f_0$, and higher, and these harmonics grow with the propagation distance (**Figure 1, *bottom***).

## Diagnostic Ultrasound Imaging

One area where generation of the second harmonic plays an important role is in diagnostic ultrasound imaging. The basis of imaging in medical diagnostics is the pulse-echo method. An ultrasonic transducer emits short tone bursts into the patient's body, and due to scattering from tissue inhomogeneities and organ interfaces, echoes propagate back to the probe and are used to build an image in the form of a brightness pattern, a B-mode image (**Figure 2, *bottom left***). Images are traditionally formed assuming


https://doi.org/10.1121/AT.2019.15.3.55

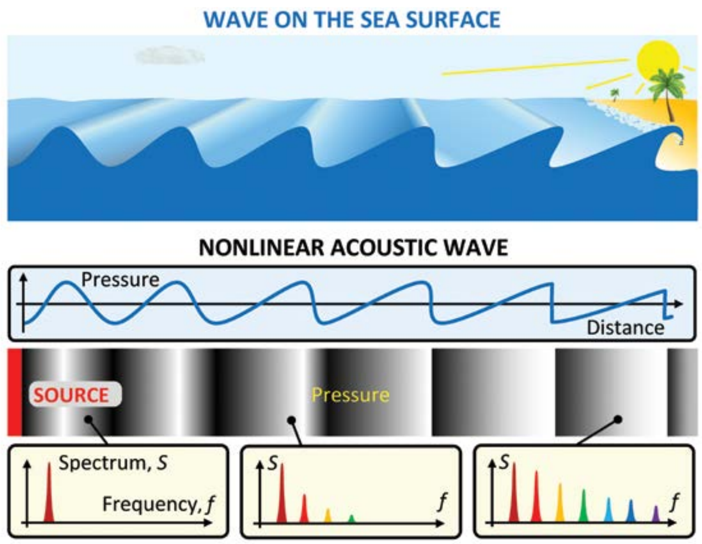


***Figure 1.*** *When a nonlinear wave propagates in the absence of dispersion, its shape distorts due to the dependence of the propagation speed on the local wave amplitude. This phenomenon is observed both for waves in shallow water (**top row**) and for a nonlinear acoustic wave (**bottom three rows**). **Third row:** gray scale representation of the sound pressure in the **second row; fourth row:** corresponding frequency (f) spectrum (S) at different distances from the source.*

that the echoes are at the same frequency as the transmitted pulse, around 2-5 MHz. However, if the emitted pulses have sufficiently high amplitude, then nonlinear effects become significant and a second harmonic is generated during propagation of the probe wave. Although the second harmonic is weaker than the wave emitted by the source, it has several properties that can result in better images.

First, the second harmonic pulse is shorter in duration and narrower in width than the pulse at the source frequency, improving spatial resolution in all directions. This effect occurs because the amplitude of the second harmonic generated in the body is proportional to the square of the local amplitude at the source frequency.

A second advantageous feature of the image built using the second harmonic is that near the ultrasound probe, where heterogeneities in the body wall introduce strong scattering of the probe beam, the second harmonic has not yet been generated to any significant degree. Imaging at the second harmonic thus substantially reduces the echoes and reverberation from the body wall, which, in turn, significantly improves the quality of images (**Figure 2, *bottom right***).

Nonlinear imaging at the second harmonic is called tissue harmonic imaging (Burns et al., 2000). It is now standard on most ultrasound systems used for echocardiography.

## The Parametric Array

Generation of second and higher harmonics is only one manifestation of acoustic nonlinearity. Consider the case where a bifrequency signal is radiated at frequencies $f_1$ and $f_2$. Quadratic nonlinearity in the first approximation generates sound in the medium at frequencies $|f_1 - f_2|$, $f_1 + f_2$, $2f_1$, and $2f_2$. These new frequencies then participate in the nonlinear interaction, with energy ultimately cascading throughout the spectrum to all possible combination frequencies $|mf_1 \pm nf_2|$, $m$, $n = 1, 2, ...$

A means of creating a very narrow beam of low-frequency sound is accomplished by radiating a bifrequency waveform from the transducer. If the initial two (primary) frequencies are close together, then among all frequencies, including the primary frequencies $f_1$ and $f_2$, the most "enduring" of them all is the difference frequency ($f_D = |f_2 - f_1|$). Because viscous

