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The scientific works of professor Keith Attenborough☆

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ABSTRACT

Prof. Attenborough's distinguished career spans over five decades during which he has made seminal contributions to the field of physical acoustics. His extensive research encompasses acoustic propagation in and above porous media, acoustic penetration into rigid frame and poro-elastic materials, and environmental noise control. This article celebrates his work highlighting its foundational basis, scientific impact, and practical applications.

1. Introduction

Prof. Attenborough's extensive research in physical acoustics is embedded in over 150 peer-reviewed papers (Scopus, May 2025), the first of which appeared in the early 1970s and the most recent over five decades later in 2025. With few exceptions, there has been no year since the early 1970s in which a publication relevant to acoustic propagation, ground impedance, or environmental noise control did not appear from Prof. Attenborough. This remarkable record of sustained scientific investigation is made even more impressive when considered alongside his contributions to teaching, mentorship, and professional development within the acoustics community.

Prof. Attenborough's interest in acoustics was triggered by Lord Rayleigh who, in his book *The Theory of Sound* [1] demonstrated inadequacies in theories of the absorption of sound in three-dimensional fluid media such as the atmosphere or the sea. This led him taking up a PhD entitled *Sound Dissipation in Porous Media* under the supervision of Prof. Lionel (John) Walker at the University of Leeds. He applied theoretical techniques typically used in underwater acoustics and sound propagation in suspensions to study sound absorption in fibrous and viscoelastic foam media. This innovative approach yielded predictions for sound absorption in fibrous materials, which showed an agreement with experimental data from glass fibre block samples. Furthermore, he provided a novel explanation of the physics of sound absorption in cellular viscoelastic materials corroborating and extending the conclusions of previous literature. By correlating theoretical models with experimental findings, he demonstrated that the dissipation of sound in these materials could be understood in terms of the microstructural properties of the media, without resorting to overly complicated measurement methods. His work has since become a cornerstone in the field of architectural acoustics, particularly in the understanding of sound absorption in porous materials, inspired new academic research and remained relevant to practical engineering applications.

Prof. Attenborough entered the field of acoustics at a time when advances in experimental techniques, numerical modelling, and materials science made it possible to build upon the theoretical foundations laid by Lord Rayleigh and to extend them to practical applications. Much of the early work in outdoor sound propagation relied on empirical formulations, such as simple inverse-square law models, with limited connection to underlying physical principles. Prof. Attenborough's research sought to bridge this gap, integrating rigorous mathematical modelling with carefully controlled experiments to improve our understanding of how sound interacts with porous surfaces, complex ground materials, and atmospheric conditions.

Early studies on ground impedance and the interaction of acoustic waves with porous media provided a framework that has remained central to research in outdoor sound propagation, noise control, and geophysical applications. His pioneering work on acoustic-to-seismic coupling has informed both military and civilian applications, including non-invasive soil characterisation, buried object (anti-

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personnel landmine) detection, and monitoring of subsurface environmental conditions. He has consistently championed the importance of linking theoretical predictions with real-world applications, a hallmark of his research philosophy.

It would be impossible to quantify fully the impact of Prof. Attenborough's works, just as it was impossible in Lord Rayleigh's time to foresee the lasting significance of his *The Theory of Sound*. In fact, if we consider the possible areas that physical acoustics broaches, the scientific works of Prof. Attenborough are extensive, as indicated in Fig. 1. While a detailed discussion of his body of work is beyond the scope of this article, its significance can be appreciated through an examination of five key areas to which he has mostly contributed.

2. Scientific areas

This section explores Prof. Attenborough's extensive research contribution to the five key areas: (1) the characterisation of porous and granular materials, (2) sound propagation over these media, (3) sound propagation into these media, (4) acoustic diffraction and scattering, (5) noise control, and environmental acoustics. His studies have yielded novel models for predicting sound absorption, scattering, and penetration, significantly improving our ability to assess and manipulate sound in real-world settings. By integrating rigorous mathematical formulations with empirical validation, he has refined predictive models for ground impedance, diffraction, and acoustic penetration into porous and rigid media. His work has also contributed to the development of advanced noise mitigation strategies, incorporating natural surfaces and novel engineered materials to optimise acoustic performance. Furthermore, his research into environmental effects, such as meteorological influences and vegetation, has deepened our understanding of outdoor sound propagation and enhanced methods for noise control. The subsections that follow provide an in-depth analysis of these contributions, highlighting both theoretical innovations and practical applications.

