Temperature-controlled acoustic surface waves

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Abstract

Conventional approaches to the control of acoustic waves propagating along boundaries between fluids and hard grooved surfaces are limited to the manipulation of surface geometry. Here we demonstrate for the first time, through theoretical analysis, numerical simulation as well as experimentally, that the velocity of acoustic surface waves, and consequently the direction of their propagation as well as the shape of their wave fronts, can be controlled by varying the temperature distribution over the surface. This significantly increases the versatility of applications such as sound trapping, acoustic spectral analysis and acoustic focusing, by providing a simple mechanism for modifying their behavior without any change in the geometry of the system. We further discuss that the dependence between the behavior of acoustic surface waves and the temperature of the fluid can be exploited conversely as well, which opens a way for potential application in the domain of temperature sensing.

1. Introduction

An important topic of recent research has been the investigation of the acoustic analog of surface electromagnetic waves, particularly surface plasmon polaritons, which occur at interfaces between highly conductive and dielectric media [1–4]. The principal difficulty in this general case is the apparent nonexistence of an acoustic analog of metals. However, it has been shown that, in the case of spoof plasmons [5–11], i.e. electromagnetic surface modes on highly conducting grooved surfaces, a corresponding acoustic phenomenon may exist in the form of an acoustic surface wave at the boundary between a fluid and a hard grooved surface [12–16]. The understanding of this analogy has opened up new ways of controlling the behavior of acoustic surface waves by tailoring the period, the width and the depth of the grooves. It has been shown that by varying the surface geometry in this way, the wave number of the propagating surface wave can be made different from its initial value $k_0$, even exceedingly large [17–21]. This has led to a number of applications such as sound trapping, where a gradient change of the surface texture has been introduced in order to slow down and finally ‘stop’ the surface wave at a desired position along the structure, or acoustic lensing, where it has been used to tailor the phase pattern of the surface wave [22]. However, the main drawback of the proposed techniques for manipulating acoustic surface waves is that the effect depends directly on the geometry of the grooves, and that it can thus be varied only through physical modifications of the geometry.

In this paper we demonstrate that an acoustic surface wave propagating at the interface between a fluid and a hard grooved surface can be efficiently controlled by varying only the temperature of the fluid, while the geometry of the grooved surface remains unchanged. This opens up a way for a number of potential new applications, all tunable by external means. Following the theoretical considerations, we further numerically demonstrate temperature-controlled sound trapping and its potentials in acoustic spectral analysis and temperature sensing. We also present a temperature-controlled gradient refractive index (GRIN) acoustic medium and apply it to achieve temperature-controlled acoustic focusing.
2. Temperature controlled propagation of acoustic surface waves

A typical example of a hard grooved surface used to support acoustic surface waves is shown in figure 1, where \(d\), \(a\), and \(h\) represent the period, the width and the depth of the grooves, respectively. It should be noted that the only relevant property of the substrate material is mechanical hardness, which prevents the grooved surface itself from vibrating.

When the period of the grooves is much smaller than the guided wavelength of the propagating acoustic surface wave, the grooved surface can be considered as an effective medium and characterized by an effective density tensor. For an acoustic surface wave propagating along the direction \(x\), the effective dispersion relation of such a medium is

\[
k_x = k_0 \sqrt{1 + \left(\frac{a}{d}\right)^2 \tan^2 \left(hk_0\right)},
\]

where \(k_0\) denotes the wavenumber in free space, considered here to be dry air and modeled as an ideal gas. To express the effective dispersion relation as a function of temperature, we first note that the wavenumber \(k_0\) in any ideal gas is the following function of temperature

\[
k_0(T) = \omega \sqrt{\frac{\rho_g(T)}{R T}},
\]

where \(\rho_g\) is the gas density, \(\kappa\) is the adiabatic constant and \(p\) is the pressure. From the ideal gas state equation, the gas density can be obtained as a function of temperature

\[
\rho_g(T) = \frac{p}{RT},
\]

where \(R\) denotes the specific gas constant, and \(T\) is the temperature in K. In case of dry air, \(\kappa = 1.4\), \(R = 827.05\ J\ kg^{-1} K^{-1}\) and \(p = 101325\ Pa\).