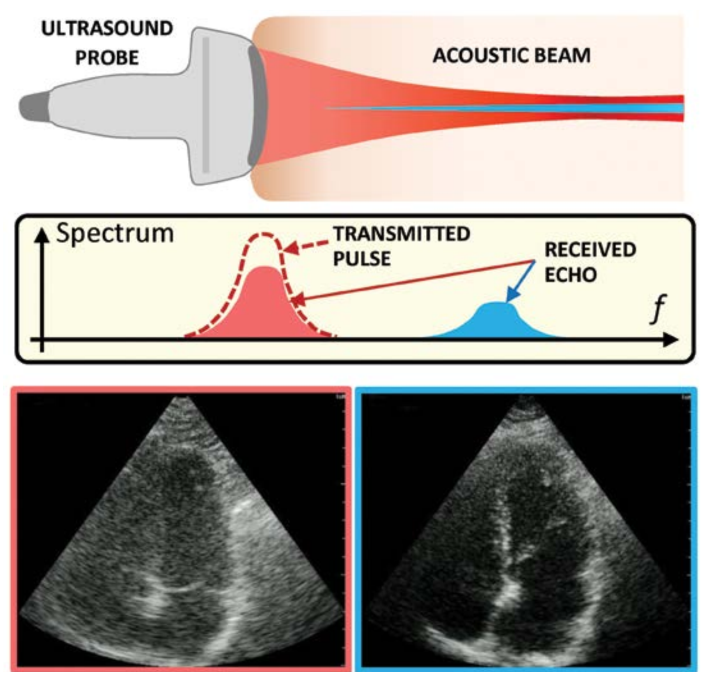


***Figure 2.*** *Use of nonlinear effects in ultrasound imaging—tissue harmonic imaging. **Top: red** indicates the fundamental and **blue** the second harmonic that originates in the patient's body and is therefore less subject to deleterious effects of the body wall and provides better resolution due to its narrower beam. **Middle:** frequency spectrum of the ultrasound echo. **Bottom:** comparison of fundamental (linear; **left**) and harmonic (nonlinear; **right**) ultrasound images of the heart. Images courtesy of M. A. Averkiou.*

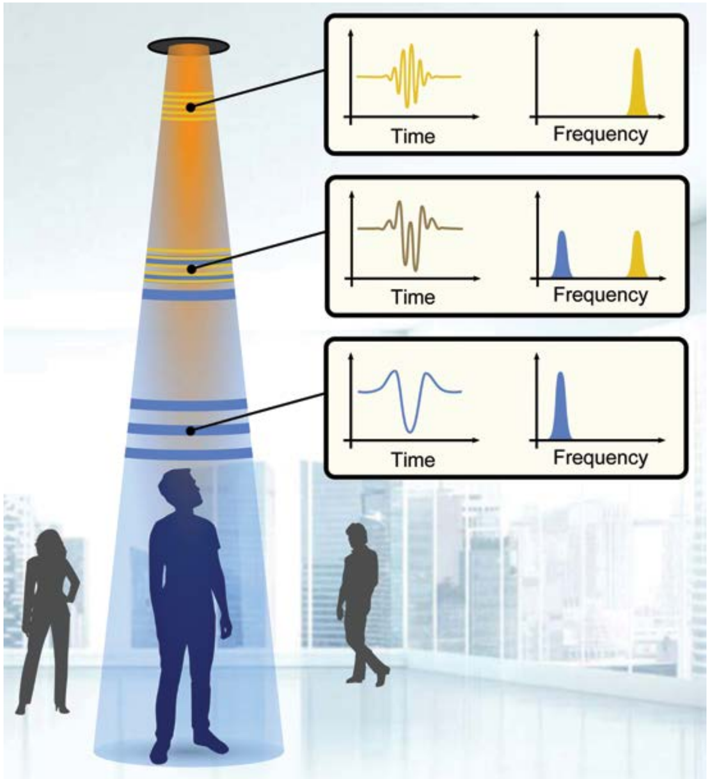


***Figure 3.*** *Depiction of a parametric array, created with radiation of ultrasound by a loudspeaker in the ceiling, used to produce an audio spotlight of highly directional speech. The amplitude-modulated ultrasound radiated by the loudspeaker, represented in the time and frequency domains in the* ***top panel****, self-demodulates into audible speech, represented in the* ***bottom panel****, during nonlinear propagation toward the listener.*

absorption increases with frequency, the medium acts as a low-pass filter and ultimately only a low-frequency ($f_D$) wave will remain. Nonlinearity thus makes it possible to create an acoustic beam at low frequency using a high-frequency source. Nonlinear acoustic sources based on this principle were proposed in the 1950s to 1960s by Westervelt in the United States and independently by Zverev and Kalachev in the Union of Soviet Socialist Republics (USSR), and they are referred to as parametric arrays. Like many studies in underwater acoustics during the era of the Cold War, the initial studies were classified (see Zverev, 1999, for a review of early research on parametric arrays in the USSR; Westervelt, 1960, 1963, for the first open publications on this subject).