2.1. Acoustic wave propagation in porous and granular materials

One of the key strengths of Prof. Attenborough's research has been his consistent focus on developing robust theoretical models for predicting the acoustic behaviour of porous and granular materials. In his early work on fibrous absorbents [2–4], he proposed scattering-based models to account for oblique-incidence and the influence of microstructural parameters on wave propagation. The conclusion was that measuring characteristic impedance and the propagation constant at normal incidence is not sufficient to describe the properties of fibrous absorbents at oblique incidence. These studies laid the groundwork for the use of "effective fluid" bulk properties and relating them to those derived using scattering theories. These early studies established a foundation for understanding the complex interaction between sound waves and the microstructure of porous materials, although the models relied on idealised representations of the material structure, which may not fully capture the heterogeneity of real-world materials.

In later research [5,6], Prof. Attenborough extended these theories to more diverse porous materials, incorporating physically measurable parameters into the expressions for effective bulk properties. A significant shift in the field emerged when he developed a streamlined model for rigid porous materials such as soils and sands, whose microstructure is quite complex. His model predicted acoustical characteristics from five parameters: porosity, flow resistivity, tortuosity, and two shape factors. He simplified this approach by relating the tortuosity to porosity and postulating a relationship between the shape factors, requiring only two measurable parameters (porosity and flow resistivity) along with one shape factor whose value could be deduced from the comparisons of the model predictions with the data. This model outperformed empirical formulas that relied solely on flow resistivity, particularly for high-resistivity soils and sands at low frequencies.

A key challenge in classical porous media theories was the prediction of the slow wave in granular materials. Prof. Attenborough's work [7] tackled this issue by modifying the Biot viscodynamic operator to resolve inconsistencies between classical models for porous materials with rigid frame and Biot's theory. The modifications he introduced included the effects of the pore shape accounted for through static and dynamic shape factors. These advancements led to an improved alignment between Biot model predictions and experimental data for realistic porous materials such as soils. This work was particularly useful in the