Finally, the effective wavenumber is obtained in the temperature dependent form as

\[
k_x(T) = \omega \sqrt{\frac{1}{RT}} \sqrt{1 + \left(\frac{a}{d}\right)^2 \tan^2 \left(h\omega \sqrt{\frac{1}{RT}}\right)}
\]

and plotted in figure 2 for a range of temperatures. It can be seen that, for a given temperature, the medium is almost non-dispersive at low frequencies (i.e. the wavenumber linearly varies with frequency). However, as frequency increases, strong dispersion occurs, the effective wavenumber asymptotically approaches infinity and finally a stop-band appears. Moreover, it can be seen that the frequency at which dispersion occurs and the position of the stop-band also depend on the temperature.

2.1. Experimental validation of concept

To validate the analytical solution given by (4), results of full-wave FEM simulations as well as of the experiment for the cases of \(T = 297\ K\) and \(T = 313\ K\) are also shown in figure 2. The FEM simulations were performed using COMSOL Multiphysics® 4.4 acoustic and heat transfer modules. Both 2D and 3D models were made to compare the responses of infinitely wide grooved surfaces and those with a finite width. The initial temperature in all simulations was defined as a constant value in the surrounding medium (air). The air was modeled as an ideal gas. The simulation was performed using two studies. In the first study the time domain was used and heat radiation sources radiated from a defined start time to a defined end time. The second study was performed in the frequency domain, with the acoustic plane wave source radiating at the defined frequency, while the temperature distribution of the medium was equal to the one observed in the first simulation study. Perfectly matched layers were assigned to the boundaries of the simulation domain in order to prevent any radiation from a reflected acoustic wave. The largest mesh element size was set to a value below 1/10 of the smallest wavelength. As for the experiment setup, the prototype, with dimensions \(d = 8\ mm\), \(a = 5\ mm\), \(h = 24\ mm\), length
L = 162 mm and width w = 40 mm, was fabricated in 3D printing technology using Felix 3.0 3D printer and PLA as filament material. Measurements were performed at controlled temperatures and pressures. The excitation signal was a 3000 s long linear chirp signal with instantaneous frequency ranging from 1 to 4 kHz, and the response of the system was recorded by two G.R.A.S. 46DP 1/8″ microphones at a fixed distance of $D = 8$ mm, using a PC with a sound card and Audacity software. The sampling frequency was 48 kHz, and the obtained signals were post-processed in MATLAB to recover their amplitudes and phases. The microphones were mounted through small holes in the structure from its reverse side, and aligned with the bottom surface of the grooves.

It can be seen that a very good agreement exists between the analytical, FEM and experimental results. Although (4) is strictly valid for infinitely wide grooved surfaces only, it has also been shown to hold for surfaces of finite width, as long as the width is sufficiently greater than the period of the grooves $d$ [10, 11]. Namely, experimental results for a grooved surface with finite overall width equal to $a = 5$ mm, $d = 8$ mm, and $h = 24$ mm, shown in figure 2, are in very good agreement with the results obtained for the infinite-width case.

The temperature dependence of the wavenumber $k_x$ and the phase velocity for the frequency of the propagating surface wave equal to $3400$ Hz is shown in figure 3. This frequency has been chosen arbitrarily within the range in which prominent dispersion occurs.

From figure 3 it can be seen that the wavenumber increases while wave velocity decreases with decreasing temperature, until the temperature reaches a critical value $T_c$ when the wavenumber rapidly increases, theoretically to infinity. Below $T_c$ no propagation can occur due to the fact that the group velocity is equal to zero. The critical temperature $T_c$ can be obtained from (4) as the following function of the operating frequency $f$ and the depth of the grooves $h$

$$T_c = \frac{16h^2f^2}{\kappa R}.$$  

(5)