One might question why one would choose to excite a low-frequency beam in such a complicated and comparatively inefficient way when it would be easier to radiate the low-frequency wave directly from the transducer. The main advantage is the ability to create very directional low-frequency sources or receivers having dimensions considerably smaller than required by linear acoustics. The volume of fluid in the medium insonified by the high-frequency primary waves at $f_1$ and $f_2$ acts as an antenna for $f_D$. The length of this antenna is limited only by the propagation distance ($L$) of the primary waves, which is determined by their attenuation due to absorption and diffraction. The insonified region corresponds to a traveling-wave antenna that emits a $f_D$ beam with an angular width on the order of $\sqrt{\lambda_D/L}$ radians, where $\lambda_D$ is the wavelength at $f_D$. In addition to this significant size advantage over conventional sound sources, another important property is that the high directivity is maintained over a wide bandwidth relative to $f_D$. Also, sidelobes typically associated with the high-frequency pump waves are significantly suppressed. The main drawback of the parametric array is its low efficiency in converting energy in the pump waves into the $f_D$ wave.

Parametric arrays were the first practical devices based on nonlinear acoustics, initially with application to sonar (Esipov et al., 2010). In recent years, parametric arrays have been used to create highly directional beams of audible sound in air. The first measurements of audible frequencies produced by a parametric array in air were reported in the mid-1970s (Bennett and Blackstock, 1975). However, engineering challenges connected with the development of transducers capable of producing sufficiently intense beams of ultrasound in the air prevented commercialization of the *audio spotlight* until the early 2000s.

The principle of the audio spotlight, which has been understood since the 1960s (Berktay, 1965), follows from recognition that using a parametric array to generate a low frequency $f_D$ due to the interaction of two high frequencies ($f_1$ and $f_2$) is a special case of *self-demodulation*. If the time waveform is expressed as $E(t)\sin(2\pi f_0 t)$, where $E(t)$ is an amplitude modulation that varies slowly in time relative to $f_0$, then the time waveform produced by the parametric array is proportional, or nearly so, to the second time derivative of the square of the modulation function ($d^2E^2/dt^2$). Creation of such a waveform in the fluid is referred to as self-demodulation.

In the context of the audio spotlight, $f_0$ is typically around 60 kHz, well above the range of human hearing. The frequency is sufficiently high to create a directional beam but not so