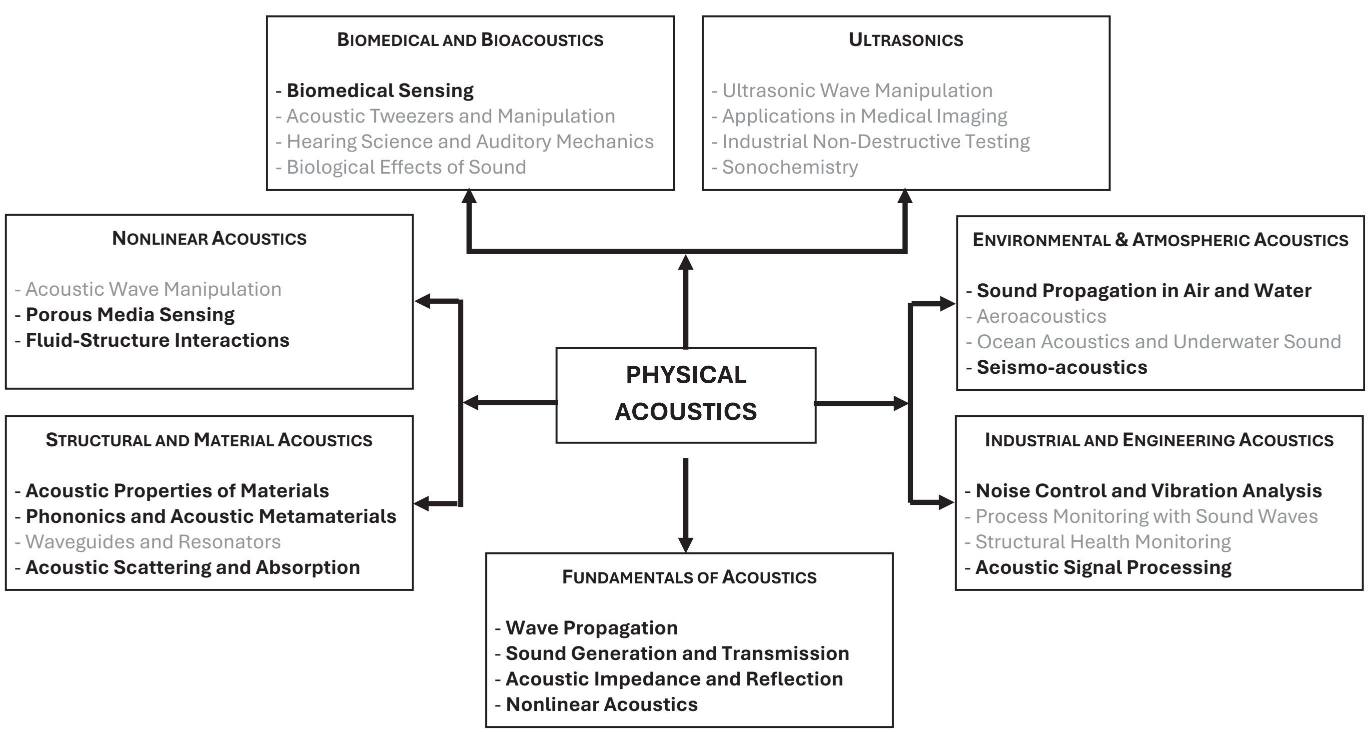

Fig. 1. Areas of research of Prof. Keith Attenborough (bold) within physical acoustics. *Framework developed by the authors to illustrate the scope of his contributions.*

study of high-frequency wave propagation in consolidated and unconsolidated granular materials.

The next stage of his research demonstrated the applicability of acoustic techniques for characterising granular materials and their microstructural properties. The move toward in situ measurements [8–10] marked a practical advancement, allowing for non-invasive acoustic techniques to measure soil properties such as the porosity, air permeability, and tortuosity. These methods offered significant advantages over traditional invasive techniques, particularly for monitoring seasonal changes in soil conditions. The agreement of acoustically derived parameters with conventional measurements (within a 10 % margin) underscores the accuracy of his models. They have significant implications for agriculture, geophysics, and environmental monitoring.

Later research focussed on designing porous materials with tailored, often simple microstructures for enhanced acoustic performance. In studies such as [11–13], he explored micro- and macro-structural designs for sound absorbers, including labyrinthine slit perforations and modular porous panels. These studies demonstrated how specific microstructures could be engineered to achieve sub-wavelength absorption at low frequencies, paving the way for innovative acoustic materials with practical implications for noise mitigation and architectural acoustics.

Prof. Attenborough's work on labyrinthine channels in non-porous and microporous skeletons [14] is an important scientific development. By combining theoretical modelling, additive manufacturing, and experimental validation, the potential for thin 3D printed panels with extreme tortuosity to achieve significant sound absorption at low frequencies was demonstrated. This work represents a significant progress in the design of acoustic metamaterials, addressing challenges related to manufacturing and scaling. The use of advanced manufacturing techniques such as 3D printing [15] to validate theoretical predictions exemplifies the commitment to bridging the gap between theory and practice.

A notable aspect of Prof. Attenborough's research is its interdisciplinary nature, with applications extending beyond traditional acoustics. His application of acoustic methods and models to stereolithographic bone replicas [16] opened new avenues for studying cancellous bone microstructures and their acoustic properties. His work also explored the prediction of dynamic drag parameters in packings of spheres using a cell model approach [17,18]. These studies derived analytical expressions for dynamic and direct current permeability, high-frequency limit of tortuosity, and the characteristic viscous dimension, showing good agreement with published data and numerical results for simple cubic and random spherical packings.

2.2. Acoustic propagation above porous media

Prof. Attenborough's works on acoustic propagation above porous media has significantly influenced the field of environmental acoustics, providing a robust theoretical foundation as well as practical tools for modelling sound behaviour in outdoor environments. He has systematically addressed key challenges associated with predicting sound propagation over various ground surfaces. Through a combination of theoretical modelling, empirical validation, and innovative applications, he has advanced the understanding of ground impedance and its role in sound attenuation and reflection, while also critiquing and improving the limitations of existing models.

A central theme in his work was the study of sound interaction with different ground surfaces, the development of impedance models, and the effects of environmental factors on sound propagation. In [19], he provided an exact solution for sound propagation over a porous half-space, clarifying the role of surface wave poles and refining the locally reacting boundary assumption. This foundational work led to the development of improved impedance models [5,6,20–24] which enabled the accurate prediction of the acoustic characteristics of various ground surfaces and their effects on outdoor sound propagation. In [22] he introduced a theoretical four-parameter model that accounted for the porosity, flow resistivity, tortuosity, and pore shape factor of soil. Supported with experimental data he demonstrated that the new model was superior in terms of its accuracy over single-parameter semi-empirical models commonly used at the time. His multi-parameter approach to porous ground modelling allowed for more precise predictions of the acoustic surface impedance and highlighted the inadequacies of some simplified models for capturing the complexities of porous media. He also demonstrated that the acoustical properties for certain classes of soils, e.g., ploughed layers, can be predicted with a theoretical model involving only the effective flow resistivity and rate of porosity change [22].

