Forces acting on a small particle in an acoustical field in a thermoviscous fluid

Karlsen, Jonas Tobias; Bruus, Henrik

Published in:
Physical Review E

Link to article, DOI:
10.1103/physreve.92.043010

Publication date:
2015

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):
Forces acting on a small particle in an acoustical field in a thermoviscous fluid

Jonas T. Karlsen* and Henrik Bruus†

Department of Physics, Technical University of Denmark, DTU Physics Building 309, DK-2800 Kongens Lyngby, Denmark

(Received 3 July 2015; published 12 October 2015)

We present a theoretical analysis of the acoustic radiation force on a single small spherical particle, either a thermoviscous fluid droplet or a thermoelastic solid particle, suspended in a viscous and heat-conducting fluid medium. Within the perturbation assumptions, our analysis places no restrictions on the length scales of the viscous and thermal boundary-layer thicknesses \( \delta_s \) and \( \delta_t \) relative to the particle radius \( a \), but it assumes the particle to be small in comparison to the acoustic wavelength \( \lambda \). This is the limit relevant to scattering of ultrasound waves from nanometer- and micrometer-sized particles. For particles of size comparable to or smaller than the boundary layers, the thermoviscous theory leads to profound consequences for the acoustic radiation force. Not only do we predict forces orders of magnitude larger than expected from ideal-fluid theory, but for certain relevant choices of materials, we also find a sign change in the acoustic radiation force on different-sized but otherwise identical particles. These findings lead to the concept of a particle-size-dependent acoustophoretic contrast factor, highly relevant to acoustic separation of microparticles in gases, as well as to handling of nanoparticles in lab-on-a-chip systems.

DOI: 10.1103/PhysRevE.92.043010 PACS number(s): 47.35.Rs, 43.25.Qp, 43.20.Fn, 43.20.+g

I. INTRODUCTION

The acoustic radiation force is the time-averaged force exerted on a particle in an acoustical field due to scattering of the acoustic waves from the particle. Theoretical studies of the acoustic radiation force date back to King in 1934 [1] and Yosioka and Kawasima in 1955 [2], who considered the force on an incompressible and a compressible particle, respectively, in an inviscid ideal fluid. Their work was summarized and generalized in 1962 by Gorkov [3], with the analysis, however, still limited to ideal fluids and valid only for particles with a radius \( a \) much smaller than the acoustic wavelength \( \lambda \).

In subsequent work, Doinikov developed general theoretical schemes for calculating acoustic radiation forces including viscous and thermoviscous effects [4–6]. The direct applicability of these studies is hampered by the generality of the developed formalism, and analytical expressions are given only in the special limits of \( \delta_s \ll a \ll \lambda \) and \( a \ll \delta_s \ll \lambda \), where \( \delta_s \) is the boundary-layer thickness. Similarly, the work of Danilov and Mironov, including viscous effects, only provides analytical expressions in these two limits [7]. However, micrometer-sized particles in water at MHz frequency used in lab-on-a-chip systems for trapping [8–10] and separation [11–21], or in gases at kHz frequency used for separation [22–24] and levitation [25–28], often fall outside of these limits as \( \delta \sim a \ll \lambda \). For example, in water at 2 MHz the viscous and thermal boundary layers are of thickness \( \delta_s = 0.4 \mu m \) and \( \delta_t = 0.2 \mu m \), respectively, while in air at 50 kHz one finds \( \delta_s = 10 \mu m \) and \( \delta_t = 12 \mu m \). Consequently, the acoustic radiation force on nanometer- and micrometer-sized particles is not well described by the limited expressions for small and large boundary layers. The more general case of arbitrary viscous boundary-layer thicknesses compared to the particle size was subsequently studied analytically by Settnes and Bruus in the adiabatic limit where thermal boundary layers are neglected [29]. Their asymptotic study demonstrated that small changes in the scattered field may significantly affect the acoustic radiation force exerted on the particle. Since a thermal boundary layer may also lead to such changes for physically relevant parameters, an extension of the theory in Ref. [29] to include nonadiabatic effects from heat conduction is desirable. Moreover, it is also of interest to extend the treatment of compressible solid particles in Ref. [29] to include droplets or elastic particles for which viscous or elastic shear must be taken into account.

In this work we extend the radiation force theory for droplets and elastic particles to include the effect of both viscosity and heat conduction, thus accounting for the viscous and thermal boundary layers of thicknesses \( \delta_s \) and \( \delta_t \), respectively, and we give closed-form analytical expressions in the limit of \( \delta_s, \delta_t, a \ll \lambda \) with no further restrictions between \( \delta_s, \delta_t, a \). Our approach to the full thermoviscous scattering problem follows that of Epstein and Carhart from 1953 [30]. The scope of their work was a theory for the absorption of sound in emulsions such as water fog in air. In 1972, Allegra and Hawley further developed the theory to include elastic solid particles suspended in a fluid in order to calculate the attenuation of sound in suspensions and emulsions [31]. The seminal work of those authors has become known as ECAH theory within the field of ultrasound characterization of emulsions and suspensions, and combined with the multiple wave scattering theories of Refs. [32,33] it has been applied to calculate homogenized complex wave numbers of suspensions and emulsions [34,35].

The field of ultrasound characterization driven by engineering applications and the field of acoustic radiation forces have developed in parallel with little overlap. Indeed, the scopes of the work in the two fields are very different. In the works of Epstein and Carhart and Allegra and Hawley, there is no mention of acoustic radiation forces [30,31]. However, the underlying scattering problem of a particle suspended in a fluid remains the same, and having once solved for the amplitude of the propagating scattered wave, the acoustic radiation force on the particle may be obtained from a far-field calculation.
In the far field, the propagating scattered field changes when taking into account the thermoviscous scattering mechanisms, including boundary-layer losses and excitation of acoustic streaming in the vicinity of the particle. In this work we will elucidate this approach, as it leads to a particularly simple and valuable formulation for the acoustic radiation force in the long-wavelength limit [29].

Considering the success of the ECAH method to describe attenuation of sound in emulsions and suspensions, we can with great confidence apply the method to analyze the consequences of thermoviscous scattering on the acoustic radiation force. Nevertheless, we find a need to re-examine the problem of thermoviscous scattering in order to apply the theory to the problem of acoustic radiation forces in a clear and consistent manner. One point of clarification relates to an ambiguity in the thermoelastic solid theory presented by Allegra and Hawley [31], where no clear distinction is made between isothermal and adiabatic solid parameters, thus tacitly implying $\gamma = c_p/c_V = 1$ in solids. Here, we will provide a self-consistent treatment of thermoviscous scattering that clarifies this issue and allows easy comparison with existing acoustic radiation force theories.

Before proceeding with the mathematical treatment, we refer the reader to Fig. 1, which illustrates the physical mechanisms responsible for the monopole, dipole, and multipole scattering from a particle subject to a periodic acoustic field [35]. The final results for the acoustic radiation force are presented in terms of corrected expressions for the monopole and dipole scattering coefficients $f_0$ and $f_1$. This approach allows an easy comparison with ideal-fluid theory; moreover, as shown by Settnes and Bruus [29], it provides a simple way of evaluating acoustic radiation forces for any given incident acoustic field. To this end, Table I provides an overview of the equations needed to evaluate the thermoviscous acoustic radiation force on small droplets or solid particles.

**II. BASIC CONSIDERATIONS ON THE ACOUSTIC RADIATION FORCE**

We consider a single particle or droplet suspended in an infinite, quiescent fluid medium with no net body force, but perturbed by a time-harmonic acoustic field with angular frequency $\omega$. The density, velocity, and stress of the perturbed fluid is denoted $\rho$, $\mathbf{v}$, and $\mathbf{\sigma}$, respectively. The region $\Omega(t)$ occupied by the particle, its surface $\partial\Omega(t)$, and the outward-pointing surface vector $\mathbf{n}$ depend on time due to the acoustic field. The instantaneous acoustic radiation force is given by the surface integral of the fluid stress $\mathbf{\sigma}$ acting on the particle surface. However, since the short time scale corresponding to the oscillation period $\tau$ is not resolved experimentally, we define the acoustic radiation force $F^{\text{rad}}$ in the conventional time-averaged sense [1–4,7,29],

$$F^{\text{rad}} = \left\langle \oint_{\partial\Omega(t)} \mathbf{\sigma} \cdot \mathbf{n} \, da \right\rangle,$$

where the angled bracket denotes the time average over one oscillation period. Notice that this definition includes the acoustic streaming generated locally near the particle, since the stresses leading to this streaming are contained in the fluid stress tensor $\mathbf{\sigma}$. In contrast, by considering an infinite domain, we are excluding effects of what Danilov and Mironov refer to as external streaming [7], which would be generated at the boundaries of any finite domain. For a given finite domain, the external streaming can be calculated [36], and the total force acting on a particle is the sum of the radiation force and the external-streaming-induced Stokes drag. This approach

\begin{table}[h]
\centering
\begin{tabular}{lll}
\hline
\textbf{Size of particle and boundary layers} & $f_0$ & $f_1$ \\
\hline
\multicolumn{3}{l}{Thermoviscous droplet:} \\
Arbitrary-width boundary layers & Eq. (59) & Eq. (68) \\
Small-width boundary layers & Eq. (60) & Eq. (69) \\
Zero-width boundary layers & Eq. (61) & Eq. (72) \\
Point-particle limit & Eq. (62) & Eq. (73) \\
\multicolumn{3}{l}{Thermoelastic particle:} \\
Arbitrary-width boundary layers & Eq. (64) & Eq. (70) \\
Small-width boundary layers & Eq. (66) & Eq. (71) \\
Zero-width boundary layers & Eq. (67) & Eq. (72) \\
Point-particle limit & Eq. (65) & Eq. (73) \\
\hline
\end{tabular}
\end{table}
has been used in studies of particle trajectories and has been validated experimentally [37,38].

We consider a state, which is periodic in the acoustic oscillation period $\tau$, tantamount to requiring that any nonperiodic phenomenon, such as particle drift, is negligible within one oscillation period. Usually, this requirement is not very restrictive, as discussed in more detail in Sec. VII. For a time-periodic state, any field can be written as a Fourier series $f(r,t) = \sum_{n=0}^{\infty} f_n(r) e^{-i\omega n t}$, with $\omega = 2\pi/\tau$, and the time average of any total time derivative is zero, $\langle \frac{d}{dt} f(r,t) \rangle = 0$.

A useful expression for $F_{rad}$ is obtained by considering the momentum flux density $\sigma - \rho \mathbf{v} \mathbf{v}$ entering the fluid volume between the particle surface $\partial\Omega(t)$ and an arbitrary static surface $\partial\Omega_1$ enclosing the particle. The total momentum $P$ of the fluid in this volume is the volume integral of $\rho \mathbf{v}$, and because the net body force on the fluid is zero, the time-averaged rate of change $\langle \frac{d}{dt} P \rangle$ is

$$\langle \frac{d}{dt} P \rangle = \left( \oint_{\partial\Omega_1} (\sigma - \rho \mathbf{v} \mathbf{v}) \cdot \mathbf{n} \, da + \oint_{\partial\Omega(t)} \sigma \cdot (-\mathbf{n}) \, da \right)$$

$$= \left( \oint_{\partial\Omega_1} (\sigma - \rho \mathbf{v} \mathbf{v}) \cdot \mathbf{n} \, da - F_{rad} \right).$$

Here, $\mathbf{n}$ is the surface vector pointing out of $\partial\Omega_1$ (out of the fluid) and out of $\partial\Omega(t)$ (into the fluid). The advection term $\rho \mathbf{v} \mathbf{v}$ is zero at $\partial\Omega(t)$, since there is no advection of momentum through the interface of the particle. Finally, using that the time average of the total time derivative $\langle \frac{d}{dt} P \rangle$ is zero in the time-periodic system, we obtain

$$F_{rad} = \left( \oint_{\partial\Omega_1} (\sigma - \rho \mathbf{v} \mathbf{v}) \cdot \mathbf{n} \, da \right).$$

Thus, even before applying perturbation theory, the acoustic radiation force can be evaluated as the total momentum flux through any static surface $\partial\Omega_1$ enclosing the particle. To second order in the acoustic perturbation, the expansions $\rho = \rho_0 + \rho_1 + \rho_2$, $\mathbf{v} = \mathbf{0} + \mathbf{v}_1 + \mathbf{v}_2$, and $\sigma = \sigma_0 + \sigma_1 + \sigma_2$, the radiation force (3) becomes

$$F_{rad} = \oint_{\partial\Omega_1} (\sigma_2 - \rho_0(\mathbf{v}_1 \mathbf{v}_1)) \cdot \mathbf{n} \, da,$$

where we have used that the time average of the time-harmonic, first-order fields is zero.

In regions sufficiently far from acoustic boundary layers, the acoustic wave is a weakly damped propagating acoustic mode, for which viscous and thermal effects are negligible. Thus the result of Ref. [29], obtained by analytically integrating Eq. (4) by placing $\partial\Omega_1$ in the far field, remains valid in the thermoviscous case. In the long-wavelength limit, where the particle radius $a$ is assumed much smaller than the wavelength $\lambda$, i.e., for $ka < 1$ with $k_0 = 2\pi/\lambda$, it was shown that the acoustic radiation force may be evaluated directly from the incident first-order acoustic field and the expressions for the monopole and dipole scattering coefficients $f_0$ and $f_1$ for the suspended particle, as [29]

$$F_{rad} = -\pi a^3 \left[ \frac{2k_0}{3} \text{Re}[f_0^* P_m^* \nabla p_m] - \rho_0 \text{Re}[f_1^* \mathbf{v}_m^* \nabla \mathbf{v}_m] \right].$$

This generalization of Eq. (5) provides a way to evaluate the acoustic radiation force on a single particle regardless of the complexity of the incident field.

III. THERMOVISCOUS PERTURBATION THEORY OF ACOUSTICS IN FLUIDS

The starting point of the theory is the first law of thermodynamics and the conservation of mass, momentum, and energy. Introducing the thermodynamic variables temperature $T$, pressure $p$, density $\rho$, internal energy $\varepsilon$ per mass unit, entropy $s$ per mass unit, and volume per mass unit 1/$\rho$, the first law of thermodynamics with $s$ and $\rho$ as independent variables becomes

$$d\varepsilon = T \, ds - p \, d\left( \frac{1}{\rho} \right) = T \, ds + \frac{p}{\rho^2} \, d\rho.$$

For acoustic wave propagation it is often convenient to use $T$ and $p$ as independent thermodynamic variables. This is obtained by a Legendre transformation of the internal energy $\varepsilon$ per unit mass to the Gibbs free energy $g$ per unit mass, $g = \varepsilon - TS + \frac{p}{\rho} S$.

Besides the first law of thermodynamics, the governing equations of thermoviscous acoustics require the introduction
of the velocity field $\mathbf{v}$ and the stress tensor $\sigma$ of the fluid. The latter can be expressed in terms of $\rho$, $p$, the dynamic shear viscosity $\eta$, the bulk viscosity $\eta^b$, and the viscosity ratio $\beta = \eta^b/\eta + 1/3$, as

$$\sigma = -p \mathbf{I} + \tau,$$  \hspace{1cm} (8a)

$$\tau = \eta [\nabla \mathbf{v} + (\nabla \mathbf{v})^T] + (\beta - 1)\eta(\nabla \cdot \mathbf{v}) \mathbf{I}. \hspace{1cm} (8b)$$

Here, $\mathbf{I}$ is the unit tensor and the superscript “T” indicates tensor transposition. The tensor $\tau$ is the viscous part of the stress tensor assuming a Newtonian fluid [39].