For the operating frequency and geometrical parameters given above $T_c$ equals 265 K. It should be noted that the discussion above does not hold in the close vicinity of $T_c$, where the wavenumber becomes too large and the effective medium concept is inadequate since the guided wavelength becomes comparable with the period $d$. The effective media concept can be applied as long as the guided wavelength is larger than approximately $d/4$, i.e. $k_x < \pi/2d$. This sets the actual critical temperature $T'_c$ to a value somewhat above the theoretical value $T_c$, namely to the value at which $k_x = \pi/2d$. Although $k_x$ depends only on the ratio of $d$ and $a$, and not on their individual values, as shown in (4), $T'_c$ does depend on $d$. Figure 4, which compares three structures with a constant $d/a$ but with a different $d$, shows that although $T'_c$ is the same for all three structures, the corresponding values of $T'_c$ are different and can be obtained from $k_x(T'_c) = \pi/2d$.

Since the critical temperature depends on the operating frequency, for fixed geometry and temperature a theoretical maximal frequency $f'_c$ can be obtained from (5), above which waves cannot propagate. However, the actual critical frequency $f'_c$ is always below this value since the period of the grooves is not infinitesimally small and the maximum obtainable wavenumber is $\pi/2d$ rather than infinity. The dependence of the critical
frequency $f'_c$ on temperature is experimentally verified in figure 5, which shows the normalized sound pressure at an arbitrarily chosen point along the grooved surface, at two different temperatures.

The results presented above indicate that a good control of acoustic surface waves can be obtained by varying the temperature alone, while the grooved surface remains unchanged. This is illustrated in figure 6, where the acoustic pressure field distribution over a grooved surface is shown for four different values of the temperature of the surrounding medium. Even for relatively small temperature variations, the wavelength of the acoustic surface wave varies significantly for the same applied frequency ($f'_c$) taken here to be 3400 Hz. Namely, it changes from 40 to 14 mm when the temperature decreases from 303 to 283 K.

2.2. Acoustic surface wave trapping

The described phenomenon can also be considered from an alternative point of view: if the temperature of the surrounding medium decreases along the propagation direction, the acoustic surface wave slows down and ‘stops’ when the temperature reaches $T'_c$. In this way, an acoustic wave of a given frequency is trapped at any desired point along the surface, simply by controlling the temperature of the surrounding medium, instead of varying the surface geometry as in [19]. This is illustrated in figure 7, where three cases are shown, each obtained...
Figure 5. Normalized sound pressure drops significantly in the vicinity of the calculated critical frequency (shown in dotted lines for two different temperatures), which experimentally verifies the dependence of the critical frequency $f_c$ on temperature.

Figure 6. Acoustic pressure field distribution over a grooved surface with $d = 1$ mm, $a = 0.2$ mm, and $h = 24$ mm, revealing a strong dependence of the wavelength of the acoustic surface wave on the temperature of the surrounding medium $T$: (a) $T = 303$ K, (b) $T = 298$ K, (c) $T = 288$ K, (d) $T = 283$ K.

Figure 7. Acoustic surface wave can be trapped at an arbitrary location along the grooved surface, determined solely by the graded temperature of the surrounding medium. The dimensions of the grooved surface and the operating frequency are the same as in the previous example.
by using a different linear temperature gradient along the propagation direction (indicated by the right $y$-axis). In each case, the trapping occurs at a different position along the grooved surface, determined solely by the applied temperature gradient. We note here that temperature distributions other than linear can also be used.

The concept presented above lends itself to a number of potential applications. For example, spatial spectral analysis of acoustic surface waves can be realized, since for a fixed temperature gradient, surface waves of different frequencies will be trapped at different points along the surface, as demonstrated in figure 8. The resolution of such a spectrum analyzer is quite high: a frequency shift of only 1.5\% (i.e. 50 Hz) corresponds to a shift of as much as 82 mm in the position of the sound intensity peak. In practical applications, if a point microphone such as G.R.A.S. 46DP 1/8" with a diameter of 3.175 mm is used to measure normalized sound intensity, it will be possible to obtain a frequency resolution of only 1.9 Hz.