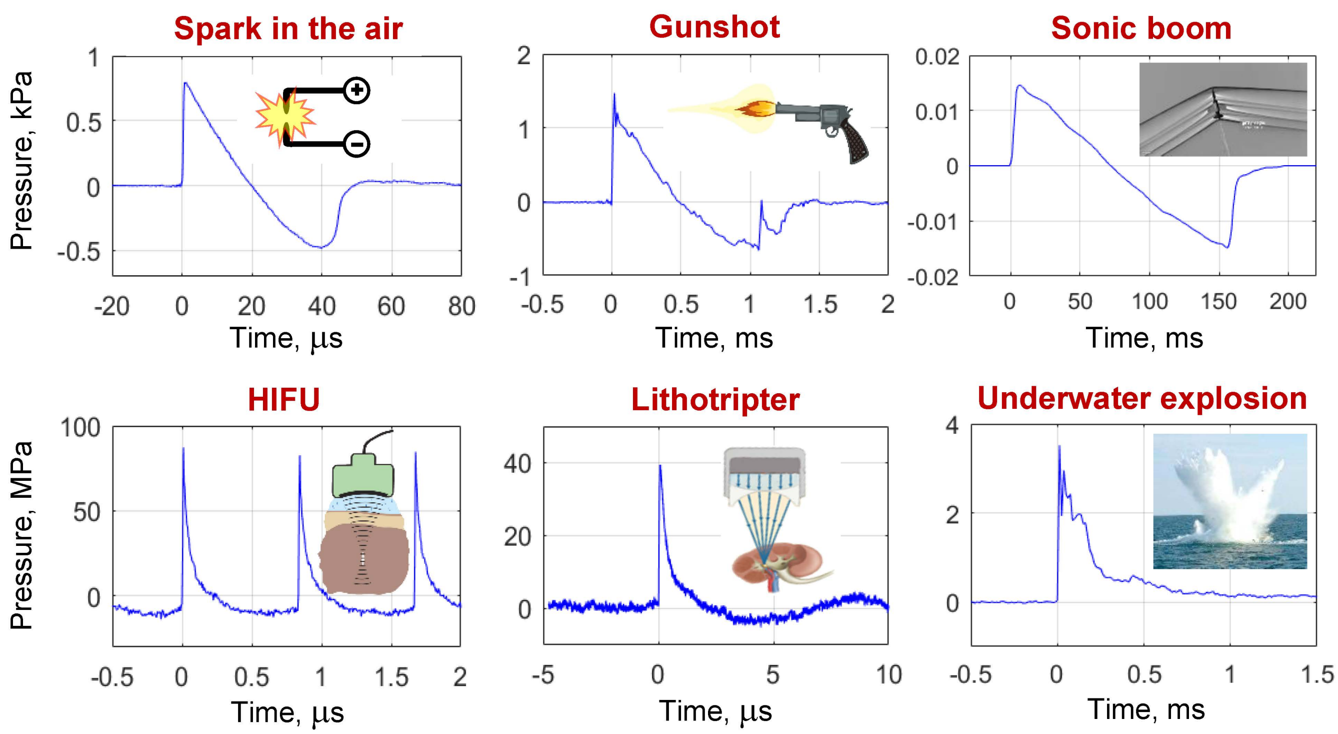


*Figure 4. Top row: pressure waveforms radiated in air by various sources. **Left**: spherical shock wave measured 19 cm from a 15-kV spark source with a 2-cm gap between tungsten electrodes (Karzova et al., 2015). **Center:** pressure waveform measured at 60° from the shooting direction and 3 m from the muzzle of a .357 Magnum handgun revolver firing a 125-grain bullet (Beck et al., 2011). **Right:** sonic boom N wave produced by a F/A-18B fighter jet flying supersonically at an altitude of 31,550 ft measured at the ground (Cho and Sparrow, 2011). **Bottom row:** acoustic waveforms with shocks in water. **Left:** pressure waveform measured at the focus of a 1.2-MHz clinical therapeutic ultrasound array (Kreider et al., 2013). HIFU stands for high-intensity focused ultrasound. **Center:** shock wave measured at the focus of an electromagnetic lithotripter (Sapozhnikov et al., 2014). **Right:** sound from an underwater explosion produced by a US Navy SUS Mk 64 charge containing 31.2 g of tetryl. The source and hydrophone were located underwater at 18 m depth and separated horizontally by 21 m distance (P. S. Wilson, personal communication).*

high that it suffers too much attenuation due to energy dissipation in the air, with the sound at 60 kHz extending out to about $L = 5$ m from the source. An electrical signal at $f_0$ is modulated by a function $[E(t)]$ related to the desired speech waveform obtained following self-demodulation, creating a signal represented by the time and frequency plots in **Figure 3**, ***top right***. This signal is radiated directly by the loudspeaker shown mounted in the ceiling.

**Figure 3**, ***center right***, illustrates a midpoint in the conversion of energy at the high frequencies around $f_0$ (**yellow spectrum**) to the frequency band of speech (**blue spectrum**), typically below 5 kHz, as the wave propagates toward the listener below. **Figure 3**, ***bottom right***, depicts the time waveform and frequency spectrum associated with the desired speech signal ($d^2E^2/dt^2$) at the listener after the process of self-demodulation is completed.

**Figure 3** depicts a common use of the audio spotlight for directing speech toward individual listeners in museums, stores, and amusement parks. The directionality of the beam is so high that it can be disorienting for the listener because such strong spatial localization of speech is not something encountered in everyday experience.

## Waveform Distortion and Shock Formation

Although the frequency domain is convenient for describing nonlinear phenomena when a small number of harmonic waves are present in the source, there are many impulsive sources that produce nonlinear acoustic waves (see **Figure 4**) for which a time domain approach is more suitable. In **Figure 1**, the peaks of the acoustic waveforms propagate faster than the troughs, and there are two reasons for this. First, when the medium is compressed, the local sound speed increases, and when rarified, it decreases. Second, the acoustic wave sets the particles in motion, and the local particle velocity is highest at the peaks and lowest at the troughs. Thus, for nonlinear acoustic waves, the regions of compression ("wave crests") in the waveform propagate faster and the regions of rarefaction ("wave troughs") propagate slower. Even if changes in the local wave speed are small, over long-enough propagation distances, they manifest as significant distortion.

If the wave is sufficiently strong, substantial nonlinear distortion can occur before the wave is attenuated due to absorption, scattering, or divergence. However, the large gradients associated with nonlinear steepening result in increased importance of loss mechanisms such as viscosity, which competes against nonlinearity. When the nonlinearity and loss mechanisms balance, a stable shock front is formed, and if the shock is sufficiently thin, it can be approximated as a discontinuous jump. Across a shock, all physical properties such as pressure, particle velocity, and density undergo abrupt jumps in their values. Shock waves have unusual properties in terms of how they propagate and the effects they can introduce in the medium through which they propagate, ranging from heating to structural damage.