Considering the fluxes of mass, momentum, and energy into a small test volume, we use Gauss’s theorem to formulate the general governing equations for conservation of mass, momentum, and energy in the fluid under the assumption of no net body forces and no heat sources,

$$\partial_t \rho = \nabla \cdot [-\rho \mathbf{v}], \hspace{1cm} (9a)$$

$$\partial_t (\rho \mathbf{v}) = \nabla \cdot [\rho (\mathbf{v} - \mathbf{v})], \hspace{1cm} (9b)$$

$$\partial_t (\rho \mathbf{v}^2) = \nabla \cdot \left[ \rho \mathbf{v} \cdot \mathbf{v} + k_{th} \nabla T - \rho (\mathbf{v} + \frac{1}{2} \mathbf{v}^2) \right]. \hspace{1cm} (9c)$$

Here, we have introduced the thermal conductivity $k_{th}$ assuming the usual linear form for the heat flux given by Fourier’s law of heat conduction.

### A. First-order equations for fluids

The zeroth-order state of the fluid is quiescent, homogeneous, and isotropic. Then, treating the acoustic field as a perturbation of this state in the acoustic perturbation parameter $\varepsilon_{ac}$, given by

$$\varepsilon_{ac} = \frac{|\rho_1|}{\rho_0} \ll 1, \hspace{1cm} (10)$$

we expand all fields as $g = g_0 + g_1$, but with $v_0 = 0$. The zero-th order terms drop out of the governing equations, while the first-order mass, momentum, and energy equations obtained from Eqs. (7) and (9) become

$$\partial_t \rho_1 = -\rho_0 \nabla \cdot \mathbf{v}_1, \hspace{1cm} (11a)$$

$$\rho_0 \partial_t \mathbf{v}_1 = -\nabla p_1 + \eta_0 \nabla^2 \mathbf{v}_1 + \beta \eta_0 \nabla(\nabla \cdot \mathbf{v}_1), \hspace{1cm} (11b)$$

$$\rho_0 T_0 \partial_t s_1 = k_{th} \nabla^2 T_1. \hspace{1cm} (11c)$$

It will prove useful to eliminate the variables $p_1$, $\rho_1$, and $s_1$ to end up with only two equations for the variables $v_1$ and $T_1$. To this end, we combine Eq. (11) with the two thermodynamic equations of state $\rho = \rho(\rho, T)$ and $s = s(\rho, T)$. The total differentials of $\rho$ and $s$ are

$$d\rho = \left( \frac{\partial \rho}{\partial \rho} \right)_T dp + \left( \frac{\partial \rho}{\partial T} \right)_\rho dT, \hspace{1cm} (12a)$$

$$ds = \left( \frac{\partial s}{\partial \rho} \right)_T dp + \left( \frac{\partial s}{\partial T} \right)_\rho dT, \hspace{1cm} (12b)$$

which may be linearized so that the partial derivatives of $\rho$ and $s$ refer to the unperturbed state of the fluid. This leads to the introduction of the isothermal compressibility $\kappa_T$, the isobaric thermal expansion coefficient $\alpha_p$, and the specific heat capacity at constant pressure $c_p$,

$$\kappa_T = \frac{1}{\rho} \left( \frac{\partial \rho}{\partial T} \right)_p, \hspace{1cm} \alpha_p = -\frac{1}{\rho} \left( \frac{\partial p}{\partial T} \right)_\rho, \hspace{1cm} c_p = T \left( \frac{\partial s}{\partial T} \right)_\rho \hspace{1cm} (13)$$

Moreover, $(d s / d p)_T = -\alpha_p / \rho$, which may be derived as a Maxwell relation differentiating $g$ after $p$ and $T$. Thus, the linearized form of Eq. (12) is

$$p_1 = \rho_0 \kappa_T p_1 - \rho_0 \alpha_p T_1, \hspace{1cm} (14a)$$

$$s_1 = \frac{c_p}{T_0} T_1 - \frac{\alpha_p}{\rho_0} p_1. \hspace{1cm} (14b)$$

We further introduce the isentropic compressibility $\kappa_s$ and the specific heat capacity at constant volume $c_v$, $\kappa_s = 1 / \rho (\partial \rho / \partial T)_s$, $c_v = T (\partial s / \partial T)_v$. Then the following two well-known thermodynamic identities may be derived [40]:

$$\kappa_T = \gamma \kappa_s, \hspace{1cm} \gamma \equiv \frac{c_p}{c_v} = 1 + \frac{\alpha_p^2 T_0}{\rho_0 \alpha_p \kappa_T}. \hspace{1cm} (15)$$

To proceed with the reduction of Eq. (11), we first differentiate Eq. (11b) with respect to time and substitute $\nabla^2 \mathbf{v}_1 = \nabla(\nabla \cdot \mathbf{v}_1) - \nabla \times \nabla \times \mathbf{v}_1$. Then, Eq. (14a) is used to eliminate $p_1$ and $s_1$ in Eqs. (11b) and (11c), followed by elimination of $\partial_1 \rho_1$ using Eq. (11a). The resulting equations for $v_1$ and $T_1$ are

$$\partial_t v_1 - \left( \frac{1}{\rho_0 \kappa_T} + (1 + \beta)v_0 \partial_t \right) \nabla(\nabla \cdot v_1) + v_0 \partial_t \nabla \times \nabla \times v_1 = -\frac{\alpha_p}{\rho_0 \kappa_T} \partial_t \nabla T_1, \hspace{1cm} (17a)$$

$$\gamma D_0 \nabla^2 T_1 - \partial_t T_1 = \frac{\gamma - 1}{\alpha_p} \nabla \cdot v_1, \hspace{1cm} (17b)$$

where we have introduced the momentum diffusion constant $v_0$ and the thermal diffusion constant $D_0$,

$$v_0 = \frac{\eta_0}{\rho_0}, \hspace{1cm} D_0 = \frac{k_{th}}{\rho_0 c_p}. \hspace{1cm} (18)$$

### B. Potential equations for fluids

The velocity field $\mathbf{v}_1$ is decomposed into the gradient of a scalar potential $\phi$ (the longitudinal component) and the rotation of a divergence-free vector potential $\mathbf{v}$ (the transverse component),

$$\mathbf{v}_1 = \nabla \phi + \nabla \times \mathbf{v}, \hspace{1cm} \nabla \cdot \mathbf{v} = 0. \hspace{1cm} (19)$$

Inserting this well-known Helmholtz decomposition into Eq. (17a) leads to the equation

$$\nabla \left[ \partial_t^2 \phi - \left( \frac{1}{\rho_0 \kappa_T} + (1 + \beta)v_0 \partial_t \right) \nabla^2 \phi + \frac{\alpha_p}{\rho_0 \kappa_T} \partial_t T_1 \right] = \nabla \times \left[ -\partial_t^2 \mathbf{v} + v_0 \partial_t \nabla^2 \mathbf{v} \right]. \hspace{1cm} (20)$$
In general, both sides of the equation must vanish separately, which leads to two equations. Combining these with Eq. (17b), into which Eq. (19) is inserted, leads to the following form of Eq. (17):

\[ \dot{\alpha}^2 \phi = \left( \frac{1}{\rho_0 \kappa T} + (1 + \beta) \nu_0 \partial_t \right) \nabla^2 \phi - \frac{\alpha_p}{\rho_0 \kappa T} \partial_t T, \tag{21a} \]

\[ \partial_t T_i = \gamma D_h \nabla^2 T_i - \frac{\gamma - 1}{\alpha_p} \nabla^2 \phi, \tag{21b} \]

\[ \partial_t \psi = \nu_0 \nabla^2 \psi. \tag{21c} \]

In the adiabatic limit, for which \( D_h = 0 \), the well-known adiabatic wave equation for \( \phi \) is obtained by inserting Eq. (21b) into (21a), from which the adiabatic speed of sound \( c \) for longitudinal waves is deduced,

\[ c = \sqrt{\frac{1}{\rho_0 \kappa T}}. \tag{22} \]

In the isothermal case, for which \( T_i = 0 \), the wave equation (21a) instead describes waves traveling at the isothermal speed of sound \( c/\sqrt{T} = 1/\sqrt{\rho_0 \kappa T} \). For ultrasound acoustics, sound propagation in the bulk of a fluid is generally very close to being adiabatic.

IV. THERMOELASTIC THEORY OF ACOUSTICS IN ISOTROPIC SOLIDS

A thermoelastic solid may be deformed by the action of applied forces or on account of thermal expansion. Following Landau and Lifshitz [41], we describe the deformation of a solid elastic body using the displacement field \( u \), which describes the displacement \( u(r,t) \) of a solid element away from its initial, undeformed position \( r \) to its new temporary position \( r + u(r,t) \). Any displacement away from equilibrium gives rise to internal stresses tending to return the body to equilibrium. These forces are described using the stress tensor \( \sigma \), which leads to the force density \( \nabla \cdot \sigma \). In the description of the thermodynamics of solids, it is advantageous to work with per-volume quantities denoted by uppercase letters, in contrast to the per-mass quantities given by lowercase letters. The first law of thermodynamics reads

\[ d \mathcal{E} = T \, dS + \sigma_{ij} \, du_{ij}, \tag{23} \]

where \( \mathcal{E} \) is the internal energy per unit volume, \( S \) is the entropy per unit volume, and \( T \) is the temperature. The work done by the internal stresses per unit volume is equal to \(-\sigma_{ij} \, du_{ij}\), where we have introduced the strain tensor \( u_{ij} \), which for small displacements is given by

\[ u_{ij} = \frac{1}{2} \left[ \partial_i u_j + \partial_j u_i \right]. \tag{24} \]

Transforming the internal energy per unit volume \( \mathcal{E} \) to the Helmholz free energy per unit volume \( F = \mathcal{E} - TS \), where temperature \( T \) and strain \( u_{ij} \) are the independent variables, the first law becomes \( dF = -S \, dt + \sigma_{ij} \, du_{ij} \).

Consider the undeformed state of an isotropic, thermoelastic solid at temperature \( T_0 \) in the absence of external forces. The free energy \( F \) is then given as an expansion in powers of the temperature difference \( T - T_0 \) and the strain tensor \( u_{ij} \).

To linear order, the stress tensor \( \sigma_{ij} = (\frac{\delta F}{\delta u_{ij}}) \) and the entropy \( S = -(\frac{\delta F}{\delta T})_u \) become

\[ \sigma_{ij} = -\alpha_p (T - T_0) \delta_{ij} + \frac{E}{1 + \sigma} \left[ u_{ij} + \frac{\sigma}{1 - 2\sigma} u_{kk} \delta_{ij} \right], \tag{25a} \]

\[ S(T) = S_0(T) + \frac{\alpha_p}{\kappa} u_{kk}, \tag{25b} \]

where \( S_0(T) \) is the entropy of the undeformed state at temperature \( T \), while \( E \) and \( \sigma \) are the isothermal Young’s modulus and Poisson’s ratio, respectively. The isothermal compressibility \( \kappa \) of the solid is given in terms of \( E \) and \( \sigma \) as

\[ \kappa = 3(1 - 2\sigma) \frac{1}{E}. \tag{26} \]

A. Linear equations for solids

In elastic solids, advection of momentum and heat cannot occur, so the momentum equation in the absence of body forces takes the linear form \( \rho \dot{\delta}^2 u = \nabla \cdot \sigma \). Assuming the material parameters \( \alpha_p \), \( \gamma \), \( E \), and \( \sigma \) to be constant, it becomes

\[ \rho \dot{\delta}^2 u = -\frac{\alpha_p}{\kappa} \nabla T + \frac{E}{2(1 + \sigma)} \left[ \nabla^2 u + \frac{1 - 2\sigma}{1 - 2\sigma} \nabla (\nabla \cdot u) \right], \tag{27} \]

where we have introduced the isothermal speed of sound of longitudinal waves \( c_\text{L} \) and of transverse waves \( c_\text{T} \).

\[ c_\text{L}^2 = \frac{(1 - \sigma)}{(1 + \sigma)(1 - 2\sigma)} \frac{E}{\rho}, \quad c_\text{T}^2 = \frac{1}{2(1 + \sigma)} \frac{E}{\rho}. \tag{28a} \]

Using the decomposition \( u = u_\text{T} + u_\text{L} \) in the transverse and longitudinal displacements \( u_\text{T} \) and \( u_\text{L} \) with \( \nabla \cdot u_\text{T} = 0 \) and \( \nabla \times u_\text{L} = 0 \), respectively, it immediately follows from Eq. (27) that in the isothermal case, transverse and longitudinal waves travel at the speed \( c_\text{T} \) and \( c_\text{L} \), respectively. Combining Eqs. (26) and (28a) one obtains an important relation connecting the isothermal compressibility \( \kappa \) of the solid to the isothermal sound speeds \( c_\text{L} \) and \( c_\text{T} \).

\[ \frac{1}{\kappa} = c_\text{L}^2 - \frac{4}{3} c_\text{T}^2. \tag{28b} \]

Turning to the energy equation, the amount of heat absorbed per unit time per unit volume is \( T (\delta S) \). If there are no heat sources in the bulk, the rate of heat absorbed is given by the influx \(-k_\text{h} \nabla T\) of heat by conduction, and the heat equation thus becomes

\[ T (\delta S) = -\nabla \cdot [-k_\text{h} \nabla T] = k_\text{h} \nabla^2 T, \tag{29} \]

where the heat conductivity \( k_\text{h} \) is taken to be constant. We rewrite this equation using expression (25b) for the entropy, and using that the time derivative of \( S_0 \) may be written as

\[ \frac{\partial S_0}{\partial t} = \left( \frac{\partial S_0}{\partial T} \right)_V \frac{\partial T}{\partial t} = \frac{C_V}{T} \frac{\partial T}{\partial t}, \tag{30} \]

where the heat capacity \( C_V \) per unit volume at constant volume enters through the relation \( C_V = T (\delta S_0/\delta T)_V \) with the
derivative taken for the undeformed state at constant volume, that is, for \( u_{ik} = \nabla \cdot u = 0 \). Combining these considerations with the identity for \( \gamma \) equivalent to Eq. (16), the heat equation (29) becomes

\[
C_V \frac{\partial t}{\partial T} + \frac{\gamma - 1}{\alpha_p} C_V \nabla \cdot u = k_0 \nabla^2 T. \tag{31}
\]

Finally, having eliminated all extensive thermodynamic variables, we return to per-mass quantities, such as \( c_V = C_V / \rho \), and thus arrive at the coupled equations for thermoelastic solids,

\[
\begin{align*}
\partial_t^2 u_1 - c_L^2 \nabla (\nabla \cdot u_1) + c_L^2 \nabla \times \nabla \times u_1 &= -\frac{\alpha_p}{\rho \kappa_T} \nabla \Gamma_1, \\
\gamma D_{th} \nabla^2 T_1 - \partial_t T_1 &= \frac{\gamma - 1}{\alpha_p} \nabla \cdot u_1,
\end{align*} \tag{32a}
\]

with \( \gamma \) and \( D_{th} \) defined in Eqs. (16) and (18), and the linearity emphasized by the addition of subscripts “1” to the field variables. In this form, the thermoelastic equations (32) correspond to the fluid equations (17).