Throughout his career, Prof. Attenborough has been a vocal critic of semi-empirical models, which often lack the physical rigor required for reliable predictions of outdoor sound propagation. In [21], he critiqued earlier asymptotic solutions for sound propagation over absorbing boundaries, emphasising the necessity of incorporating surface wave effects. His more recent review [25] provided a broader critique of single-parameter models, demonstrating their failure to meet physical reality and causality conditions that can only be satisfied if the expression for the surface impedance is analytic. He advocated for physically admissible multi-parameter models, such as the two-parameter variable porosity and slit-pore microstructural models, which consistently outperform semi-empirical models in both short- and long-range propagation scenarios [22]. These models have become benchmarks in the field, offering reliable predictions across diverse ground surfaces, including grassland, forest floors, and gravel.

Continued development of improved models for sound propagation above rigid porous media, e.g., [26–28], and their application to realistic outdoor surfaces such as snow [20] and farmland [30] provided a foundation for more accurate predictions and robust inversion of the ground properties from acoustical data. A strong aspect of his work is the continuous reliance on experimental validation. In [28] and [29] he developed methods to measure ground impedance using microphone arrays, refining indirect in situ techniques. The agreement between his impedance models and measured data [22–24] suggests that the modelling approach captures essential physical parameters accurately. His validation efforts in [31], comparing various sound propagation models, further solidified confidence in his numerical and analytical methodologies. His work on sound propagation above rigid porous media has led to the development and subsequent revisions of the ASA/ANSI S1.18–2018 (R2023) standard to determine the acoustic impedance of ground surfaces. He was the Chair of the S1/WG 20 working group that has developed this standard that now incorporates his two-parameter model proposed in [22].

An important aspect of Prof. Attenborough's commitment to improving outdoor sound propagation predictions has been his investigations into the influence of atmospheric factors drawing on ray-tracing methods and developing numerical solutions for stratified moving atmospheres [32–34]. However, challenges remain in addressing large-scale environmental variability, as seen in [31], where different computational methods yield varying results under complex atmospheric conditions. His research on ground characterisation under different meteorological conditions [35,36] highlighted his awareness of real-world complexities and pointed out to the need for a more comprehensive approach to integrate dynamic environmental factors over long propagating distances. His following work [37] on ground attenuation for moving sources was an important step toward practical applications that require further validation under diverse conditions.

Studies of complex surfaces, including layered [38,39], rough [40,41], and mixed-impedance [42] terrains further demonstrated the importance of considering surface microstructures in propagation models. The work in [39] addressed extended-reaction ground and was particularly relevant for snow-covered surfaces and multi-layered ground types. However, while these studies advanced our understanding of the phenomenological nature, they also reveal challenges in model generalisation. The variability of impedance parameters across different terrains suggested that further research was needed to refine these models for broader applications. He highlighted the challenges in modelling highly heterogeneous outdoor environments where multiple factors such as vegetation, soil moisture, and terrain irregularities interact in complex ways that are not always easily captured by existing models, e.g., [43]. He addressed these challenges in his follow-on works.

In addition to linear acoustics, Prof. Attenborough has made significant contributions to the study of nonlinear acoustic propagation. His more recent studies [44–46] focussed on high-amplitude pulse propagation and laser-generated acoustic shocks in porous and elastic media. His research in [44,47] investigated shock wave interactions with porous materials, revealing the effects of nonlinear attenuation and shape distortion due to factors such as Forchheimer's nonlinearity and hydrodynamic effects, while [45] explored laser-induced acoustic shocks as potential tools for laboratory simulations. These works demonstrated a shift toward practical and high-energy applications, but they also introduced additional complexities that might require interdisciplinary approaches, integrating materials science and fluid dynamics more deeply.

2.3. Acoustic penetration into rigid frame and poro-elastic media

Prof. Attenborough's works on acoustic penetration into rigid frame and poro-elastic media have provided significant theoretical and experimental insights into acoustic-seismic coupling, wave propagation in porous media, and their practical applications.

Early investigations laid the foundation for understanding sound penetration into rigid porous media. In [48] he established a method for asymptotic approximations in wave field predictions at an interface between air and a rigid porous medium, confirming the locally reacting nature of porous boundaries. This was followed by the development of a Biot-Stoll-based model for porooelastic soil layers and validated impedance predictions with experimental data [49]. The comparison between rigid- and elastic-frame models for porous media in [50] further refined these theoretical approaches, emphasising frequency-dependent differences in behaviour. Although these works demonstrate rigorous mathematical modelling and validation through controlled experiments, their reliance on idealised boundary conditions and limited material parameter variability somewhat restricts their applicability to heterogeneous and naturally occurring soil structures.