The distortion of a wave profile and its evolution into a shock wave are observed in any elastic medium (air, water, or a solid). The shock waves can be generated by explosions, lightning, electric spark, gunshots, or other pulsed sources that cause sudden pressure changes. Even sources of moderate amplitude radiating smooth waveforms, such as piezoelectric sources of ultrasound, can achieve shock formation, especially when focused.

Some examples of measured shock wave profiles are shown in **Figure 4**. Regardless of the propagation medium and the type of source, they are all seen to possess a universal form in which the shocks are connected by smooth transitions. The characteristic durations of the waveforms can vary over a wide range, from microseconds to fractions of seconds, but the duration of the shock itself (referred to as shock rise time) can be extremely short, in fact, so short that often it cannot be resolved by a microphone or hydrophone. Shock waves do not propagate in the same way as ordinary weak acoustic waves. Compression shock waves (e.g., all of the shocks at time = 0 in **Figure 4**) propagate faster than sound waves of infinitesimal amplitude, and their speed increases with increasing amplitude. The amplitude of the shock wave also

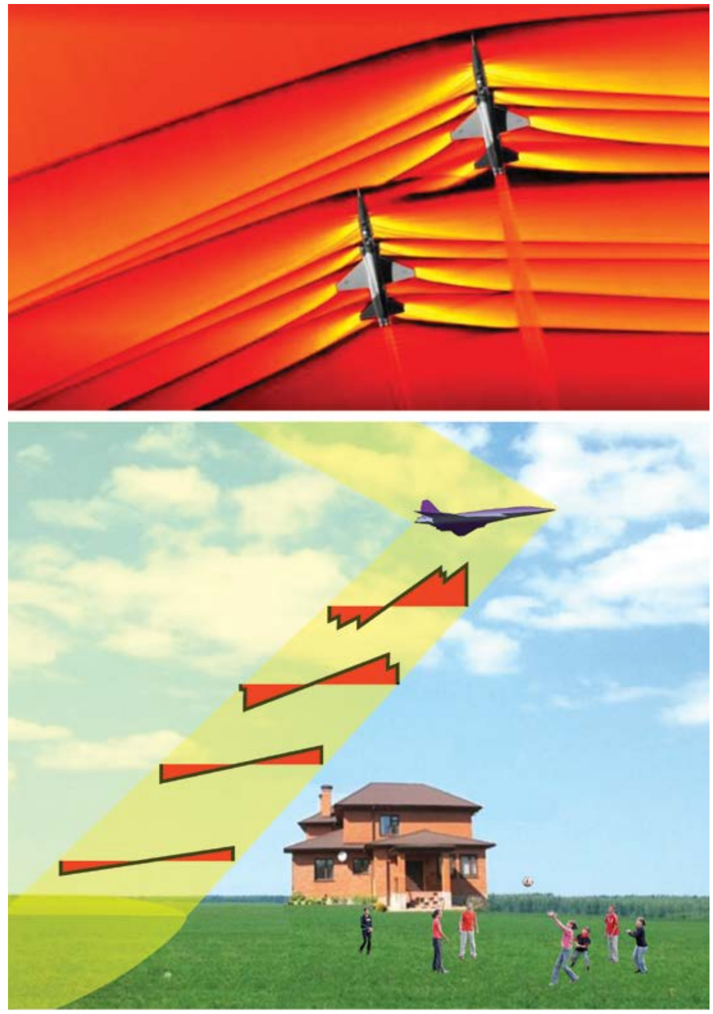

***Figure 5.*** *Supersonic aircraft produce a shock wave that is heard on the ground as a sonic boom.* ***Top:*** *NASA photo (created by NASA and in the public domain in the United States [PD-USGov-NASA]) showing a schlieren image (based on refraction of light by density gradients in the medium) of shock waves produced by two US Air Force T-38 aircraft flying at supersonic speeds.* ***Bottom:*** *cartoon showing the Mach cone (**yellow**) that is created in the wake of a supersonic aircraft. The waveforms inside the cone show the evolution of the sonic boom, due to nonlinear acoustic distortion, from an initial irregular waveform near the aircraft to an N wave at the ground. A sonic boom sounds similar to an explosion or a thunderclap to the human ear and may even cause damage to some structures.*

decreases faster than that of an ordinary sound wave due to strong energy dissipation at the shock front.