**B. Potential equations for solids**

The time derivative \( \partial_t u_1 \) of the displacement field \( u_1 \) describes the velocity field in the solid. Analogous to the fluid case, we make a Helmholtz decomposition of this velocity field in terms of the velocity potentials \( \phi \) and \( \psi \)

\[
\partial_t u_1 = \nabla \phi + \nabla \times \psi, \text{ with } \nabla \cdot \psi = 0. \tag{33}
\]

Inserting this into Eq. (32) and following the procedure leading to Eq. (21) for fluids, we obtain the corresponding three equations for solids:

\[
\begin{align*}
\partial_t^2 \phi &= c_L^2 \nabla^2 \phi - \frac{\alpha_p}{\rho \kappa_T} \partial_t \Gamma_1, \tag{34a} \\
\partial_t \Gamma_1 &= \gamma D_{th} \nabla^2 \Gamma_1 - \frac{\gamma - 1}{\alpha_p} \nabla^2 \phi, \tag{34b} \\
\partial_t^2 \psi &= c_L^2 \nabla^2 \psi. \tag{34c}
\end{align*}
\]

The main difference between the fluid and the solid case is in Eq. (34c) for the vector potential \( \psi \), which now takes the form of a wave equation describing transverse waves traveling at the transverse speed of sound \( c_T \) instead of the diffusion equation (21c).

The usual adiabatic wave equation for the scalar potential \( \phi \) is obtained in the limit of \( D_{th} = 0 \) combining Eqs. (34a) and (34b), and the speed \( c \) of adiabatic, longitudinal wave propagation in an elastic solid becomes

\[
c^2 = c_L^2 + \frac{\gamma - 1}{\rho \kappa_T}. \tag{35}
\]

For most solids, \( \gamma - 1 \ll 1 \), leading to a negligible difference between the isothermal \( c_L \) and the adiabatic \( c \), the latter being closest to the actual speed of sound measured in ultrasonic experiments.

**V. UNIFIED POTENTIAL THEORY OF ACOUSTICS IN FLUIDS AND SOLIDS**

The similarity between the potential equations (21) and (34) allows us to write down a unified potential theory of acoustics in thermoviscous fluids and thermoelastic solids. The main result of this section is the derivation of three wave equations with three distinct wave numbers corresponding to three modes of wave propagation, namely, two longitudinal modes describing propagating compressional waves and damped thermal waves and one transverse mode describing a shear wave, which is damped in a fluid but propagating in a solid.

We work with the first-order fields in the frequency domain considering a single frequency \( \omega \). Using complex notation, we write any first-order field \( g_1(\mathbf{r}, t) \) as

\[
g_1(\mathbf{r}, t) = g_1(\mathbf{r}) e^{-i \omega t}. \tag{36}
\]

Assuming this form of time-harmonic first-order field, Eqs. (21a) and (34a) lead to expressions for the temperature field \( T_1 \) in a fluid (f) and a solid (s), respectively, in terms of the corresponding scalar potential \( \phi \)

\[
\begin{align*}
T_1^f &= \frac{i \alpha_p \sqrt{\kappa T}}{\alpha_p} \left[ \phi + c_f^2 \frac{1}{\omega^2} - \frac{1}{\alpha_p} \nabla^2 \phi \right], \tag{37a} \\
T_1^s &= \frac{i \alpha_p \sqrt{\kappa T}}{\alpha_p} \left[ \phi + c_s^2 \frac{1}{\omega^2} \nabla^2 \phi \right]. \tag{37b}
\end{align*}
\]

Here, we have introduced the dimensionless bulk damping factor \( \Gamma_1 = \frac{1}{\alpha_p} \) accounting for viscous dissipation in the fluid. For convenience, we also introduce the thermal damping factor \( \Gamma_1 = D_{th} \) accounting for dissipation due to heat conduction both in fluids and in solids. These two bulk damping factors are given by

\[
\Gamma_1 = \frac{1 + \beta_0 \alpha_p}{c^2}, \quad \Gamma_1 = \frac{D_{th} \alpha_p}{c^2}. \tag{38}
\]

Substituting expression (37a) for \( T_1^f \) into Eq. (21b), or expression (37b) for \( T_1^s \) into Eq. (34b), and assuming time-harmonic fields [Eq. (36)], we eliminate the temperature field and obtain a biharmonic equation for the scalar potential \( \phi \)

\[
\alpha_s \nabla^2 \nabla^2 \phi + \beta_s k_0^2 \nabla^2 \phi + k_0^2 \phi = 0, \quad \text{with} \quad k_0 = \frac{\omega}{c}, \tag{39a}
\]

where we have introduced the undamped adiabatic wave number \( k_0 = \omega / c \), and where the parameters \( \alpha_s \) and \( \beta_s \) for fluids (xL = f) and solids (xL = s) are

\[
\alpha_s = -i(1 - \gamma \Gamma_1), \quad \beta_s = 1 - (\Gamma_1 + \gamma \Gamma_1), \tag{39b}
\]

\[
\alpha_s = -i(1 + \alpha_s), \quad \beta_s = 1 - i \gamma \Gamma_1. \tag{39c}
\]

Here, we have used relation (35) for solids and further introduced the parameters \( X \) and \( \chi \),

\[
X = (\gamma - 1)(1 - \chi), \tag{39d}
\]

\[
\chi = \frac{1}{\rho_0 \kappa_T c^2} = 1 - \frac{4 c_f^2}{3 c^2}, \tag{39e}
\]

the latter equality following from combining Eq. (35) with Eq. (28b) and using \( \kappa_T = \gamma \kappa_T \) from Eq. (16). Note that for fluids, \( \chi = 1, c_T = 0 \), and \( X = 0 \).
The biharmonic equation (39a) is factorized and written on the equivalent form

\[(\nabla^2 + k_c^2)(\nabla^2 + k_t^2)\phi = 0,\]  \hspace{1cm} (40a)

and thus the wave numbers \(k_c\) and \(k_t\) are obtained from

\[k_c^2 = 2k_0^2\left[\beta_{sl} + (\beta_{sl}^2 - 4\alpha_{sl})^{1/2}\right]^{-1},\]  \hspace{1cm} (40b)

\[k_t^2 = 2k_0^2\left[\beta_{sl} - (\beta_{sl}^2 - 4\alpha_{sl})^{1/2}\right]^{-1},\]  \hspace{1cm} (40c)

with \(\text{"xl"}\) being either \(\text{"fl"}\) for fluids or \(\text{"sl"}\) for solids.

In the frequency domain, the equation for the vector potential \(\Psi\), Eq. (21c) for fluids and Eq. (34c) for solids, can be written as \(\nabla^2\Psi + k_0^2\Psi = 0\), which describes a transverse shear mode with shear wave number \(k_s\). By introducing a shear constant \(\eta_0\), which for a fluid is the dynamic viscosity, and for a solid is defined as

\[\eta_0 = i\frac{\beta_0\omega^2}{\omega} \text{ (solid)},\]  \hspace{1cm} (41a)

the shear wave number \(k_s\) is given by the same expression for both fluids and solids,

\[k_s^2 = \frac{10p\rho_0}{\eta_0} \text{ (fluid and solid)}.\]  \hspace{1cm} (41b)

A. Wave equations and modes

The general solution \(\phi\) of the biharmonic equation (40a) is the sum

\[\phi = \phi_c + \phi_t\]  \hspace{1cm} (42)

of the two potentials \(\phi_c\) and \(\phi_t\), which satisfy the harmonic equations

\[\nabla^2\phi_c + k_c^2\phi_c = 0,\]  \hspace{1cm} (43a)

\[\nabla^2\phi_t + k_t^2\phi_t = 0,\]  \hspace{1cm} (43b)

where \(\phi_c\) describes a compressional propagating mode with wave number \(k_c\), while \(\phi_t\) describes a thermal mode with wave number \(k_t\). These two scalar wave equations together with the vector wave equation for \(\Psi\), describing the shear mode with wave number \(k_s\),

\[\nabla^2\Psi + k_s^2\Psi = 0,\]  \hspace{1cm} (43c)

comprise the full set of first-order equations in potential theory. These wave equations, coupled through the boundary conditions, govern acoustics in thermoviscous fluids and thermoelastic solids. The distinction between fluids and solids is to be found solely in the wave numbers of the three modes.

1. Approximate wave numbers for fluids

For most systems of interest, \(\Gamma_s, \Gamma_t \ll 1\) allowing a simplification of the expressions for \(k_c\) and \(k_t\) in Eq. (40). To first order in \(\Gamma_s\) and \(\Gamma_t\) one finds

\[k_c = \frac{\omega}{c}\left[1 + \frac{i}{2}(\gamma - 1)\Gamma_t\right],\]  \hspace{1cm} (44a)

\[k_t = \frac{(1 + i)}{\delta_t}\left[1 + \frac{i}{2}(\gamma - 1)(\Gamma_t - \Gamma_s)\right],\]  \hspace{1cm} (44b)

\[k_s = (1 + i)\frac{\delta_t}{\delta_s},\]  \hspace{1cm} (44c)

where we have introduced the thermal diffusion length \(\delta_t\) and the momentum diffusion length \(\delta_s\). Heat and momentum diffuses from boundaries, such that the characteristic thicknesses of the thermal and viscous boundary layers are \(\delta_t\) and \(\delta_s\), respectively, given by

\[\delta_t = \sqrt{\frac{2D_t}{\omega}}, \quad \delta_s = \sqrt{\frac{2\nu_t}{\omega}}.\]  \hspace{1cm} (45)

For water at room temperature and 2 MHz frequency, \(\delta_t \approx 0.4 \mu m, \delta_s \approx 0.2 \mu m, \text{ and } \lambda \approx 760 \mu m\). Consequently, the length scales of the thermal and viscous boundary-layer thicknesses are the same order of magnitude and much smaller than the acoustic wavelength. With \(k_0 = \omega/c\) we note that

\[\Gamma_s = \frac{1}{2}(1 + \beta)(k_0\delta_s)^2, \quad \Gamma_t = \frac{\chi}{\Gamma_{10}}(k_0\delta_t)^2,\]  \hspace{1cm} (46)

and consequently

\[\Gamma_s \sim (k_0\delta_t)^2 \sim \frac{k_c^2}{k_s^2} \ll 1,\]  \hspace{1cm} (47a)

\[\Gamma_t \sim (k_0\delta_s)^2 \sim \frac{k_t^2}{k_s^2} \ll 1.\]  \hspace{1cm} (47b)

In the long-wavelength limit of the scattering theory to be developed, we expand to first order in \(k_0\delta_t\) and \(k_0\delta_s\), and thus neglect the second-order quantities \(\Gamma_s\) and \(\Gamma_t\). For water at room temperature and MHz frequency one finds \(k_0\delta_t \sim k_0\delta_s \sim 10^{-3}\), and \(\Gamma_s \sim \Gamma_t \sim 10^{-6}\).

Clearly, the compressional mode with wave number \(k_c\) describes a weakly damped propagating wave with \(\text{Im}[k_c] \ll \text{Re}[k_c] \approx \omega/c\). In contrast, \(\text{Im}[k_c] \approx \text{Re}[k_c]\) for the thermal mode and \(\text{Im}[k_c] = \text{Re}[k_c]\) for the shear mode, which correspond to waves that are damped within their respective wavelengths. Hence, these modes describe boundary layers near interfaces of walls and particles, which decay exponentially away from these interfaces on the length scales set by \(\delta_t\) and \(\delta_s\).

2. Approximate wave numbers for solids

Similar to the fluid case, we use the smallness of the thermal damping factor, \(\Gamma_t \ll 1\), to expand the exact wave numbers of Eq. (40). To first order we obtain

\[k_c = \frac{\omega}{c}\left[1 + \frac{i}{2}X\Gamma_t\right],\]  \hspace{1cm} (48a)

\[k_t = \frac{(1 + i)}{\delta_t}\frac{1}{\sqrt{1 - X}}\left[1 + \frac{i}{8}(\gamma^2\Gamma_t)X\right],\]  \hspace{1cm} (48b)

\[k_s = \frac{\omega}{c\Gamma_t},\]  \hspace{1cm} (48c)
An important distinction between a fluid and a solid is that a solid allows propagating transverse waves while a fluid does not. This is evident from the shear mode wave number \(k_s\), which for solids is purely real, \(k_s = \omega/c_v\), while for fluids \(\text{Im}[k_s] = \text{Re}[k_s] = 1/\delta_s\).

### B. Acoustic fields from potentials

For a given thermoacoustic problem, the boundary conditions are imposed on the acoustic fields \(v_1, T_1, \) and \(\sigma_1\) and not directly on the potentials \(\phi_\epsilon, \phi_\delta, \) and \(\psi\). We therefore need expressions for the acoustic fields in terms of the potentials in order to derive the boundary conditions for the latter.

The velocity fields follow trivially from the Helmholtz decompositions and are obtained from the same expression in both fluids and solids:

\[
v_1 = \nabla(\phi_\epsilon + \phi_\delta) + \nabla \times \psi,
\]

where \(v_1 = -i\omega \text{out}_1\) for solids.

A single expression for \(T_1\) in terms of \(\phi_\epsilon\) and \(\phi_\delta\), valid for both fluids and solids, is obtained from Eq. (37) in combination with Eqs. (40)–(43) by introducing the material-dependent parameters \(b_c\) and \(b_t\):

\[
T_1 = b_c \phi_\epsilon + b_t \phi_\delta,
\]

\[
b_c = \frac{i \alpha (\gamma - 1)}{\alpha \rho c^2}, \quad b_t = \frac{1}{\chi \alpha_p D_h}.
\]

Here, we have neglected \(\Gamma_s, \Gamma_t\) relative to unity. Note that the ratio \(b_c/b_t \sim \Gamma_s < 1\).

In a fluid, the pressure field \(p_1\) is obtained by inserting Eq. (19) into the momentum equation (11b) and using the wave equations (43):

\[
p_1 = i \omega \rho_0 (\phi_\epsilon + \phi_\delta) - (1 + \beta) \eta_0 (k_c^2 \phi_\epsilon + k_s^2 \phi_\delta).
\]

Inserting this expression into Eq. (8a), the stress tensor for fluids becomes

\[
\sigma_1 = \eta_0 \left[(2k_c^2 - k_s^2) \phi_\epsilon + (2k_c^2 - k_s^2) \phi_\delta\right] I
+ \eta_0 [i \nabla v_1 + (\nabla v_1)^T],
\]

where \(v_1\) can be expressed by the potentials through Eq. (49). This expression also holds true for the solid stress tensor in Eq. (25a) using the shear constant \(\eta_0\), Eq. (41a), and the velocity field \(v_1 = -i\omega \text{out}_1\), Eq. (33). This conclusion is obtained by inserting Eq. (37b) for \(T_1^{th}\) into Eq. (25a) for \(\sigma_1\) and using the wave equations (43).

### VI. SCATTERING FROM A SPHERE

The potential theory allows us in a unified manner to treat linear scattering of an acoustic wave on a spherical particle, consisting of either a thermoelastic solid or a thermoviscous fluid. The system of equations describing the general case of an arbitrary particle size is given, and analytical solutions are provided in the long-wavelength limit \(a, \delta_s, \delta_t \ll \lambda\). In this limit, the particle and boundary layers are much smaller than the acoustic wavelength, but the ratios \(\delta_s/a\) and \(\delta_t/a\) are unrestricted. This is essential for applying our results to micro- and nanoparticle acoustophoresis. In particular, we derive analytical expressions for the monopole and dipole scattering coefficients \(f_0\) and \(f_1\), which together with the incident acoustic field serve to calculate the acoustic radiation force as shown in Sec. II and summarized in Table I.