A critical step in Prof. Attenborough's research was the exploration of seismic wave generation induced by airborne sound. In [51] he extended earlier models to investigate acoustic-to-seismic energy transfer, demonstrating reasonable agreement between theoretical predictions and field measurements. This work introduced key factors such as soil layering and attenuation effects, which were further refined in subsequent studies. In [52] he expanded upon this by identifying an air-coupled Rayleigh wave and characterising its significant contribution to surface particle motion. These contributions advanced the understanding of seismic energy transmission, but the practical challenges of parameter estimation and the sensitivity of results to soil heterogeneity remained as open questions.

His continued pursuit of improved measurement techniques led to studies employing advanced sensing methodologies. In [53] Laser-Doppler vibrometry was utilised to overcome limitations of geophones showing improved accuracy in measuring acoustic-to-seismic coupling. Similarly, in [54] he employed accelerometers to analyse the nonlinear response of buried objects. This paper showed the potential of acoustics for a safe and non-invasive method for detecting objects buried in the ground.

The application of wave propagation principles to soil characterisation further underscores the practical implications of Prof. Attenborough's work. In [55] he demonstrated the relationship between the elastic wave velocities and penetrometer resistance, offering a potential non-invasive means of soil property assessment. Similarly, in [56] he extended acoustic-to-seismic measurement techniques to estimate soil strength profiles in agricultural settings. These works showcase the interdisciplinary applications of acoustic-seismic coupling, yet they also reveal the challenges of adapting theoretical models to dynamic and variable field conditions.

A more applied aspect of Prof. Attenborough's research in this area is the study of ground vibrations induced by explosions. In [57] he provided empirical data on seismic wave generation from detonations and compared measured signals with numerical models. This work is particularly notable for its real-world implications in blast impact assessment and structural safety. However, while the predictions align well with observations, the study focused on a limited range of soil types so a need for broader validation under more diverse environmental conditions was suggested.

2.4. Acoustic diffraction and scattering

Prof. Attenborough's research on diffraction and scattering has deepened our understanding of sound field in presence of rough surfaces and acoustic scatterers and barriers. His research has improved predictive models for noise control applications, particularly in urban and natural environments. By combining theoretical frameworks with experimental data he has provided practical solutions for mitigating environmental noise.

One of the central themes of Prof. Attenborough's research has been the impact of acoustic scatterers on sound propagation. The analysis of sound dissipation by a small cylindrical obstacle [58] provided an early example of how effects of viscous and thermal fluid waves at the boundary contribute to attenuation. Another work in this area explored sound absorption in fibrous media employing multiple scattering [59]. Among other studies, these works laid the groundwork for better understanding the acoustic behaviour of highly porous fibrous materials avoiding reliance on phenomenological parameters.

He also studied scattering phenomena on a larger scale, such as those in forested environments [60]. This compared measurements of sound attenuation in British woodlands with a model that summed contributions from the ground, trunks, branches, and foliage, using an empirically modified multiple scattering approach. While the composite model tolerably predicted key features of the measured spectra, further refinement would be needed to capture the intricacies of acoustic propagation in diverse woodland areas. The work on forested environments was further expanded upon in [61] which focussed on reverberation and attenuation in a pine forest. The study proposed that high-frequency attenuation and reverberation are dominated by multiple scattering among tree trunks and highlighted the limitations of simple addition when accounting for the interaction between ground effect and trunk scattering. The latter was proposed to be tackled with a phenomenological adjustment of the ground effect. The study found that the widely used Dutch–Scandinavian noise prediction scheme significantly underpredicted measured attenuation, indicating a need for improved predictive models [61].

Following his studies on sound propagation in forests and other complex natural environments, Prof. Attenborough extended his investigation of scattering phenomena to more controlled configurations. The boundary integral equation method was employed [62] to predict the acoustic field due to a point source above a rigid porous half-space containing a smooth rigid obstacle. The numerical solution demonstrated good agreement with analytical results for scattering by a rigid sphere and rigidly backed layer, reinforcing the robustness of the boundary integral approach. In [63], boundary integral equations and the semi-analytical multiple scattering techniques were used to resolve acoustic scattering problem for an array of cylinders in air aligned parallel to the rigid or impedance surface. This work showed the interference of the ground effect with the band gaps typical to the periodic array. The semi-analytical solution in this study was enabled by earlier work of Prof. Attenborough on surface roughness [64] offering an exact solution of acoustic scattering by a surface modelled as a distribution of semi-circles embedded into a hard surface. In [65] Prof. Attenborough investigated diffraction problems for sound propagating over convex impedance surfaces. With the help of theoretical calculations, a rigorous analogy was established between sound propagation above a large circular cylinder and propagation in a medium where the sound speed varies exponentially with height, differing from the commonly used bilinear profile of sound speed.