## Supersonic Sources

Pressure waves generated by a moving object deserve separate consideration. At low velocities (much less than the sound speed), sound waves are barely excited because the liquid or gas in which the body moves merely flows around it without experiencing much compression. At higher velocities, the flow over the body begins to be accompanied by compression of the medium just ahead of the body and expansion just behind it. These disturbances become acoustic waves. The most interesting situation is when the speed of the object exceeds the speed of sound (about 343 m/s in air) because another type of wave phenomenon arises, a sonic boom. A supersonic object (typically a plane, but it can be a bullet from a gun or a meteor coming from space) moves through the medium faster than the acoustic waves can propagate away. This results in the waves combining to form a cone (the Mach cone) that follows the supersonic object, much like a boat wake. The ratio of the speed of the object ($V$) to the speed of sound ($c$) is defined as the Mach number ($M = V/c$). A Mach cone is created whenever $M > 1$, and the angle of the Mach cone becomes smaller as $M$ increases.

Sonic booms currently attract the interest of researchers in connection with the possibility of developing a new generation of supersonic civilian aircraft. A loud bang sweeping across land under the plane can have an undesirable effect on buildings, structures and, of course, people (**Figure 5**). The impact of the sonic boom depends largely on the size of the aircraft, the distance to the observer, and, to a lesser extent, the shape of the aircraft (Rogers and Maglieri, 2015; Loubeau and Page, 2018). Near the aircraft, the sonic boom can have a complex shape with a spatial extent approximately the size as the aircraft; this results in a duration of about 0.1 s for a fighter size aircraft and about 0.5 s for a space shuttle or an airplane such as the Concorde. The duration of the sonic boom increases during propagation because the head (compression) shock is supersonic and the tail (rarefaction) shock is subsonic, and the shocks merge until near the ground where the waveform typically resembles the letter N with a bow shock and stern shock. For longer durations, the sonic boom can be perceived as a double "boom" because the two shocks are sufficiently separated in time to be resolved by the human ear. When the plane is nearby, the N wave is shorter, and the sonic boom sounds like a single sharp bang.

## Ultrasonic Heating

Nonlinear acoustic effects extend beyond the waveform distortion and harmonic generation. For example, energy transfer to higher harmonics results in increased attenuation because high frequencies are typically absorbed more readily. The loss mechanisms convert wave energy into heat. Consequently, the temperature of the medium increases, an effect that depends nonlinearly on the wave amplitude. In the simplest case of a sinusoidal wave, the heat sources and the resulting temperature increase are proportional to the wave intensity, such as the square of the wave amplitude. If the wave contains shocks then the heat sources are even stronger, proportional to the cube of the pressure jump at the shock front (Sapozhnikov, 2015).

One current application of heating generated by acoustic waves is in medicine, where high-intensity focused ultrasound (HIFU) is used for remote thermal or mechanical destruction of tumor tissue deep inside the body (Bailey et al., 2003). When strongly nonlinear waves are used, a sinusoidal waveform radiated by the transducer evolves into periodic

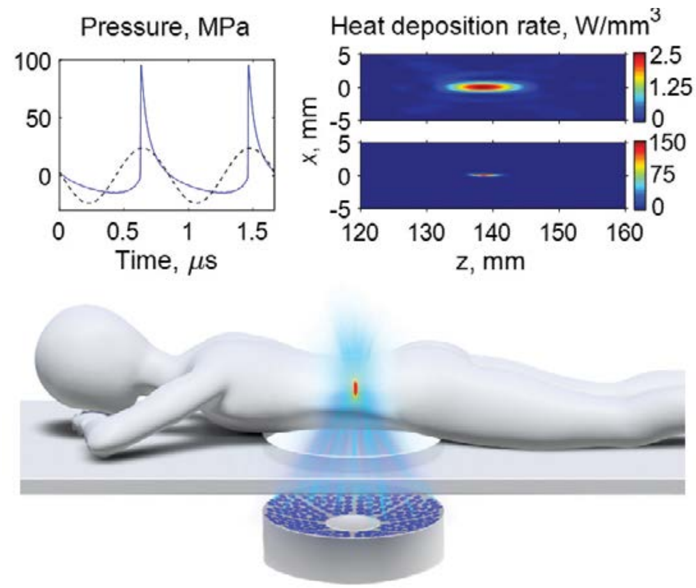


*Figure 6. The role of shock waves in noninvasive HIFU therapy. **Top left:** numerical modeling of a pressure waveform at the focus of a 1.2-MHz, 256-element, 14-cm-diameter, 14-cm focal length therapeutic array operating at 800 W acoustic power assuming linear (**black curve**) and nonlinear (**blue curve**) propagation regimes (MR-HIFU system). **Top right:** Corresponding heat sources: linear (**top**) and nonlinear (**bottom;** Karzova et al., 2018). Peak heating is 75 times higher with nonlinearity. **Bottom:** in HIFU therapy, an extracorporeal source is focused at a target location in the body and used to ablate tissue in a region about the size of a grain of rice.*