#### A. System setup

We place the spherical particle of radius \(a\) at the center of the coordinate system and use spherical coordinates \((r, \theta, \phi)\) with the radial distance \(r\), the polar angle \(\theta\), and the azimuthal angle \(\phi\). We let unprimed variables and parameters characterize the region of the fluid medium, \(r > a\), while primed variables and parameters characterize the region of the particle, \(r < a\). For example, the parameter \(k'_s\) is the compressibility of the particle, while \(k_s\) is the compressibility of the fluid medium. Ratios of particle and fluid parameters are denoted by a tilde, e.g. \(\kappa_s = \kappa'_s/\kappa_s\). Due to linearity, we can without loss of generality assume that in the vicinity of the particle, the incident wave is a plane wave propagating in the positive \(z\) direction, \(\phi_t = \phi_0 e^{ik'_s \cdot r} e^{i \alpha_t z}\). The fields do not depend on \(\phi\) due to azimuthal symmetry.

#### B. Partial wave expansion

The solution to the scalar and the vector wave equations [Eq. (43)] with wave numbers \(k\) [Eqs. (44) and (48)] in spherical coordinates is standard textbook material. Avoiding singular solutions at \(r = 0\) and considering outgoing scattered waves, the solution is written in terms of spherical Bessel functions \(j_n(kr)\), outgoing spherical Hankel functions \(h_n(kr)\), and Legendre polynomials \(P_n(\cos \theta)\). As a consequence of azimuthal symmetry, only the \(\phi\) component of the vector potential is nonzero, \(\psi(r) = \psi_\epsilon(r, \theta) e^{i \phi}\). The solution is written as a partial wave expansion of the incident propagating wave \(\phi_t\), the scattered reflected propagating wave \(\phi_s\), the scattered thermal wave \(\psi_s\), and the scattered shear wave \(\psi_s\):

For the particle, \(r < a\)

\[
\phi_t = \phi_0 \sum_{n=0}^{\infty} i^n (2n + 1) j_n(k_s r) P_n(\cos \theta),
\]

\[
\phi_s = \phi_0 \sum_{n=0}^{\infty} i^n (2n + 1) B_n h_n(k_s r) P_n(\cos \theta),
\]

\[
\psi_s = \phi_0 \sum_{n=0}^{\infty} i^n (2n + 1) C_n j_n(k'_s r) \tilde{\delta}_0 P_n(\cos \theta).
\]

In the fluid medium, \(r > a\)

\[
\phi_t' = \phi_0 \sum_{n=0}^{\infty} i^n (2n + 1) A'_n j_n(k'_s r) P_n(\cos \theta),
\]

\[
\phi_s' = \phi_0 \sum_{n=0}^{\infty} i^n (2n + 1) B'_n j_n(k'_s r) \tilde{\delta}_0 P_n(\cos \theta),
\]

\[
\psi_s' = \phi_0 \sum_{n=0}^{\infty} i^n (2n + 1) C'_n j_n(k'_s r) \tilde{\delta}_0 P_n(\cos \theta).
\]
where the parameter $\phi_0$ is an arbitrary amplitude of the incident wave with unit $m^2 \cdot s^{-1}$. The different components of the resulting acoustic field are illustrated in Fig. 2.

### C. Boundary conditions

Neglecting surface tension, the appropriate boundary conditions at the particle surface are continuity of velocity, normal stress, temperature, and heat flux. Assuming sufficiently small oscillations, see Sec. VII C, the boundary conditions are imposed at $r = a$,

\[
\begin{align*}
v_{\theta r} &= v'_{\theta r}, & v_{\theta \theta} &= v'_{\theta \theta}, & T_1 &= T'_1, \\
\sigma_{\theta r r} &= \sigma'_{\theta r r}, & \sigma_{\theta \theta r} &= \sigma'_{\theta \theta r}, & k_0 \partial_r T_1 &= k'_0 \partial_r T'_1.
\end{align*}
\]

The boundary conditions are expressed in terms of the potentials using Eqs. (49), (50), and (52). The components of velocity and stress in spherical coordinates are given in Appendix A.

It is convenient to introduce the nondimensionalized wave numbers $x_c$, $x_i$, and $x_t$ for the particle:

\[
\begin{align*}
x_c &= k_c a, & x_i &= k_i a, & x_t &= k_t a, \\
x'_c &= k'_c a, & x'_i &= k'_i a, & x'_t &= k'_t a.
\end{align*}
\]

Inserting the expansion (53) into the boundary conditions (54), and making use of the Legendre equation (C1), we obtain the following system of coupled linear equations for the expansion coefficients in each order $n$:

\[
\begin{align*}
&av_{\theta r} = av'_{\theta r}, \\
&av_{\theta \theta} = av'_{\theta \theta}.
\end{align*}
\]

\[
\begin{align*}
x_c j'_n(x_c) + A_n x_i h'_n(x_i) + B_n x_t h'_n(x_t) - C_n n(n+1) j_n(x_c) \\
&= A'_n x'_c j'_n(x'_c) + B'_n x'_i j'_n(x'_i) - C'_n n(n+1) j_n(x'_t), \quad (56a)
\end{align*}
\]

\[
\begin{align*}
T_1 &= T'_1, \\
b_c j_n(x_c) + A_n b_i h_n(x_i) + B_n b_t h_n(x_t) \\
&= A'_n b'_c j'_n(x'_c) + B'_n b'_i j'_n(x'_i), \quad (56c)
\end{align*}
\]

\[
\begin{align*}
&ak_0 \partial_r T_1 = ak'_0 \partial_r T'_1, \\
&k_0 b_c x_c j'_n(x_c) + A_0 k_0 b_i x_i h'_n(x_i) + B_0 k_0 b_t x_t h'_n(x_t) \\
&= A'_n k'_0 b'_c x'_c j'_n(x'_c) + B'_n k'_0 b'_i x'_i j'_n(x'_i), \quad (56d)
\end{align*}
\]

\[
\begin{align*}
&\eta_0 [x_c j'_n(x_c) - j_n(x_c)] + A_\eta_0 [x_i h'_n(x_i) - h_n(x_i)] \\
&+ B_\eta_0 [x_t h'_n(x_t) - h_n(x_t)] \\
&- \frac{1}{2} C_n \eta_0 \left[ x'_c j'_n(x'_c) - j_n(x'_c) \right] + B'_n C'_n \eta_0 [x'_i j'_n(x'_i) - j_n(x'_i)] \\
&\quad - \frac{1}{2} C'_n \eta_0 \left[ x'_t j'_n(x'_t) - j_n(x'_t) \right] \left( n^2 + n - 2 \right) j_n(x'_t), \quad (56e)
\end{align*}
\]

\[
\begin{align*}
&\eta [x'_c j'_n(x'_c) - 2 x'_c j''_n(x'_c)] \\
&+ A_\eta [x'_c j'_n(x'_c) - 2 x'_c j''_n(x'_c)] \\
&+ B_\eta [x'_c j'_n(x'_c) - 2 x'_c j''_n(x'_c)] \\
&+ 2n(n+1) C_n \eta_0 [x'_c j'_n(x'_c) - h_n(x_c)] \\
&= A'_\eta [x'_c j'_n(x'_c) - 2 x'_c j''_n(x'_c)] \\
&+ B'_\eta [x'_t j'_n(x'_t) - 2 x'_t j''_n(x'_t)] \\
&+ 2n(n+1) C'_n \eta_0 [x'_c j'_n(x'_c) - j_n(x'_c)]. \quad (56f)
\end{align*}
\]

Here, primes on spherical Bessel and Hankel functions indicate derivatives with respect to the argument. The equations are valid for both a fluid and a solid particle, with $\eta_0$ being the viscosity for a fluid particle and the shear constant [Eq. (41a)] for a solid particle.

For $n = 0$, the boundary conditions for $v_{\theta r}$ and $\sigma_{\theta r r}$ are trivially satisfied because there is no angular dependence in
the zeroth-order Legendre polynomial, \( P_0(\cos \theta) = 1 \). Consequently, \( \psi_s = 0 \), and we are left with four equations with four unknowns, namely, Eqs. (56a), (56c), (56d), and (56f) with \( C_0 = C_0' = 0 \).

The linear system of equations (56) may be solved for each order \( n \) yielding the scattered field with increasing accuracy as higher-order multipoles are taken into account, an approach referred to within the field of ultrasound characterization of emulsions and suspensions as ECAH theory after Epstein and Carhart [30] and Allegra and Hawley [31]. However, care must be taken due to the system matrix often being ill conditioned [42].

The long-wavelength limit is characterized by the small dimensionless parameter \( \varepsilon \), given by

\[
\varepsilon = k_0 \alpha = 2\pi \frac{a}{\lambda} \ll 1.
\]

In this limit, the dominant contributions to the scattered field are due to the \( n = 0 \) monopole and the \( n = 1 \) dipole terms, both proportional to \( \varepsilon^4 \), while the contribution of the \( r \)-th order multipole for \( r > 1 \) is proportional to \( \varepsilon^{2r+1} \ll \varepsilon^3 \).

### D. Monopole scattering coefficient

To obtain the monopole scattering coefficient \( f_0^\beta \) in Eq. (5), we solve for the expansion coefficient \( A_0 \) in Eq. (56) and use the identity \( f_0 = 3i x^{-2} A_0 \). The \( f_n \) coefficients are traditionally used in studies of acoustic radiation force, while the \( A_n \) coefficients are used in general scattering theory.

The solution to the inhomogeneous system of linear equations for \( n = 0 \) involves straightforward but lengthy algebra presented in Appendix B.1. In Eq. (B8) is given the general analytical expression for \( f_0 \) in the long-wavelength limit valid for any particle. In the following, this expression is given in explicit, simplified, closed analytical form for a thermoviscous droplet and a thermoelastic particle, respectively.

### 1. Thermoviscous droplet in a fluid

For a thermoviscous droplet in a fluid in the long-wavelength limit, the particle radius \( a \) and the viscous and thermal boundary layers both inside (\( \delta_s', \delta_i' \)) and outside (\( \delta_s, \delta_i \)) the fluid droplet are all much smaller than the acoustic wavelength \( \lambda \), while nothing is assumed about the relative magnitudes of \( a, \delta_s, \delta_i' \) and \( \delta_s' \). Thus, using the nondimensionalized wave numbers of Eq. (55) and \( \varepsilon = k_0 a \), the long-wavelength limit is defined as

\[
|x_s^2,|x'_s|^2 \sim \varepsilon^2 \ll 1 \quad \text{and} \quad |x_i^2,|x'_i|^2 \sim \varepsilon^2 \ll |x_s^2,|x'_s|^2,|x_i^2,|x'_i|^2,
\]

which implies

\[
|b_s|,|b'_s| \sim |b_i|,|b'_i| \sim \varepsilon^2 \ll 1.
\]

To first order in \( \varepsilon \), the analytical result for the monopole scattering coefficient \( f_0^\beta \) obtained from Eq. (B8) is most conveniently written as

\[
f_0^\beta = 1 - \tilde{k}_s - 3(y - 1) \left( 1 - \frac{\tilde{a}_p}{\tilde{\rho}_0 \tilde{c}_p} \right)^2 H(x_s, x'_s), \quad (59a)
\]
\[
H(x_s, x'_s) = \frac{1}{x_t^2} \left[ \frac{1}{1 - ix_t} - \frac{1}{k_{th}} \tan x'_t - x'_t \right]^{-1}, \quad (59b)
\]

where \( H(x_s, x'_s) \) is a function of the particle radius \( a \) through the nondimensionalized thermal wave numbers \( x_s \) and \( x'_s \). Epstein and Carhart obtained a corresponding result for \( A_0 \) but with a sign error in the thermal correction term [30], while the result of Allegra and Hawley [31] is in agreement with what we present here. The factor \( (y - 1) \) quantifies the coupling between heat and the mechanical pressure waves. This factor is multiplied by \( \left[ 1 - \tilde{a}_p/\tilde{\rho}_0 \tilde{c}_p \right]^2 \), where the quantity \( \tilde{c}_p = \alpha_p/(\tilde{\rho}_0 \tilde{c}_p) \), with unit \( m^2/s \), may be interpreted as an isobaric expansion coefficient per added heat unit. The thermal correction can only be nonzero if there is a contrast \( \tilde{c}_p \neq 0 \) in this parameter.

In the weak dissipative limit of small boundary layers the function \( H(x_s, x'_s) \) is expanded to first order in \( \delta_i/a \) and \( \delta_s/a \), and using \( \tan(x'_s) \approx i \), we obtain

\[
f_0^\beta = 1 - \tilde{k}_s - \frac{3}{2} \left( 1 + \frac{i}{2} (y - 1) \right) \left[ 1 - \frac{\tilde{a}_p}{\tilde{\rho}_0 \tilde{c}_p} \right]^2 \frac{\delta_t}{a} \quad \text{(small-width boundary layers).} \quad (60)
\]

In the limit of zero boundary-layer thickness \( \delta_i/a \rightarrow 0 \), the thermal correction vanishes, and we obtain

\[
f_0^\beta = 1 - \tilde{k}_s \quad \text{(zero-width boundary layers),} \quad (61)
\]

which is the well-known result for a compressible sphere in an ideal [3] or a viscous [29] fluid.

In the opposite limit of a point particle, \( a/\delta_i, a/\delta_t \rightarrow 0 \), we find \( H(x_s, x'_s) = -(1/3) \tilde{\rho}_0 \tilde{c}_p \), yielding

\[
f_0^\beta = 1 - \tilde{k}_s - (y - 1) \tilde{\rho}_0 \tilde{c}_p \left[ 1 - \frac{\tilde{a}_p}{\tilde{\rho}_0 \tilde{c}_p} \right]^2 \quad \text{(point-particle limit).} \quad (62)
\]

Since \( y > 1 \), the correction from thermal effects in the point-particle limit is negative. This implies that the thermal correction enhances the magnitude of \( f_0^\beta \) for acoustically soft particles (\( \tilde{k}_s > 1 \)), while it diminishes the magnitude and eventually may reverse the sign of \( f_0^\beta \) for acoustically hard particles (\( \tilde{k}_s < 1 \)).