The characterisation of rough surfaces, and their impact on acoustic surface properties (i.e., impedance) and reflected acoustic wavefield have been another focus of Prof. Attenborough's research. In [66] an extended boss theory was proposed in application to measurements of the impedance of a rough surface. The proposed heuristic model of rough impedance surface explained instances where the impedance reactance exceeds resistance at low frequencies and when the measured ground impedance tends to zero at the higher frequencies. The study further demonstrated that the model matched the measurements made with an elevated source and vertically separated receivers, reinforcing its practical applicability. This work was later compared with heuristic extension of Twersky's model [43] indicating that the modified Twersky theory performed well over a range of rough impedance surfaces including sand surfaces and uncultivated soil. These studies extended the relevance of the effective impedance models to engineering applications, such as urban noise control and ground impedance modelling. Further improvement of boss theories was proposed in [64] by constructing a semi-analytical model of multiple scattering of cylindrical acoustic waves.

Work on rough sea surfaces [67,68] further highlights the interdisciplinary applications of Prof. Attenborough's research, demonstrating how effective impedance models can predict sonic boom distortion and atmospheric sound propagation. Additionally, in [67] the effect of roughness-induced surface waves on the excess attenuation was investigated for the range of grazing angles.

A multiple scattering approach was also employed to investigate sound propagation in airborne particulate suspensions [69–72]. In [71,72] audible and ultrasound waves were used to predict the effects of particle size distribution on sound attenuation. In [71] the fractal modification of scattering theory was extended to the case of airborne particulate suspensions to recover the fractal dimension of the suspension which was linked to particle irregularity and aggregation. Pulverised coal flows were considered in [72] demonstrating the potential for monitoring changes in particle size by measuring cross-pipe sound attenuation and applying multiple scattering approach extended with the fractal dimensions approach.

Prof. Attenborough addressed the diffraction problems in application to acoustic performance of noise barriers. A hybrid boundary integral/fast field program method was developed in [73] to assess the acoustical performance of the barriers in the presence of an arbitrary sound speed profile, predicting a considerable reduction in the insertion loss performance under moderate downwind conditions. In [74] the diffraction of sound from a dipole source near a barrier or mixed impedance ground surface was tackled with a closed-form solution of the diffraction problem. This work had applications relating to transportation noise prediction, particularly railway noise abatement. The research on sound diffraction from moving sources [75] resulted in a new model showing that motion-induced effects must be accounted for accurate prediction of the sound field. It was also found that noise barriers remain effective for moving sources despite motion-induced variations. In [42], he showed that sound propagation over mixed-impedance ground can be more accurately represented when the averaging of sound pressures across different impedance regions is carried out in the pressure domain rather than by averaging decibel levels weighted by Fresnel zone area.

In his later career, Prof. Attenborough introduced the term "diffraction-assisted ground effect" to describe the strong enhancement of soft-ground effects caused by the interaction between ground impedance and diffracted sound waves. This concept reflected his enduring interest in how diffraction influences outdoor sound propagation, and it was revisited in studies of environmentally responsive surfaces, such as green roofs and vegetated grounds, where soft-ground mechanisms play a key acoustic role.

Finally in this section, Prof. Attenborough's work on periodic arrays and metamaterials explored acoustic transmission through periodic arrays and of the use of analytical approximations for low-frequency band gaps [76–80]. A semi-analytical model for sound propagation through a periodic array of cylinders with porous covering was proposed in [76] demonstrating the covering thickness effect on the sound attenuation spectrum of the transmitted acoustic wave. An effect of locally resonating scatterers in [78,79] were modelled with the multiple scattering technique and low-frequency approximations showing the advantage of metamaterial structure in sound transmission problems at low frequencies. An effective medium approach was investigated in [78–80] showing its efficiency in predicting metamaterial performance and periodicity effect. A more recent contribution [81] focussed on the effects of scattering by a rough surface made of periodically and randomly spaced elements of various cross-sections, providing new perspectives on how engineered surfaces can enhance sound absorption. His investigations into airborne surface waves effect [82,83] for porous layers and periodically rough surfaces illustrate the practical applications of his theoretical models in noise reduction technologies.

2.5. Noise control and environmental acoustics

This article would not be complete without a discussion of Prof. Attenborough's extensive body of research on noise control and environmental acoustics. His works in this area addresses a diverse range of topics, from theoretical modelling to practical applications, and has significantly contributed to understanding and mitigating environmental noise. They demonstrates a consistent focus on the interaction between sound and ground surfaces, and the development of innovative noise control measures, often grounded in empirical investigations and theoretical advancements.