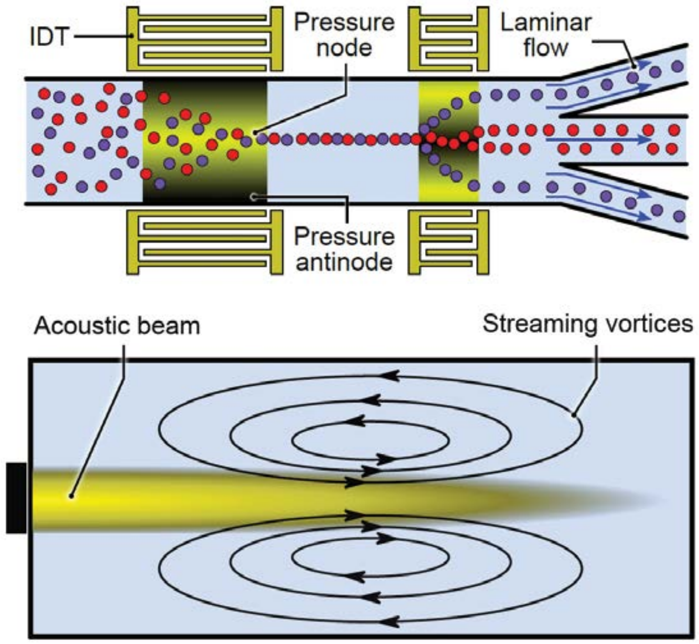


*Figure 7. **Top:** particle separation in an acousto-microfluidic device accomplished with acoustic radiation forces produced by standing waves generated in the fluid by interdigital transducers (IDT; after Jo and Guldiken, 2012). **Bottom:** acoustic streaming vortices produced by the absorption of a sound beam in an enclosed fluid. See text for further description.*

shocks at the focus (**Figure 6**). In this case, a symmetrical sawtooth waveform does not occur due to the presence of diffraction, which results in different frequencies focusing at slightly different distances, producing the highly asymmetrical waveform with a strong short peak and a longer trough of lower amplitude. The shocks are thus superfocused and confined to a much narrower focal region. This occurs because the very short rise times of the shocks are associated with very high frequencies generated during nonlinear propagation of the wave toward the focus, and they are less affected by diffraction (spreading) than the frequencies radiated directly by the source.

Acoustic cavitation is a common by-product of HIFU, especially histotripsy (Maxwell et al., 2012) and shock-wave lithotripsy (Bailey et al., 2006). Bubbles are created when the negative pressure phase of the acoustic wave drops below the vapor pressure, and in the case of shock-wave lithotripsy, the subsequent bubble collapse is often sufficiently violent to become a secondary source of shock waves. Alternatively, various therapeutic applications of acoustically driven bubbles, which are strongly nonlinear oscillators, employ micron- and submicron-size bubbles injected into the bloodstream (Gray et al., 2019).

## Radiation Force and Streaming

Other physical effects of high-intensity sound are related to the fact that a wave carries momentum that can be transferred to the medium. This momentum transfer creates a volume force, called the *radiation force*, which depends nonlinearly on the amplitude of the wave. In liquids, the resulting force generates hydrodynamic flows (*acoustic streaming*), and in elastic media such as soft biological tissues, it generates shear waves.

The relevant quantity is the time average of the product of the mass density and particle velocity, a quadratic quantity equal to the average momentum per unit volume. When a progressive sound wave encounters an obstruction, whether it be an object that scatters sound in different directions or a planar interface that produces reflected and transmitted waves, the magnitude and direction of the wave momentum change. From Newton's second law, a force equal to the rate of change of the wave momentum acts on the obstruction. Although standing and multidimensional wave fields add complexity, the physical principle is the same.

For a particle that is small relative to a wavelength, the magnitude of the radiation force is proportional to the differences in compressibility and density of the particle compared with the corresponding properties of the surrounding fluid (Gor'kov, 1962). The force acting on larger objects is similarly related to these parameters (Sapozhnikov and Bailey, 2013; Ilinskii et al., 2018). This relationship is exploited to separate small particles in microfluidic devices. An example of one such device described by Jo and Guldiken (2012) is illustrated in **Figure 7**, ***top***.

Radiation force can separate particles not only in a standing wave but also in a traveling wave. A possibility of biological cell sorting based on this principle is discussed by Matula et al. (2018). Even larger particles like kidney stones can be effectively manipulated (Simon et al., 2017).