Importantly, an inspection of the point-particle limit [Eq. (62)] leads to two noteworthy conclusions not previously discussed in the literature. First, the thermal contribution to \( f_0^\beta \) allows a sign change of the acoustic radiation force for different-sized but otherwise identical particles. Second, the thermal contribution may result in forces that are orders of magnitude larger than expected from both ideal [3] and viscous [29] theory. For example, \( \tilde{\rho}_0 \gg 1 \) for particles or droplets in gases leads to a thermal contribution to \( f_0^\beta \) two orders of magnitude larger than \( 1 - \tilde{k}_s \). These predictions are discussed in more detail in Sec. VIII.
2. Thermoelastic particle in a fluid

For a thermoelastic particle in a fluid, the long-wavelength limit differs from that of a thermoviscous droplet [Eq. (58)] by the shear mode describing a propagating wave and not a viscous boundary layer. The wavelength of this transverse shear wave is comparable to that of the longitudinal compressional wave, and in the long-wavelength limit both are assumed to be large,

\[ |\chi_c|^2, |\chi_s|^2, |\chi_t|^2 \sim \varepsilon^2 \ll |\chi_d|^2, |\chi_i|^2, |\chi_l|^2, \]

which implies

\[ \Gamma_s, \Gamma_l, \frac{1}{|\tilde{b}_c|}, \frac{|\tilde{b}_l|}{|\tilde{b}_c|}, \frac{|\tilde{b}_s|}{|\tilde{b}_c|} \sim \varepsilon^2 \ll 1. \]

To first order in \( \varepsilon \), the result Eq. (B8) for \( f^{sl}_0 \) may be simplified as outlined in Appendix B, and one obtains after some manipulation

\[ f^{sl}_0 = \frac{1 - \tilde{k}_s + 3(\gamma - 1)}{1 + 4(\gamma - 1) \frac{\chi^2}{3} \frac{\tilde{k}_s}{c^2} \tilde{H}(x_i, x'_i)} \]  

where the function \( \tilde{H}(x_i, x'_i) \) is still given by the expression in Eq. (59b) with \( x'_i \) being the nondimensionalized thermal wave number in the solid particle obtained from Eq. (48b). In the limit of a point particle, \( a/\delta, v/a' \rightarrow 0 \), we find

\[ f^{sl}_0 = \frac{1 - \tilde{k}_s - \frac{(\gamma - 1)\tilde{\rho}_p c_p}{1 - \chi^2}}{1 - \frac{4}{3} \gamma - 1 \frac{\chi^2}{c^2} \frac{\tilde{H}(x_i, x'_i)}{\tilde{k}_s}} \]  

(point-particle limit).  

Remarkably, in the point-particle limit, \( f^{sl}_0 \) and \( f^{sl}_0 \) differ in general. However, as expected, letting \( c'_T \rightarrow 0 \) in Eq. (64), \( f^{sl}_0 \) reduces to \( f^{sl}_0 \) [Eq. (59)] for all particle sizes.

In the weak dissipative limit of small boundary layers, \( \delta_i, \delta'_i \ll a \), the second term in the denominator of Eq. (64) is small for typical material parameters. An expansion in \( \delta_i/a \) and \( \delta'_i/a \) then yields in analogy with Eq. (60).

\[ f^{sl}_0 = 1 - \tilde{k}_s - \frac{3}{2} \frac{1}{1 + (1 - \chi^2) D_{th}^{1/2} D_{th}^{-1}} \times \left( \frac{1 - \tilde{a}_p}{\tilde{a}} \right)^2 \tilde{a} \]  

(small-width boundary layers),  

simplified using Eq. (39c). In the limit \( \delta_i/a \rightarrow 0 \), the thermal correction term vanishes,

\[ f^{sl}_0 = 1 - \tilde{k}_s \]  

(zero-width boundary layers).  

In this limit, where boundary-layer effects are negligible, \( f^{sl}_0 \) and \( f^{sl}_0 \) are identical and, as expected, equal to the ideal [3] and viscous [29] results.

E. Dipole scattering coefficient

To obtain the dipole scattering coefficient \( f_1 \) in Eq. (5), we solve for the expansion coefficient \( A_1 \) in Eq. (56) and use the identity \( f_1 = -6i \chi^{-3} A_1 \). In the long-wavelength limit, the terms involving the coefficients \( B_1 \) and \( B'_1 \) are neglected to first order in \( \varepsilon \). This reduces the system of equations (56) for \( n = 1 \) from six to four equations with the unknowns \( A_1, A'_1, C_1, \) and \( C'_1 \). In Appendix B 2 we solve explicitly for \( A_1 \). Physically, the smallness of the \( B_1 \) and \( B'_1 \) terms means that thermal effects are negligible compared to viscous effects. This is consistent with the dipole mode describing the center-of-mass oscillations of the undeformed particle.

1. Thermoviscous droplet in a fluid

The analytical expression for \( A_1 \) in the long-wavelength limit for a thermoviscous droplet in a fluid, as defined in Eq. (58), is given in Eq. (B23) of Appendix B 2. This expression for \( A_1 \) was also obtained by Allegra and Hawley [31] and, with a minor misprint, by Epstein and Carhart [30] in their studies of sound attenuation in emulsions and suspensions. We write the result for the dipole scattering coefficient \( f_1 \) in a form more suitable for comparison to the theory of acoustic radiation forces as presented by Gorkov [3] and Settnes and Bruus [29],

\[ f_1 = \frac{2(\beta_0 - 1)[1 + F(x_s, x'_s) - G(x_s)]}{\beta_0 + 1}[1 + F(x_s, x'_s) - 3G(x_s)] \]

(68a)

\[ G(x_s) = \frac{3}{x_s} \left( \frac{1}{x_s} - i \right) \]

(68b)

\[ F(x_s, x'_s) = \frac{1 - i x_s}{2(1 - \beta_0) + \beta_0 x_s^2 \tan x'_s - x'_s} \]

(68c)

Even though no thermal effects are present in \( f_1 \), Eq. (68) is nevertheless an extension of the result by Settnes and Bruus [29], since we have taken into account a finite viscosity in the droplet entering through the parameters \( \beta_0 \) and \( \chi_s \). In the limit \( \beta_0 \rightarrow \infty \) of infinite droplet viscosity, the function \( F(x_s, x'_s) \) tends to zero, and we recover the result for \( f_1 \) obtained in Ref. [29].
In the weak dissipative limit of small boundary layers, \( \delta_s \delta_r \ll a \), the dipole scattering coefficient for the thermoviscous droplet reduces to

\[
    f_{1i}^a = \frac{2(\rho_0 - 1)}{2 \rho_0 + 1} \left[ 1 + \frac{3(1 + i) (\rho_0 - 1) \delta_s}{1 + \nu_0^{1/2} \eta_0^{-1} 2 \rho_0 + 1 + a} \right]
\]

(small-width boundary layers). \( \text{(69)} \)

2. Thermoelastic particle in a fluid

In the long-wavelength limit Eq. (63) of a thermoelastic solid particle in a fluid, we obtain the result

\[
    f_{1i}^s = \frac{2(\rho_0 - 1)[1 - G(x_s)]}{2 \rho_0 + 1 - 3G(x_s)},
\]

with the function \( G(x_s) \) given in Eq. (68). In this expression, the only particle-related parameters are density and radius, and it is identical to that derived by Settnes and Bruus [29], who included the same two parameters in their study of scattering from a compressible particle in a viscous fluid using asymptotic matching.

In the small-width boundary layer limit, \( \delta_s \ll a \), the dipole scattering coefficient for the thermoelastic solid particle \( f_{1i}^s \) reduces to

\[
    f_{1i}^s = \frac{2(\rho_0 - 1)}{2 \rho_0 + 1} \left[ 1 + \frac{3(1 + i) (\rho_0 - 1) \delta_s}{2 \rho_0 + 1 + a} \right]
\]

(small-width boundary layers), \( \text{(71)} \)

which closely resembles Eq. (69) for \( f_{1i}^a \).

3. Asymptotic limits

In the zero-width boundary layer limit, the dipole scattering coefficients \( f_{1i}^a \) and \( f_{1i}^s \) both reduce to the ideal-fluid expression [3],

\[
    f_{1i}^a = f_{1i}^s = \frac{2(\rho_0 - 1)}{2 \rho_0 + 1} \quad \text{(zero-width boundary layers).} \quad \text{(72)}
\]

In the opposite limit of a point particle, \( F(x_s, x_r) = 1/(2 + 3 \eta_0) \) is finite and the expression for \( f_{1i}^a \) and \( f_{1i}^s \) is dominated by the \( G(x_s) \) terms, with both cases yielding the asymptotic result

\[
    f_{1i}^a = f_{1i}^s = \frac{1}{2} (\rho_0 - 1) \quad \text{(point-particle limit).} \quad \text{(73)}
\]

It is remarkable that for small particles suspended in a gas where \( \rho_0 \gg 1 \), the value of \( f_1 \) in Eq. (73) is three to five orders of magnitude larger than the value \( f_1 \) predicted by ideal-fluid theory [3].

VII. RANGE OF VALIDITY

Before turning to experimentally relevant predictions derived from our theory, we discuss the range of validity of our results imposed by the three main assumptions: the time periodicity of the total acoustic fields, the perturbation expansion of the acoustic fields, and the restrictions associated with size, shape, and motion of the suspended particle.

A. Time periodicity

The first fundamental assumption in our theory is the restriction to time-periodic total acoustic fields, which was used to obtain Eq. (3) for the acoustic radiation force evaluated at the static far-field surface \( \partial \Omega_1 \). Given a time-harmonic incident field, as studied in this work, a violation of time periodicity can only be caused by a nonzero time-averaged drift of the suspended particle. Denoting the speed of this drift by \( v_p(t) \), we consider first the case of a steady particle drift. The assumption of time periodicity is then a good approximation if the displacement \( \Delta \) is small compared to the particle radius \( a \) during one acoustic oscillation cycle \( \tau = 2\pi/c \) used in the time averaging. A nonzero, acoustically induced particle drift speed \( v_p \) must be of second or higher order in \( \epsilon_{ac} \), \( v_p/c \sim \epsilon_{ac}^2 \), as all first-order fields have a zero time average. Thus

\[
    \frac{\Delta}{a} \sim \frac{v_p \tau}{a} = \frac{\Delta a}{\omega a} = \frac{2\pi v_p}{ka \omega} = \frac{\lambda}{a} \frac{\epsilon_{ac}^2}{2} \ll 1,
\]

and time periodicity is approximately upheld for reasonably small perturbation strengths \( \epsilon_{ac} \ll \sqrt{\alpha}/\lambda \), which is not a severe restriction in practice. In a given experimental situation, it is also easy to check if a measured nonzero drift velocity fulfills \( v_p \tau \ll a \).

In the case of an unsteady drift speed \( v_p(t) \), the time-averaged rate of change of momentum \( \langle \frac{dP}{dt} \rangle \) in the fluid volume bounded by \( \partial \Omega_1 \) in Eq. (2) is nonzero, thus violating the assumption \( \langle \frac{dP}{dt} \rangle = 0 \) leading to Eq. (3). Only the unsteady growth of the viscous boundary layer in the fluid surrounding the accelerating particle contributes to \( \langle \frac{dP}{dt} \rangle \), since equal amounts of momentum are fluxed into and out of the static fluid volume in the steady problem. For Eq. (3) to remain approximately valid, we must require \( \langle \frac{dP}{dt} \rangle \) to be much smaller than \( F_{\text{rad}} \). To check this requirement, we consider a constant radiation force accelerating the particle. When including the added mass from the fluid, this leads to the well-known time scale \( \tau_p \) for the acceleration,

\[
    \tau_p = \frac{2 \rho_0 + 1}{9 \pi} \frac{a^2}{\delta_s^2} \tau.
\]

(75)

Thus, small particles \( (a \ll \delta_s) \) are accelerated to their steady velocity in a time scale much shorter than the acoustic oscillation period \( \tau_p \ll \tau \), while the opposite \( (\tau_p \gg \tau) \) is the case for large particles \( (a \gg \delta_s) \). The unsteady momentum transfer to the fluid bounded by \( \partial \Omega_1 \) is obtained from the unsteady part \( F_{\text{unsteady}}(t) \) of the drag force on the particle as \( \langle \frac{dP}{dt} \rangle = \frac{1}{\partial t} \int_0^\tau F_{\text{unsteady}}(t) \, dt \). Using the explicit expression for \( F_{\text{unsteady}}(t) \) given in problems 7 and 8 in §24 of Ref. [43], we obtain to leading order

\[
    \frac{1}{F_{\text{rad}}} \int_0^\tau \frac{dP}{dt} \, dt = \left\{ \begin{array}{c}
    \frac{4 a}{2 \rho_0 + 1 + a} \delta_s \ll 1, \quad \text{for } a \gg \delta_s, \\
    \frac{2 a}{\pi \delta_s^2} \ll 1, \quad \text{for } a \ll \delta_s.
\end{array} \right.
\]

(76)

We conclude that \( \langle \frac{dP}{dt} \rangle \ll F_{\text{rad}} \) in both the large and small particle limits, and hence the assumption of Eq. (3) is fulfilled in those limits.

Considering typical microparticle acoustophoresis experiments, the unsteady acceleration takes place on a time
scale between micro- and milliseconds, much shorter than
the time of a full trajectory. Typically, the unsteady part
of the trajectory is not resolved and it is not important to
the experimentally observed quasisteady particle trajectory.
In acoustic levitation [25–28], where there is no drift, the
assumption of time periodicity is exact. We conclude that
the assumption of time periodicity is not restricting practical
applications of our theory.

B. Perturbation expansion and linearity

The second fundamental assumption of our theory is the
validity of the perturbation expansion, which requires the
acoustic perturbation parameter \( \varepsilon_{ac} \) of Eq. (10) to be much
smaller than unity. For applications in particle handling in
acoustophoretic microchips [12,14], this constraint is not very
restrictive because typical resonant acoustic energy densities
of 100 J/m³ result in \( \varepsilon_{ac} \sim 10^{-4} \).

Given the validity of the linear first-order equations, the
solutions we have obtained for \( f_0 \) and \( f_1 \) based on the particular
incident plane wave \( \psi_i = \phi_0 e^{i k_x x} \) are general, since any
incident wave at frequency \( \omega \) can be written as a superposition
of plane waves.

C. Oscillations of the suspended particle

The third fundamental assumption of our theory is the
assumption of small particle oscillation amplitudes, allowing
the boundary conditions to be evaluated at the fixed interface
distance \( r = a \). In general, the oscillation amplitudes must
be small in comparison to all other length scales. For small
particles, \( a \ll \delta_h, \delta_v \), the smallest length scale is set by the
particle radius \( a \). In the opposite limit of small boundary
layers, \( a \gg \delta_h, \delta_v \), thermoviscous theory reduces to ideal-fluid
theory, and the boundary-layer length scales drop out of the
equations, again leading to the smallest relevant length scale
being the particle radius \( a \). The assumption of small particle
oscillation amplitudes leads to physical constraints on the
volume oscillations, Figs. 1(a) and 1(b), and the center-of-mass
oscillations, Fig. 1(c), discussed in the following.

The volume oscillations of the particle are due to me-
chanical and thermal expansion. From the definition of the
compressibility \( \kappa' \) and the volumetric thermal expansion
coefficient \( \alpha' \), we estimate the maximum relative change in
particle radius \( \Delta a / a \) to be

\[
\frac{\Delta a}{a} \approx \frac{k'}{3} p_1 = \tilde{k}_s \varepsilon_{ac} \ll 1, \quad (77a)
\]

\[
\frac{\Delta a}{a} \approx \frac{\alpha'}{3} T_1 \approx \frac{1}{3} (\gamma - 1) \tilde{\alpha}_p \varepsilon_{ac} \ll 1. \quad (77b)
\]

Here, we have used \( k_s, p_1 = \varepsilon_{ac} \) and \( T_1 = (\gamma - 1) a_p / \alpha_p p_1 \)
obtained from Eq. (14) in the adiabatic limit \( \gamma = 0 \) combined with
Eq. (16). Except for gas bubbles in liquids, for which \( \kappa_s, \alpha' \gg 1 \),
these inequalities are always fulfilled for small perturbation
parameters \( \varepsilon_{ac} \).