Early research reflected a strong emphasis on noise prediction models and background noise surveys. In [84,85] he explored the challenges of estimating background noise levels in different environments. By employing multiple regression analysis of extensive data collected by Open University students, he developed models to predict background noise levels based on area type, time of day, and proximity to major noise sources. These studies highlighted significant limitations, particularly the large standard error of prediction (10.2 dB(A)), underscoring the difficulty of solely relying on such parameters for accurate noise estimation. Nevertheless, these foundational studies provided critical insights into the variability of background noise and questioned the overestimation tendencies of the British Standard BS 4142:1967.

Prof. Attenborough's work on ground effects and the interaction of sound with various surfaces has been particularly impactful. In [20] he examined the propagation of highway noise over impedance boundaries, focussing on surface waves and impedance characteristics. This study combined theoretical predictions with empirical data, offering valuable insights into how ground type influences noise attenuation. Later, in [86] he extended this work by incorporating turbulence and refraction effects into ground impedance models, providing a more comprehensive understanding of how environmental factors influence noise propagation. The findings indicated that the low-frequency noise attenuation could be optimised by selecting specific ground surface parameters, a theme revisited in numerous subsequent studies.

His contributions to the field of environmental noise prediction were further exemplified in [87] where area-based noise prediction methods were developed. These models, derived from regional data, showcased the potential for a national framework for ambient noise prediction. This work emphasised the importance of incorporating region-specific coefficients to improve prediction accuracy and to enhance practical applications in urban planning and environmental noise management.

Prof. Attenborough's research has also delved into the complexities of sound propagation in controlled environments. For instance, in [88] he applied statistical energy analysis (SEA) to predict sound fields in rooms with noise sources showing that SEA provided more accurate predictions than traditional methods based on Sabine's theory. This work demonstrated his ability to address noise control challenges across diverse contexts, from outdoor environments to indoor spaces.

In the area of transportation noise mitigation, Prof. Attenborough's studies have consistently explored innovative solutions. In [89] he analysed noise generated by aircraft engines on the ground incorporating the ground effect and impedance discontinuities into predictive models. His findings highlighted the influence of the source directionality and ground impedance on the noise levels and provided valuable data for airport noise management. Similarly, [90,91] focussed on surface transport noise abatement through ground treatments and artificial roughness configurations. The introduction of lattice designs and acoustically soft ground surfaces demonstrated significant potential for reducing traffic noise without requiring traditional noise barriers. These findings are particularly compelling given their practicality and adaptability to urban and rural settings.

A recurring theme in Prof. Attenborough's work is the use of natural and sustainable solutions for noise control. In [92–94] he explored the role of vegetation and greening strategies in reducing noise levels. His investigations into sound propagation through crops and the acoustical properties of hedges revealed the interplay between the ground effects and vegetation, emphasising the importance of optimising natural surfaces for noise mitigation. Furthermore, in [94] he reviewed the physics underlying greening strategies identifying key contributors to sound attenuation, such as viscous drag and heat exchange at leaf surfaces. These studies not only showcased the potential of natural noise reduction methods but also highlighted the need for improved predictive models to exploit fully their benefits.

Prof. Attenborough's later research expanded into material science and the development of novel sound-absorbing materials. In [95,96] he investigated the potential of slitted sound absorbers and wood chip-based materials for sustainable noise control. His work on wood chip absorbers, in particular, demonstrated the feasibility of creating eco-friendly materials with the acoustic performance comparable to synthetic counterparts. By combining theoretical modelling with empirical validation, these studies illustrated his commitment to advancing sustainable solutions in acoustics.

Prof. Attenborough's collaborative endeavours in large-scale experimental studies, such as those reported in [97,98], further underscore his contributions to practical noise control applications. The studies on blast sound absorbers at Fort Drum provided critical data on high-energy noise mitigation, revealing the effectiveness of specific surface treatments in reducing blast sound over varying distances. The experiments not only validated theoretical models but also offered actionable insights for military and industrial noise management.

Meteorological effects on noise mitigation continued to be a significant focus of Prof. Attenborough's work. In his more recent work [99] he investigated the influence of atmospheric conditions on the performance of low parallel wall structures for road traffic noise reduction. His findings demonstrated that while meteorological factors could significantly alter noise shielding at higher frequencies, the overall performance of such structures remained robust under moderate atmospheric conditions. This research highlighted the importance of accounting for environmental variables in noise control designs.