2.3. Temperature sensing using acoustic surface waves

Another application of the proposed concept would be temperature sensing (i.e. temperature mapping), where the temperature is estimated from the distribution of acoustic pressure on the grooved surface. To illustrate this numerically, let us consider a grooved surface with two radiation heat sources arbitrarily positioned along the surface. The corresponding temperature distribution in the stationary regime is shown in figure 9, together with the consequent distribution of the acoustic pressure at 3400 Hz. It can be seen that the guided wavelength increases with the temperature, due to the decreased wavenumber in warmer regions. Under the assumption that the temperature in a certain area is approximately constant, it can be uniquely estimated from the guided wavelength, which can in practice be readily determined from phase measurements at two close locations along the structure. To avoid the case where the phase difference includes a non-zero integer multiple of $2\pi$, the distance between measurement locations has to be smaller than the guided wavelength. For a given excitation frequency, the described temperature sensor thus functions in a certain temperature range, sufficient for some applications. However, by combining different excitation frequencies and measuring corresponding phase differences, this range can be expanded.

2.4. Acoustic surface wave bending and focusing

In all preceding applications, a temperature was varied along the direction of propagation of surface waves. However, a temperature variation can also be applied in a transverse direction, resulting in an acoustic graded-index (GRIN) medium. Let us consider a host medium composed of a $w = 500$ mm wide grooved surface, with the dimensions $d$, $a$ and $h$ as given above, and with a constant temperature of the surrounding medium of $T_0 = 306$ K. One section of length $l = 100$ mm of this medium is divided into 25 channels with individual widths of 20 mm, to each of which a different temperature is applied (figure 10). Since the width of each channel is 20 times larger than the surface period ($d = 1$ mm), the dispersion relation (1) is still usable.
Figure 9. Temperature sensing can be achieved by determining the wavelength of the acoustic wave propagating along the grooved surface.

Figure 10. Acoustic graded-index (GRIN) medium is realized when a temperature variation is applied in a transverse direction.

Figure 11. Required temperature distribution across the GRIN medium calculated to obtain $\theta = 15^\circ$ and $\theta = 30^\circ$ bending of incoming acoustic waves.
By applying different temperature distributions in the channels $T(y)$, different profiles of the refractive index of GRIN medium can be achieved, resulting in a range of effects, such as steering (i.e. bending) and focusing of acoustic waves.

To bend incoming acoustic waves for an arbitrary angle, the temperature distribution $T(y)$ is calculated by combining (4) and the corresponding refractive index profile given in [23]. The resulting temperature profiles are shown in figure 11 for two arbitrarily selected bending angles of $15^\circ$ and $30^\circ$.

The entire structure has been simulated, and ideal thermal isolation has been assumed between its different regions. The resulting acoustic pressure is shown in figure 12, demonstrating the bending of acoustic waves for a specified angle.

To achieve focusing of acoustic waves, hyperbolic secant refractive index profile is used [24], and the refractive index in the center of the structure is arbitrarily selected to be $n_0 = 1.8$. The calculated required temperature distribution across the GRIN medium is shown in figure 13. The resulting acoustic pressure distribution, shown in figure 14, clearly demonstrates that the focusing of acoustic waves has been achieved. Namely, a flat slab of GRIN medium behaves as an acoustic lens, controlled only by temperature.

3. Conclusion

We have numerically and experimentally shown that the temperature of the surrounding medium can be used to manipulate acoustic surface waves at the interface of a fluid and grooved hard surface in a variety of ways, through applications such as acoustic wave trapping, spatial spectral analysis of wideband acoustic waves, as well as acoustic wave steering and focusing. Unlike standard techniques for manipulation of acoustic surface waves, which require careful design of the surface geometry, this approach offers a simple solution, applicable to surfaces with uniform geometries and easily adaptable to any change in system specifications, thus allowing wave steering over variable paths or wave focusing with a variable focal length. Conversely, the same phenomenon can be used in the opposite direction, i.e., for sensing the temperature of the fluid through the behavior of the acoustic wave, which extends the field of its potential application even further.
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Figure 13. Required temperature distribution across the GRIN medium calculated to obtain acoustic wave focusing.

Figure 14. Simulation results for distributions of (a) acoustic pressure and (b) sound intensity, demonstrating the focusing of acoustic waves.
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