The velocity of the center-of-mass oscillations is found
from Eq. (37) of Ref. [29] to be \( v_p^{oc} = \frac{3}{2} \tilde{p}_0 - \frac{1}{3} v_{in} \). In the
large-particle limit, \( f_1 \) is given by Eq. (72), which implies
0 < \( v_p^{oc} < 3 v_{in} \), where the lower and the upper limit is
for \( \tilde{p}_0 \gg 1 \) and \( \tilde{p}_0 \ll 1 \), respectively. In the point-particle
limit, Eq. (73), \( v_p^{oc} = v_{in} \) independent of \( \tilde{p}_0 \). The relative
displacement amplitude \( \Delta \ell / a \) is hence estimated as

\[
\frac{\Delta \ell}{a} \approx \frac{v_p^{oc}}{c a} \approx \begin{cases} \frac{3}{2} \rho_0 + 1 \pi a \varepsilon_{ac} \ll 1, & \text{for } a \gg \delta_s, \\ \frac{\lambda}{2 \pi a} \varepsilon_{ac} \ll 1, & \text{for } a \ll \delta_s, \end{cases} \quad (78)
\]

and thus the general requirement is that \( \varepsilon_{ac} \ll 2 \pi a / \lambda \). For
large particles in typical experiments, this restriction is not
severe. However, for small particles it can be restrictive. For
example, to obtain \( \Delta \rho / a < 0.05 \), we find for particles of
radius \( a = 100 \) nm in water at 1 MHz and particles of radius
\( a = 1 \) μm in air at 1 kHz, that \( \varepsilon_{ac} \lesssim 10^{-3} \) and \( \varepsilon_{ac} \lesssim 10^{-6} \),
respectively.

VIII. MICROPARTICLES AND DROPLETS
IN STANDING PLANE WAVES

The special case of a one-dimensional (1D) standing plane
wave is widely used in practical applications of the acoustic
radiation force in microchannel resonators [8–21] and acoustic
levitators [25–28]. The many application examples as well as
its relative simplicity make the 1D case an obvious and useful
testing ground of our theory. In the following, we illustrate the
main differences between our full thermoviscous treatment
and the ideal-fluid or viscous-fluid models using the typical
parameter values listed in Table II.

We consider a standing plane wave of the form \( p_{in} =
\rho_c \cos(k_{0} y), \psi_{in} = \frac{1}{\rho_c} \rho_p \sin(k_{0} y) \vec{e}_y \), with acoustic energy
density \( E_{ac} = \frac{1}{2} \kappa_s p_a^2 = \frac{1}{2} \rho_0 v_a^2 \), where \( \rho_p \) and \( v_a \) are the pressure
and the velocity amplitude, respectively. Expression (5) for
the radiation force then simplifies to

\[
F_{rad}^{1D} = 4 \pi \Phi_{ac} a^3 k_0 E_{ac} \sin(2 k_0 y) \vec{e}_y, \quad (79a)
\]

\[
\Phi_{ac} = \frac{1}{3} \text{Re} [f_0] + \frac{1}{3} \text{Re} [f_1]. \quad (79b)
\]

where \( \Phi_{ac} \) is the so-called acoustic contrast factor. The
radiation force is thus proportional to \( \Phi_{ac} \), which contains the
effects of thermoviscous scattering in \( f_0 \) and \( f_1 \). Note that
for positive acoustic contrast factors, \( \Phi_{ac} > 0 \), the force is
directed towards the pressure nodes of the standing wave, while
for negative acoustic contrast factors, \( \Phi_{ac} < 0 \), it is directed
against the antinodes.

The acoustic contrast factor \( \Phi_{ac} \) may be evaluated directly
for an arbitrary particle size by using the expressions for the
scattering coefficients, either \( f_0^a \) and \( f_1^a \) for a fluid droplet
or \( f_0^d \) and \( f_1^d \) for a solid particle. For ease of comparison
to the work of King [1], Yosika and Kawasima [2], and
Doinikov [4–6], we give the expression for the acoustic
contrast factor \( \Phi_{ac}^d \) of a fluid droplet for small boundary layers
and in the point-particle limit. In the small-width boundary
layer limit one obtains

\[
\Phi_{ac}^d = \frac{1}{3} \left( \frac{5 \rho_0 - 2}{2 \rho_0 + 1} - \tilde{k}_s \right) + \frac{3}{1 + \tilde{k}_0^2 / \tilde{\eta}^2} \left( \frac{\tilde{\rho}_0 - 1}{2 \rho_0 + 1} \right)^2 \tilde{\delta}_s
\]

\[
- \frac{1}{2} \left( k_{in}^2 / \tilde{k}_0^2 \right) \left( 1 - \frac{\tilde{\alpha}_p}{\tilde{p}_0 \tilde{c}_p} \right)^2 \tilde{\delta}_s
\]

\[
\left( \text{small-width boundary layers} \right). \quad (80)
\]
The first term is the well-known result given by Yoshioka and Kawasima [2], which reduces to that of King [1] for incompressible particles for which $\kappa_s = 0$. The second term is the viscous correction, which agrees with the result of Settnes and Bruus [29] for infinite particle viscosities, but extends it to finite particle viscosities. Note that the viscous correction yields a positive contribution to the acoustic contrast factor, while the thermal correction from the third term is negative. The result given in Eq. (80) is in agreement with the expression for the radiation force in a standing plane wave given by Doinikov [6] in the weak dissipative limit of small boundary layers. However, this is not seen without considerable effort combining and reducing a number of equations. Although we find Doinikov’s approach rigorous, it lacks transparency and is difficult to apply with confidence.

In the point-particle limit of infinitely large boundary-layer thicknesses compared to the particle size, we obtain

$$\Phi_{\infty}^n = \frac{1}{3} \left[ (1 - \kappa_s) - (1 - \rho_0) - (\gamma - 1)\rho_0 \alpha_p \left(1 - \frac{\alpha_p}{\rho_0 \alpha_p^2 p} \right)^2 \right],$$

(point-particle limit),

$$= \frac{1}{3} \left[ (1 - \kappa_s) - (1 - \rho_0) - (\gamma - 1)\rho_0 \alpha_p \left(1 - \frac{\alpha_p}{\rho_0 \alpha_p^2 p} \right)^2 \right]$$

with $\kappa_s = 0$, $\rho_0 = 1$, and $\alpha_p = 1$, the scattering due to compressibility and density (inertia) mechanisms vanishes. This is true for large particles [1–3,29], and it is reasonable that it remains true in the point-particle limit. The expressions for the acoustic radiation force on a point particle in a standing plane wave given by Doinikov [6] do not have this property, which is likely due to a sign error or a misprint in the term corresponding to our dipole scattering coefficient $f_1$ in the point-particle limit in Eq. (73), as was also suggested by Settnes and Bruus [29].

The small-width boundary layer limit and the point-particle limit are useful for analyzing consequences of thermoviscous scattering on the acoustic radiation force, but we emphasize that our theory is not restricted to these limits. In general, the scattering coefficients $f_0$ and $f_1$ are functions of the nondimensionalized wave numbers $x_s$, $x_t$, $x'_s$, and $x'_t$. These may all be expressed in terms of the particle radius $a$ normalized by the thickness of the viscous boundary layer in the medium $\delta_s$,

$$x_s = (1 + i) \frac{a}{\delta_s}, \quad x'_s = (1 + i) \sqrt{\frac{\rho_0}{\rho_0 + (\gamma - 1)\kappa_s}} \frac{a}{\delta_s}, \quad (82a)$$

$$x_t = (1 + i) \sqrt{Pr} \frac{a}{\delta_s}, \quad x'_t = \frac{(1 + i) \sqrt{Pr}}{\sqrt{1 - X'}} \frac{a}{\delta_s} \frac{1}{D_{th}}, \quad (82b)$$

where we have used $\delta'_s = \delta_s / \rho_0 / \rho_0$, $\delta'_t = \delta_t / \sqrt{Pr}$, $\delta'_t = \delta_t / \sqrt{[(1 - X')D_{th}]/Pr}$, with $Pr = \rho_0 / D_{th}$ being the Prandtl number of the fluid medium and $X'$ set to zero for the fluid droplet case. Below, we investigate the thermoviscous effects on the acoustic radiation force by plotting the acoustic contrast factor $\Phi_{ac}$ as a function of $\delta_s/a$, ranging from zero boundary-layer effects at $\delta_s/a = 0$ to maximum effects in the limit $\delta_s/a \to \infty$.

### A. Oil droplets in water and water droplets in oil

We first consider the cases of water with a suspended oil (wa-oil) and of oil with a suspended water droplet (oil-wa) using the parameters of a typical food oil given in Table II. Since the density contrast of water and oil is small, the dipole scattering with its viscous effects is small, while on the other hand the thermal effects in the monopole scattering are significant. This is clearly seen from Fig. 3, where the acoustic contrast factor $\Phi_{ac}$ is plotted for the two cases as a function of $\delta_s/a$ using ideal theory, viscous theory (obtained from our thermoviscous theory by setting $D_{th} = 0$), and full thermoviscous theory. In Fig. 3, we see that for submicrometer droplets at MHz frequency the thermoviscous theory leads to corrections around 100% as compared to the ideal and the viscous theory, which manifestly demonstrates the importance of thermal effects in such systems.

We note from Fig. 3(a) that the acoustic contrast factor of oil droplets in water is negative, which means that oil droplets are focused at the pressure antinodes. Conversely, water droplets in oil are thus expected to be focused at the pressure nodes.
However, in Fig. 3(b) we see that thermoviscous theory predicts a tunable sign change in the acoustic contrast factor as a result of the negative thermal corrections to the monopole scattering coefficient. This means that droplets above a critical size threshold experience a force directed towards the pressure nodes, while droplets smaller than the threshold experience a force towards the antinodes, even though the only distinction between the droplets is their size. This sign change in $\Phi_{ac}$ can also be achieved for elastic solid particles under properly tuned conditions. By changing, for example, the compressibility contrast $\kappa_s$, the curves for $\Phi_{ac}(\delta_s/a)$ may be shifted vertically and a possible size-threshold condition may be changed. Moreover, since $\delta_s = \sqrt{2\eta_0/(\rho_0 c_p)}$ and $\delta_t = \sqrt{2\eta_b/(\rho_b c_p)}$, there are several direct ways of tuning a threshold value, e.g., by frequency or by changing the density of the medium.

### B. Polystyrene particles and water droplets in air

Using the particular cases of a polystyrene particle and a water droplet suspended in air as main examples, we study the effects of a large density contrast $\rho_0 \gg 1$, for which our thermoviscous theory predicts much larger radiation forces on small particles than ideal-fluid theory, for which $\Phi_{ac}^{ideal} = 5/6$ independent of particle size. This is demonstrated in Fig. 4, where $\Phi_{ac}$ is plotted as a function of $\delta_s/a$ for the two particle types. In the large-particle limit $\delta_s/a = 0$, boundary-layer effects are negligible, and ideal, viscous ($D_b = 0$), and thermoviscous theories predict the same contrast factor $\Phi_{ac} = 5/6$, but as $\delta_s/a$ increases, the thermoviscous and viscous theories predict an increased value of $\Phi_{ac}$, approximately $2\Phi_{ac}^{ideal}$ for $\delta_s/a = 1$ as seen in the insets of Figs. 4(a) and 4(b). Decreasing the particle size further, $\delta_s/a \gg 1$, the thermoviscous effects become more pronounced with $\Phi_{ac}/\Phi_{ac}^{ideal} \sim 10^2$. Choosing the frequency to be 1 kHz, this remarkable deviation from ideal-fluid theory is obtained for moderately-sized particles of radius $a \approx 2 \mu m$.

While $\Phi_{ac}^{ideal}$ in Fig. 4(a) for the polystyrene particle is a monotonically increasing function of $\delta_s/a$, the $\Phi_{ac}^{air-wa}$ in Fig. 4(b) of a water droplet exhibits a nonmonotonic behavior. For small values of $\delta_s/a \lesssim 25$, the viscous dipole scattering dominates resulting in a positive contrast factor $\Phi_{ac}^{air-wa} \lesssim 10^2$. For larger values, $\delta_s/a \gtrsim 25$, thermal effects in the monopole scattering become dominant leading to a sign change in $\Phi_{ac}^{air-wa}$ and finally to large negative contrast factors approximately equal to $-10^2$ as the point-particle limit $\delta_s/a \gg 1$ is approached. This example clearly demonstrates how the acoustic contrast factor may exhibit a nontrivial size dependency with profound consequences for the acoustic radiation force on small particles. The detailed behavior depends on the specific materials but can be calculated using Eq. (79) and the expressions for $f_0$ and $f_1$ listed in Table I.

### IX. CONCLUSION

Since the seminal work of Epstein and Carhart [30] and Allegra and Hawley [31], the effects of thermoviscous scattering have been known to be important for ultrasound attenuation in emulsions and suspensions of small particles. In this paper, we have by theoretical analysis shown that thermoviscous effects are equally important for the acoustic radiation force $F_{rad}$ on a small particle. $F_{rad}$ is evaluated from Eq. (5), or more generally from Eq. (6), using our analytical results for the thermoviscous scattering coefficients $f_0$ and $f_1$ summarized in Table I. Our analysis places no restrictions on the viscous and thermal boundary-layer thicknesses $\delta_t$ and $\delta_s$ relative to the particle radius $a$, a point which is essential to calculation of the acoustic radiation force on micrometer- and nanometer-sized particles.

The discussion in Sec. II leading to Eq. (5) for $F_{rad}$ as well as the discussion of the range of validity presented in Sec. VII are intended to provide clarification and a deeper insight into the fundamental assumptions of the theory for the acoustic radiation force. Foremost, we have extended the discussions of the role of streaming, the fundamental assumption of time periodicity, and the trick of evaluating the radiation force in the far field, which led to the exact nonperturbative expression (3) for the radiation force evaluated in the far field.

For the simple case of a 1D standing plane wave at a single frequency, the expression (6) for $F_{rad}$ simplifies to the useful expression given in Eq. (79), which involves the acoustic...
contrast factor \( \Phi_{ac} \). Similar simplified expressions can be derived for other cases of interest such as that of a 1D traveling plane wave. An important result from the discussion of the simple 1D case in Sec. VIII is that we must abandon the notion of a purely material-dependent acoustic contrast factor \( \Phi_{ac} \). In general, \( \Phi_{ac} \) also depends on the particle size, and in many cases this size dependency can even lead to a sign change in \( \Phi_{ac} \) at a critical threshold. Recent acoustophoretic experiments on submicrometer-sized water droplets and smoke particles in air may provide the first evidence of this prediction [57]. Considering only viscous corrections, however, the authors could not fully explain their data. Our analysis suggests that thermoviscous effects must be taken into account when designing and analyzing such experiments.

Our results for the acoustic radiation force in a standing plane wave evaluated using Eq. (79) agree with the expressions obtained from the work of Doinikov [4–6] in the limit of small boundary layers, but not in the opposite limit of a point particle. In our theory both of these limits are evaluated directly using the derived analytical expressions valid for arbitrary boundary-layer thicknesses, and we have furthermore given a physical argument supporting our result in the point-particle limit. Considering the viscous theory of Danilov and Mironov [7], we remark that their result is based on the viscous reaction force on an oscillating rigid sphere [43] instead of a direct solution of the governing equations for an acoustic field scattering on a sphere.