In contrast with acoustic radiation force acting on scatterers, radiation force that creates acoustic streaming is due to momentum transferred to the bulk of the liquid caused by absorption of the wave; it thus accompanies energy dissipation in a sound field. Whereas energy dissipation due to

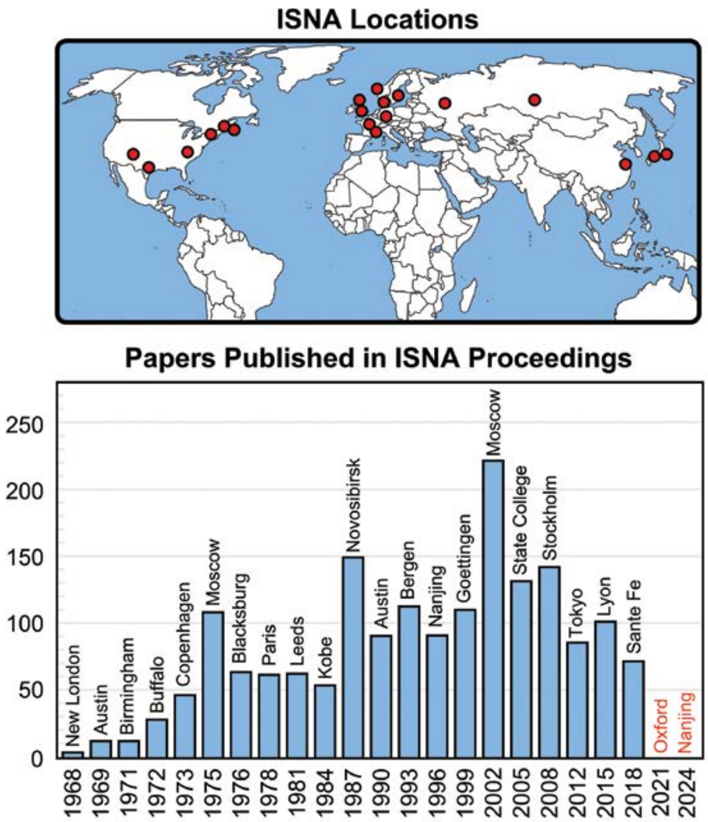


***Figure 8. Top:*** *locations where the International Symposium on Nonlinear Acoustics (ISNA) has been held starting in 1968.* ***Bottom:*** *year, city, and number of proceedings papers published for each ISNA, including the dates and locations of the next two symposia.*

viscosity converts mechanical energy in a sound wave into heat, momentum is associated with inertia and can only be conserved by mechanical means. Therefore, the time average of the momentum lost by a sound wave as its energy is reduced due to acoustic absorption is replaced by the momentum corresponding to mass transport associated with steady flow of the fluid. This steady flow is referred to as acoustic streaming (Nyborg, 1965).

An example of acoustic streaming created by the absorption of a sound beam in a fluid in a closed container is depicted in **Figure 7**, ***bottom***, in which the sound beam propagates from left to right. The time average of the acoustic momentum in the beam is also directed to the right, and therefore absorption of the sound generates fluid flow in the same direction. This type of streaming is called Eckart streaming. In the case of a standing wave in a narrow tube, the vortices generated by viscous losses along the walls of the tube are referred to as Rayleigh streaming. The latter is more prevalent in microfluidic devices.

## International Symposia on Nonlinear Acoustics

Nonlinear acoustics as an established discipline within the broader area of physical acoustics came of age in 1968 when the first International Symposium on Nonlinear Acoustics (ISNA) was held in New London, CT. Although the first ISNA was convened largely in response to the surge in research spawned by the invention of the parametric array and its application to sonar, by the end of the 1970s, the field had expanded to include fundamental and applied research in nonlinear acoustics in all media (gases, liquids and solids), including the areas of acoustic cavitation and bubble dynamics.

As illustrated in **Figure 8**, ISNA continues to maintain an enduring presence in the international acoustics community by holding a symposium typically every three years, with its venue alternating between North America, Europe, and Asia (Hamilton et al., 2012). It is, in fact, extremely rare for a specialized subdiscipline of physics to exhibit such vitality for half a century, yet ISNA has surpassed this milestone with future symposia already scheduled for 2021 in Oxford, UK, and 2024 in Nanjing, China. Such longevity is testimony to the fundamental nature of nonlinear acoustics and its manifestations in all areas of acoustics.

The mathematical framework underlying the basic physical principles discussed in this overview may be found in several textbooks on nonlinear acoustics that have been published over the years (Rudenko and Soluyan, 1977; Beyer, 1997; Naugolnykh and Ostrovsky, 1998; Hamilton and Blackstock, 2008).

## Acknowledgments

We thank Jason Sagers and Aleksander Smetanka for creating several of the figures.

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