Importantly, we have shown that the acoustic radiation force on a small particle including thermoviscous effects may deviate by orders of magnitude from the predictions of ideal-fluid theory when there is a large density contrast between the particle and the fluid. This result is particularly relevant for acoustic levitation and manipulation of small particles in gases [22–28]. Thermoviscous effects can also be significant in many lab-on-a-chip applications involving ultrasound handling of nanoparticles and nanodroplets. In general, acoustic boundary-layer effects should be expected for any type of submicrometer particle, including biological particles such as microvesicles, bacteria, and viruses [8,9,18]. A firm theoretical understanding of thermoviscous effects and of the particle-size-dependent sign change of the acoustic contrast factor could prove important for future applications relying on ultrasound manipulation of micrometer- and nanometer-sized particles.

APPENDIX A: VELOCITY AND NORMAL STRESS IN SPHERICAL COORDINATES

In spherical coordinates \((r, \theta, \phi)\) with azimuthal symmetry, using that \(v_1 = \nabla \phi + \nabla \times \psi\) with \(\phi = \phi_e + \phi_i\) and \(\psi = \psi_s + \psi_v\), the first-order velocity components are

\[
\begin{align*}
    v_{1r} & = \partial_r \phi + \frac{1}{r \sin \theta} \partial_\theta [\sin \theta \psi_s], \\
    v_{1\theta} & = \frac{1}{r} \partial_\theta \phi - \frac{1}{r} \partial_r [r \psi_s].
\end{align*}
\]  
(A1a)  
(A1b)

Inserting this into Eq. (52), we obtain the normal components of the first-order stress tensor

\[
\begin{align*}
    \sigma_{1rr} & = \eta_0 (2k_1^2 - k_s^2) \phi_e + \eta_0 (2k_1^2 - k_s^2) \phi_i + 2\eta_0 \partial_\theta \psi_s + \frac{2\eta_0}{r \sin \theta} \frac{1}{r} \partial_r [\sin \theta \psi_s] \\
    & - \frac{2\eta_0}{r^2} \partial_\theta \psi_v + \frac{2\eta_0}{r} \partial_r [\frac{1}{\sin \theta} \partial_\theta (\sin \theta \psi_v)], \\
    \sigma_{1\theta\theta} & = 2\eta_0 \partial_\theta \left( \frac{1}{r^2} \partial_r \phi - \frac{1}{r} \frac{\partial_\phi}{r} \right) - \eta_0 \left( \frac{1}{r^2} \partial_\phi \psi_s - \frac{2}{r} \frac{\partial_\phi}{r} \psi_v \right) + \frac{\eta_0}{r} \frac{1}{\sin \theta} \partial_\theta [\sin \theta \psi_v].
\end{align*}
\]  
(A2a)  
(A2b)
APPENDIX B: SCATTERING COEFFICIENTS $f_0$ AND $f_1$

Here, we outline the calculation of the monopole and dipole scattering coefficients $f_0$ and $f_1$ in the long-wavelength limit where the particle radius and the boundary-layer thicknesses are assumed much smaller than the wavelength. Defining the small parameter $\varepsilon = k_0 a \ll 1$, we note that $k_0 a, k_0 \delta_s, k_0 \delta_c$, and for a fluid particle furthermore $k_0 \delta_v$, are all of order $\varepsilon$. The calculation is carried out to first order in $\varepsilon$.

1. Monopole scattering coefficient $f_0$

The monopole scattering coefficient $f_0$ may be obtained from Eqs. (56a), (56c), (56d), and (56f) setting $n = 0$ and $C_0 = C'_0 = 0$. All Bessel functions of the small arguments $x_c, x'_c \sim \varepsilon \ll 1$ are expanded to first order in $\varepsilon$ using Eq. (C5) of Appendix C, and in the (unprimed) fluid medium we neglect $x^2_s$ in comparison to $x^2_c$. Thus, we arrive at

\[
A_0 \frac{i}{x_c} + A'_0 \frac{1}{3} x'^2_c - B_0 x_c h_1(x_t) + B'_0 x'_c j_1(x'_t) = \frac{1}{3} x^2_c, \tag{B1a}
\]

\[
A_0 b_c \left( 1 - \frac{i}{x_c} \right) - A'_0 b'_c = B_0 b_c h_0(x_t) - B'_0 b'_c j_0(x'_t) = -b_c, \tag{B1b}
\]

\[
A_0 k_0 b_c x_c \left( 1 - \frac{i}{x_c} \right) + A'_0 k'_0 b'_c x'^2_c - B_0 k_0 b_c x_c h_1(x_t) + B'_0 k'_0 b'_c x'_c j_1(x'_t) = \frac{1}{3} k_0 b_c x^2_c, \tag{B1c}
\]

\[
A_0 \eta_0 \left[ (4 - x^2_c) \frac{i}{x_c} + x^2_c \right] - A'_0 \eta'_0 \left[ x'^2_c - \frac{1}{3} x'^2_c \right] + B_0 \eta_0 \left[ (x^2_s - 2 x^2_t) h_0(x_t) - 2 x^2_t h'_0(x_t) \right] - B'_0 \eta'_0 \left[ (x'^2_c - 2 x'^2_t) j_0(x'_t) - 2 x'^2_t j'_0(x'_t) \right] = -\eta_0 x^2_c, \tag{B1d}
\]

where Eq. (C3) is used to write $g'_0(x) = -g_1(x)$ for any spherical Bessel or Hankel function $g_0(x)$.

Multiplying Eq. (B1c) by $1/(k_0 b_c)$ and using the ratios

\[
\frac{b_c}{b'_c} = \frac{-(\gamma - 1)x^2_c}{x^2_s}, \quad \frac{b'_c}{b'_t} = \tilde{\chi} \frac{\tilde{\alpha}}{\beta} \rho D_0, \quad \frac{b'_t}{b_t} = \frac{b_c}{b'_c} = - \frac{1}{\tilde{\chi}} \frac{\tilde{\alpha}}{\beta} \rho D_0 x^2_c, \tag{B2}
\]

of the $b$ coefficients defined in Eq. (50) [here, $\tilde{\chi} = 1$ for a droplet and $\tilde{\chi} = \chi'$ for a solid particle, respectively, while Eqs. (16), (22), and (39e) are used to reduce $b'_c/b_t$], we note that the $A_0$ terms can be neglected to order $\varepsilon$, and we obtain

\[
B'_0 = \frac{k_0 b_c}{k'_0 b'_c} \frac{x_c h_1(x_t)}{x'_c j_1(x'_t)} B_0 = \tilde{\chi} \frac{\tilde{\alpha}}{\beta} \rho D_0 \frac{x_c h_1(x_t)}{x'_c j_1(x'_t)} B_0. \tag{B3}
\]

With this, we eliminate $B'_0$ from the system of equations (B1), and the remaining three equations become

\[
\left( \begin{array}{ccc}
\frac{b_c}{b'_c} & \frac{i}{x_c} & -S_1 \\
\frac{b'_c}{b'_t} & \frac{b'_c}{b'_t} & -S_2 \\
\frac{b'_t}{b_t} & \frac{b_t}{b_t} & -S_3
\end{array} \right) \left( \begin{array}{c}
A_0 \\
A'_0 \\
B_0
\end{array} \right) = \left( \begin{array}{c}
\frac{x^2_c}{x^2_s} \\
\frac{x'^2_c}{x'^2_s} \\
\frac{\eta_0}{\eta_0}
\end{array} \right), \tag{B4}
\]

where we have introduced the functions $S_1$, $S_2$, and $S_3$

\[
S_1 = \left[ 1 - \frac{1}{k_0 b_c} \right] x_c h_1(x_t), \tag{B5a}
\]

\[
S_2 = x^2_c \left[ x'_c h_1(x'_t) - \frac{1}{k_0 b'_c} j_0(x'_t) \right] x_c h_1(x_t), \tag{B5b}
\]

\[
S_3 = x^2_c \left[ x'_c h_0(x'_t) - 4 \left( 1 - \frac{\eta_0}{\eta_0} \frac{b_c}{b'_c} \right) \frac{\eta_0}{\eta_0} \frac{b'_c}{b'_t} \right] x'_c j_1(x'_t) \right] x_c h_1(x_t), \tag{B5c}
\]

and the relative shear constant $\eta_0$ obtained from Eq. (41b),

\[
\frac{\eta_0}{\eta_0} = \frac{\eta'_0}{\eta_0} = \tilde{\beta} \frac{x^2_c}{x'^2_c}. \tag{B6}
\]

In obtaining the expression for $S_1$ we have used Eq. (C3) to substitute $g'_0(x) = -g_0(x) + (2/x)g_1(x)$ for any spherical Bessel or Hankel function $g(x)$. Using Eqs. (B2), (B6), and the explicit forms (C4) of the Bessel functions, the $S$ functions are expressed
in terms of the dimensionless wave numbers as

\[
S_1 = \left[ 1 - \frac{\chi}{\rho_0 \tilde{c}_p} \right] \frac{x_1 h_1(x_1)}{x_1}, \quad (B7a)
\]
\[
S_2 = \frac{1}{H(x_s, x_s')} x_s h_1(x_s), \quad (B7b)
\]
\[
S_3 = \left[ \frac{x_s^2}{1 - i x_s} - 4 + \frac{\chi \tilde{c}_p}{\bar{c}_p} \left( \frac{4x_s^2}{x_s^2} - \frac{x_s^2 \tan x_s'}{\tan x_s' - x_s'} \right) \right] x_s h_1(x_s), \quad (B7c)
\]

where \(H(x_s, x_s')\) is given in Eq. (59b). The coefficient \(A_0\) is now found from Eq. (B4) by the method of determinants (Cramer’s rule) as \(A_0 = D(A_0)/D\), where \(D\) is the determinant of the left-hand-side system matrix and \(D(A_0)\) is the determinant of the system matrix in which the first column (the \(A_0\) coefficients) are replaced by the right-hand-side column with the inhomogeneous terms. The monopole scattering coefficient \(f_0\) in the long-wavelength limit can then be expressed as

\[
f_0 = \frac{3i}{\chi^3} A_0 = \frac{3i}{\chi^3} \frac{D(A_0)}{D}, \quad (B8)
\]

with the determinants \(D\) and \(D(A_0)\) given by

\[
D = -S_1 \left[ \tilde{\eta}_0 \frac{b_c}{b_t} \left( \frac{i}{x_s} - 1 \right) \left( \frac{4}{3} x_s^2 - x_s^2 \right) - b_c' \left( \frac{4 - x_s^2}{x_s} + x_s \right) \right] - S_2 \left[ \frac{x_s^2}{3} \left( \frac{i(4 - x_s^2)}{x_s} + x_s \right) - \frac{i}{\tilde{\eta}_0} \left( \frac{4}{3} x_s^2 - x_s^2 \right) \right] - S_3 \left[ \frac{1}{3} x_s^2 \frac{b_c}{b_t} \left( \frac{i}{x_s} - 1 \right) - \frac{i}{x_s} \left( \frac{b_c}{b_t} \right)^2 \right], \quad (B9a)
\]
\[
D(A_0) = -S_1 \left[ \tilde{\eta}_0 \frac{b_c}{b_t} \left( \frac{4}{3} x_s^2 - x_s^2 \right) + b_c' \frac{b_t}{b_c} \right] - S_2 \left[ -\tilde{\eta}_0 \left( \frac{4}{3} x_s^2 - x_s^2 \right) - x_s^2 \right] - S_3 \left[ \frac{1}{3} \frac{b_c}{b_t} \frac{b_t}{b_c} - \frac{b_c'}{b_c} \right]. \quad (B9b)
\]

The solution \(A_0 = D(A_0)/D\), though written somewhat differently, agrees with Allegra and Hawley’s Eq. (10) of Ref. [31].

\[a. \, f_0 \text{ for a suspended thermoviscous droplet}\]

For a suspended thermoviscous droplet, the precise definition of the long-wavelength limit is given in Eq. (58). In this case, the shear mode characterized by \(x_s'\) inside the droplet corresponds to a boundary layer, and consequently comparison to the compressional mode inside and outside the droplet yields \(x_s^2/x_s'^2 \sim x_s^2/x_s'^2 \sim \epsilon^2 \ll 1\). This, combined with \(b_c'/b_t \sim b_c'/b_t \sim x_s^2/x_s'^2 \sim \epsilon^2 \ll 1\) from Eq. (B2), leads to the following simplification of Eq. (B9) to first order in \(\epsilon\),

\[
D \approx -\frac{i}{x_s} \left( \frac{2}{3} \tilde{\eta}_0 \right) S_2, \quad (B10a)
\]
\[
D(A_0) \approx -\frac{\tilde{\eta}_0 x_s^2}{3} \left( x_s^2 - \frac{x_s'^2}{\tilde{\eta}_0} \right) S_2 + \tilde{\eta}_0 x_s^2 \frac{b_c}{b_t} \left( 1 - \frac{\tilde{c}_p}{\bar{c}_p} \right) S_1. \quad (B10b)
\]

When inserting this into Eq. (B8), we obtain

\[
f_0^{\parallel} = 1 - \kappa + 3(\gamma - 1) \left( 1 - \frac{\tilde{c}_p}{\bar{c}_p} \right) \frac{S_1}{S_2}, \quad (B11)
\]

which upon substitution with \(\tilde{\eta}_0 = (1 - \tilde{\eta}_0)H(x_s, x_s')\) from Eq. (B7) with \(\kappa = 1\), leads to the final analytical result for \(f_0^{\parallel}\) given in Eq. (59).

\[b. \, f_0 \text{ for a suspended thermoelastic particle}\]

The qualitative change going from the thermoviscous droplet to the thermoelastic particle lies in the shear mode, which changes from a highly damped boundary-layer mode to a propagating transverse wave with \(x_s^2 \sim \epsilon^2\). A further implication is that the shear constant ratio of Eq. (B6) becomes large, \(\tilde{\eta}_0 = \tilde{\eta}_0 x_s^2/x_s'^2 \sim \epsilon^2 \gg 1\); and the order of magnitude of the \(S\) functions of Eq. (B7) obey \(S_1 \sim S_2 \sim \epsilon^5 S_3\). Combining this with the following expression derived from Eqs. (39e), (48), and (B6),

\[
\tilde{\eta}_0 \left( \frac{4}{3} x_s^2 - x_s'^2 \right) = -\chi' \bar{x}_0 x_s^2, \quad (B12)
\]
the leading-order expansions in $\varepsilon$ of the determinants $D$ and $D(A_0)$ in Eq. (B9) become

$$
D = \frac{i}{\kappa_c} \left( -\tilde{\chi} \tilde{\rho}_0 \frac{x^2}{x_s^2} S_2 + \frac{b'_c}{b_c} S_3 \right),
$$

$$
D(A_0) = x^2 \frac{b'_c}{b_c} \left( -1 + \tilde{\chi} \tilde{\rho}_0 \frac{b_x}{b_c} S_1 + \frac{x^2}{3} \frac{x^2}{x_s^2} \left( \frac{x^2}{x_s^2} - \tilde{\chi} \tilde{\rho}_0 \right) S_2 + \frac{x^2}{3} \frac{b'_c}{b_c} \left( 1 - \frac{b_x}{b_c} \frac{x^2}{x_s^2} \right) S_3 \right).
$$

From this and Eq. (B8), we obtain the monopole scattering coefficient $f_0^{\text{sl}}$ for a thermoelastic particle suspended in a thermoviscous fluid,

$$
f_0^{\text{sl}} = \frac{3i}{x_s^2} A_0 = \frac{1}{\tilde{\chi} \tilde{\rho}_0 \frac{x^2}{x_s^2}} - \frac{1}{\tilde{\chi} \tilde{\rho}_0 \frac{b_x}{b_c} S_1 + \frac{x^2}{3} \frac{x^2}{x_s^2} \left( \frac{x^2}{x_s^2} - \tilde{\chi} \tilde{\rho}_0 \right) S_2 + \frac{x^2}{3} \frac{b'_c}{b_c} \left( 1 - \frac{b_x}{b_c} \frac{x^2}{x_s^2} \right) S_3}.
$$

From Eq. (B7) we obtain the leading-order expansions in $\varepsilon$ for the ratios $S_1/S_2$ and $S_3/S_2$,

$$
\frac{S_1}{S_2} = \left( 1 - \frac{1}{k_{\tilde{\rho}_0} b'_c} \right) H(x_1, x'_1), \quad \frac{S_3}{S_2} = \frac{4}{k_{\tilde{\rho}_0} b'_c} \tilde{\eta} H(x_1, x'_1),
$$

with the function $H(x_1, x'_1)$ defined in Eq. (59b). Inserting this into Eq. (B14) and using Eqs. (B2) and (B6), and the expression (39e) for $C^f$, we arrive at the final analytical form for $f_0^{\text{sl}}$ given in Eq. (64).

2. Dipole scattering coefficient $f_1$

In the long-wavelength limit, for each order $n \geq 1$, the terms containing $B_n$ and $B'_n$, and thus the variables $x_i$ and $x'_i$, in the system of boundary equations (56) are of negligible order relative to the terms containing $A_n$, $A'_n$, $C_n$, $C'_n$, and the inhomogeneous terms. Formally, this is seen by writing up and inverting the entire 6-by-6 matrix equation for the six coefficients for a given $n \geq 1$. A quicker way to see this is to write Eqs. (56c) and (56d) as

$$
\begin{pmatrix}
 h_0(x_1) & -j_0(x'_1) \\
 x_i h'_0(x_1) & -x'_i j'_0(x'_1)
\end{pmatrix}
\begin{pmatrix}
 B_n \\
 B'_n
\end{pmatrix}
\sim \varepsilon^2
\begin{pmatrix}
 A'_n j_0(x'_1) - A_n h_0(x_1) - j_0(x_1) \\
 A'_n j'_0(x'_1) - A_n h'_0(x_1) - j'_0(x_1)
\end{pmatrix},
$$

where we have used $\frac{b_c}{b'_c} \sim \varepsilon^2$ and $\frac{b'_c}{b_c} \sim 1$. Inserting the expressions for $B_n$ and $B'_n$ obtained by inversion of this system into Eqs. (56a), (56b), (56e), and (56f), we see that due to the factor $\varepsilon^2$ all terms related to $B_n$ or $B'_n$ are negligible in all four equations. In treating Eq. (56e) it might be useful to use the Bessel’s equation (C2). Consequently, returning to the dipole problem with $n = 1$, terms with $B_1$ or $B'_1$ are omitted and the system of equations reduces to four equations with four unknowns, namely, Eqs. (56a), (56b), (56e), and (56f) without the terms of $B_1, B'_1$. For $n = 1$ we thus obtain the simplified system of equations

$$
x x'_1 j'_1(x_1) + A_1 x_h h'_1(x_1) - 2C_1 h_1(x_1) = A'_1 x'_1 j'_1(x'_1) - 2C'_1 j_1(x'_1),
$$

$$
j_1(x_1) + A_1 h_1(x_1) - C_1 [x_h h'_1(x_1) + h_1(x_1)] = A'_1 j_1(x'_1) - C'_1 [x'_h j'_1(x'_1) + j'_1(x'_1)],
$$

$$
\eta_0 [x x'_1 j_1(x_1) + A_1 x_h h_1(x_1) + \frac{1}{2} C_1 x^2 h'_1(x_1)] = \eta_0 [A'_1 x'_1 j'_1(x'_1) + \frac{1}{2} C'_1 x'^2 j'_1(x'_1)],
$$

$$
\eta_0 \left[ x x'_1 j'_1(x_1) - 4x x'_1 j_1(x_1) - 4C_1 \eta_0 x_h h_1(x_1) - 4x_h h_1(x_1) + A_1 \eta_0 [x^2 h'_1(x_1) - 4x_h h'_1(x_1)] = A'_1 \eta_0 [x'_1 j'_1(x'_1) - 4x'_1 j_1(x'_1)] - 4C'_1 \eta_0 x'_1 j_1(x'_1),
$$

where we have rewritten the last two equations using the recurrence relations obtained from Eq. (C3)

$$
x g'_1(x) - g_1(x) = -x g_2(x),
$$

$$
g'_1(x) = -g_1(x) + \frac{2}{x} g_2(x),
$$

valid for any spherical Bessel or Hankel function $g$.

Simplifying the system of equations we multiply Eq. (B17a) by $(-1)$ and add to it Eq. (B17b), then use the recurrence relation (B18a). Equation (B17b) is multiplied by 2 and Eq. (B17a) is added while using the recurrence relation $x g'_1(x) + 2 g_1(x) = x g_0(x)$. We leave Eq. (B17c) as it is. To Eq. (B17d) we add 4 times Eq. (B17c) and use the recurrence relation (B18b). With some
rearrangements, these manipulations give

\begin{align}
A_1 x_c h_2(x_c) + C_1 x_c h_2(x_c) - A'_1 x'_c j_2(x'_c) - C'_1 x'_c j_2(x'_c) &= -x_c j_2(x_c), \\
A_1 x_c h_0(x_c) - 2 C_1 x_c h_0(x_c) - A'_1 x'_c j_0(x'_c) + 2 C'_1 x'_c j_0(x'_c) &= -x_c j_0(x_c), \\
A_1 x_c h_2(x_c) + \frac{1}{2} C_1 x_c^2 h'_0(x_c) - \tilde{\eta}_0 [A'_1 x'_c j_2(x'_c) + \frac{1}{2} C'_1 x'_c^2 j'_0(x'_c)] &= -x_c j_2(x_c), \\
A_1 h_1(x_c) - 2 C_1 h_1(x_c) - \tilde{\rho}_0 [A'_1 j_1(x'_c) - 2 C'_1 j_1(x'_c)] &= -j_1(x_c),
\end{align}

where \( \tilde{\eta}_0 x_c^2 = \tilde{\rho}_0 x_c^2 \) was used to simplify the last equation. The equations may be further simplified using the relevant scalings in the long-wavelength limit for the fluid droplet and the solid particle, respectively.

**a. \( f_1 \) for a suspended thermoviscous droplet**

In the long-wavelength limit for the fluid droplet case the scalings of Eq. (58) apply. Using the approximate expressions for the spherical Bessel and Hankel functions [Eq. (C5)] applicable for small arguments and examining the resulting system of equations (B19) one finds that some terms may be omitted to first order in \( \epsilon \). The simplified system of equations (B19) for the fluid droplet case takes the form

\[- \frac{3i}{x_c^2} A_1 + C_1 x_c h_2(x_c) - C'_1 x'_c j_2(x'_c) = 0, \tag{B20a} \]

\[-2 C_1 x_c h_0(x_c) - A'_1 x'_c + 2 C'_1 x'_c j_0(x'_c) = -x_c, \tag{B20b} \]

\[- \frac{3i}{x_c^2} A_1 + \frac{1}{2} C_1 x_c^2 h'_0(x_c) - \frac{1}{2} C'_1 \tilde{\eta}_0 x_c^2 j'_0(x'_c) = 0, \tag{B20c} \]

\[\frac{3i}{x_c^2} A_1 + 6 C_1 h_1(x_c) + A'_1 \tilde{\rho}_0 x'_c - 6 C'_1 \tilde{\rho}_0 j_1(x'_c) = x_c. \tag{B20d} \]

Subtracting Eq. (B20c) from Eq. (B20a) and using Eq. (B18b), we can express \( C'_1 \) by \( C_1 \),

\[C'_1 = \frac{x_c^2 h_1(x_c)}{\tilde{\eta}_0 x_c Q(x'_c)} C_1, \tag{B21a} \]

\[Q(x'_c) = x'_c j_1(x'_c) - 2 \left(1 - \frac{1}{\tilde{\rho}_0} \right) j_2(x'_c). \tag{B21b} \]

Then, using this relation to eliminate \( C'_1 \) in Eq. (B20a), we arrive at the first of the two equations in Eq. (B22). The second equation (B22b) is obtained by adding Eqs. (B20b) and (B20d) in order to eliminate \( A'_1 \), then making use of the recurrence relation \( 3 g_1(x) - x g_0(x) = x g_2(x) \). The resulting two equations for \( A_1 \) and \( C_1 \) are

\[- \frac{3i}{x_c^2} A_1 - C_1 \left[ x_c h_2(x_c) - \frac{x_c^2 h_1(x_c) j_2(x'_c)}{\tilde{\eta}_0 Q(x'_c)} \right] = 0, \tag{B22a} \]

\[\frac{3i}{x_c^2} A_1 + 2 C_1 \tilde{\rho}_0 \left[ \frac{3}{\tilde{\rho}_0} h_1(x_c) - x_c h_0(x_c) - \frac{x_c^2 h_1(x_c) j_2(x'_c)}{\tilde{\eta}_0 Q(x'_c)} \right] = (1 - \tilde{\rho}_0) x_c. \tag{B22b} \]

From this, and using again the relation \( 3 g_1(x) - x g_0(x) = x g_2(x) \), we obtain the dipole expansion coefficient \( A_1 \),

\[A_1 = \frac{\frac{1}{3} x_c^2 (\tilde{\rho}_0 - 1) [h_2(x_c) \tilde{\eta}_0 Q(x'_c) - x_c h_1(x_c) j_2(x'_c)]}{3 h_2(x_c) - 2 (\tilde{\rho}_0 - 1) h_0(x_c) \tilde{\eta}_0 Q(x'_c) - (2 \tilde{\rho}_0 + 1) x_c h_1(x_c) j_2(x'_c)}. \tag{B23} \]

This result, but with a small error in the numerator, was first obtained by Epstein and Carhart [30]. We reduce the factor by \( \tilde{\eta}_0 Q(x'_c) h_0(x_c) \) and use the explicit expressions for the Bessel and Hankel functions in Eq. (C4) to introduce the functions \( G(x_c) \) and \( F(x_c, x'_c) \) given explicitly in Eqs. (68b) and (68c), respectively,

\[G(x_c) = 1 + \frac{h_2(x_c)}{\tilde{\eta}_0 h_0(x_c)} \tag{B24a} \]

\[F(x_c, x'_c) = \frac{x_c h_1(x_c) j_2(x'_c)}{\tilde{\eta}_0 h_0(x_c) Q(x'_c)} \tag{B24b} \]

Then, using that \( f_1 = -6i x_c^{-3} A_1 \), we arrive at the final expression (68a) for the dipole scattering coefficient \( f_1^\# \).
b. \( f_1 \) for a suspended thermoelastic particle

In the long-wavelength limit for the solid particle the scalings of Eq. (63) apply. Using the approximate expressions for the spherical Bessel and Hankel functions [Eq. (C5)] applicable for small arguments and examining the resulting system of equations (B19) one finds that some terms may be omitted to first order in \( \varepsilon \). The simplified system of equations (B19) in the solid particle case takes the form

\[
-\frac{3i}{x^2} A_1 + C_1 x_i h_2(x_i) = 0, \quad (B25a)
\]

\[
-2C_1 x_i h_0(x_i) - A_1 x'_i + 2C'_1 x'_i = -x_i, \quad (B25b)
\]

\[
-\frac{3i}{x^2} A_1 + \frac{1}{2} C_1 x_i^2 h''_i(x_i) - \frac{1}{15} A_1 \eta \varrho x_i^3 + \frac{1}{10} C'_1 \eta \varrho x_i^3 = 0, \quad (B25c)
\]

\[
-\frac{3i}{x^2} A_1 - 6C_1 h_1(x_i) = -A'_1 \eta \varrho x_i' + 2C'_1 \eta \varrho x_i' = -x_i, \quad (B25d)
\]

Multiplying Eq. (B25b) by \((-\rho_0)\) and adding it to Eq. (B25d), then substituting \( C_1 \) using Eq. (B25a), and finally using the recurrence relation \( 3g_1(x) - x g_0(x) = x g_2(x) \) leads to the expansion coefficient \( A_1 \),

\[
A_1 = \frac{ix^2(\rho_0 - 1) h_2(x_i)}{3h_2(x_i) - 2(\rho_0 - 1) h_0(x_i)}. \quad (B26)
\]

Again, using that \( f_1 = -6i x^{-3} A_1 \) and introducing \( G(x) \) as defined in Eq. (B24a), we obtain after some rearrangement the final result for \( f_1 \) given in Eq. (70).

**APPENDIX C: SPECIAL FUNCTIONS**

The Legendre differential equation solved by Legendre polynomials \( P_n(\cos \theta) \) of order \( n \) is [58]

\[
\frac{1}{\sin \theta} \frac{d}{d\theta} \left( \sin \theta \frac{d}{d\theta} P_n(\cos \theta) \right) + n(n + 1) P_n(\cos \theta) = 0. \quad (C1)
\]

The Bessel differential equation solved by spherical Bessel or Hankel functions \( g_n(x) \) of order \( n \) is [58]

\[
x^2 g''_n(x) + 2x g'_n(x) = n(n + 1) g_n(x) - 2x g'_n(x), \quad (C2)
\]

with a prime indicating differentiation with respect to the argument. Useful recurrence relations for \( g_n(x) \) are

\[
\frac{d}{dx} [x^n g_n(x)] = -x^{-n} g_{n+1}(x), \quad (C3a)
\]

\[
\frac{d}{dx} [x^{n+1} g_n(x)] = x^{n+1} g_{n-1}(x). \quad (C3b)
\]

The lowest-order spherical Bessel functions \( j_n(x) \) and Hankel functions of the first kind \( h_n(x) \) are [58]

\[
j_0(x) = \frac{\sin x}{x}, \quad j_1(x) = \frac{1}{x} \left( \frac{\sin x}{x} - \cos x \right), \quad (C4a)
\]

\[
j_2(x) = \frac{1}{x} \left[ \left( \frac{3}{x^2} - 1 \right) \sin x - \frac{3}{x} \cos x \right], \quad (C4b)
\]

\[
h_0(x) = -i \frac{e^{ix}}{x}, \quad h_1(x) = -\frac{e^{ix}}{x} \left( 1 + \frac{i}{x} \right), \quad (C4c)
\]

\[
h_2(x) = i \frac{e^{ix}}{x} \left( 1 + \frac{3i}{x} - \frac{3}{x^2} \right). \quad (C4d)
\]

For small arguments, \( x \ll 1 \), to first order

\[
j_0(x) \simeq 1, \quad j'_0(x) \simeq -\frac{x}{3}, \quad j''_0(x) \simeq -\frac{1}{3}, \quad (C5a)
\]

\[
h_0(x) \simeq 1 - \frac{i}{x}, \quad h'_0(x) \simeq \frac{i}{x^2}, \quad h''_0(x) \simeq \frac{-2i}{x^3}, \quad (C5b)
\]

\[
j_1(x) \simeq \frac{x}{3}, \quad j'_1(x) \simeq \frac{x^2}{15}, \quad (C5c)
\]

\[
h_1(x) \simeq -\frac{i}{x}, \quad h'_1(x) \simeq -\frac{3i}{x^2}. \quad (C5d)
\]