3. Summary

Prof. Attenborough's sustained contributions to the field of acoustics have been transformative, significantly advancing our understanding of sound propagation, acoustic materials, and environmental noise control. His groundbreaking research spans five major areas: the acoustics of porous materials, sound propagation over porous surfaces, acoustic penetration into rigid-frame and poro-elastic materials, diffraction and scattering, and noise control. Over a distinguished career, he has developed and experimentally validated new theoretical models and used his research for practical applications to address complex challenges in acoustics laying a foundation for future innovation.

One of Prof. Attenborough's notable achievements is the development of theoretical frameworks that connect the microstructure of porous and granular materials to their macroscopic acoustic properties. Early in his work he introduced models capable of predicting sound absorption in fibrous and granular materials with remarkable accuracy. These models, validated by experimental data, have since become benchmarks in the field. Many of these models relied on idealised assumptions of material properties allowing future research to focus on incorporating more complex and realistic pore geometries and the heterogeneity of real-world materials. Additionally, advancements in additive manufacturing have enabled the creation of novel acoustic materials, but challenges related to scalability and cost-effective production methods remain. These limitations provide opportunities for further exploration, especially in developing sustainable and high-performance acoustic materials.

In the realm of sound propagation over porous media, Prof. Attenborough's work has significantly improved predictive accuracy through multi-parameter impedance models. His models have enhanced our ability to account for the influence of the ground structure and environmental factors, e.g., roughness, pore size gradient atmospheric variations, on sound propagation. His well-known "crusade" against semi-empirical, non-causal one-parameter ground impedance models, often delivered with a characteristic mix of rigour and dry humour, became an enduring hallmark of his legacy. His commitment to bridging theory and practice was also evident in the comprehensive datasets of measured ground impedance parameters he compiled. These data provided a practical foundation for adopting physically based two- and three-parameter models, helping to move the field beyond oversimplified, single-parameter descriptions. While these contributions have advanced the field, challenges still exist in extending model predictions to account for large-scale environmental variability and atmospheric dynamics. Emerging technologies, such as machine learning, offer promising avenues for refining parameter estimation and enhancing predictive capabilities in outdoor acoustics.

Prof. Attenborough has also made substantial contributions to understanding acoustic wave penetration into rigid-frame and poro-elastic media. His research has advanced the practical application of acoustic-to-seismic coupling for subsurface detection, soil characterisation, and environmental monitoring. Despite these advancements, the inherent variability of natural soils and environmental complexities, such as temperature fluctuations and vegetation cover, present challenges for universal model applicability. Future efforts could integrate remote sensing, sensor fusion, data-driven modelling, and interdisciplinary collaboration to expand the utility of acoustic-to-seismic techniques across diverse environmental contexts.

In the study of diffraction and scattering, Prof. Attenborough's research has provided robust models for sound propagation in complex environments, including forests, urban spaces, and engineered surfaces. These models have been instrumental in designing noise mitigation strategies, such as barriers and structured materials. He later extended this line of research through the concept of "diffraction-assisted ground effect," linking diffraction mechanisms with soft-ground and green-roof acoustics. However, further refinement of predictive models for irregular surfaces and non-homogeneous media is needed to improve their real-world applicability. The integration of advanced experimental techniques, such as 3D printing, could lead to innovative solutions for noise control and sound manipulation.

Finally, Prof. Attenborough's work in noise control and environmental acoustics has addressed challenges in transportation noise mitigation, ground effects, and sustainable sound absorption materials. His investigations have emphasised the potential of natural and eco-friendly solutions, such as vegetation and wood-based materials, for noise reduction. Future research can explore adaptive noise management systems, smart surfaces, and large-scale experimental validation to optimise these approaches for diverse environments. Sustainable material development and the application of green infrastructure also offer promising opportunities for advancing noise control technologies.

In summary, Prof. Attenborough's research has laid a comprehensive foundation for future work in acoustics. Key directions include using physics based machine learning models for parameter estimation and real-time noise prediction, developing advanced acoustic metamaterials with enhanced absorption properties, and exploring scalable, sustainable materials for noise reduction. Additionally, integrating enhanced modelling approaches to account for environmental variability and drawing on geophysical sensing for large-scale subsurface monitoring are promising areas for further development. Prof. Attenborough's legacy of pioneering research ensures that his contributions will continue to inspire innovation in theoretical and applied acoustics, fostering advancements in noise management and engineered acoustic solutions. A key legacy of his work is the 2nd edition of the Predicting Outdoor Sound textbook that is a comprehensive reference for students, academics, researchers and consultants studying problems related to outdoor sound propagation and environmental noise control [100].

CRediT authorship contribution statement

David L. Berry: Conceptualization, Writing – original draft. **Shahram Taherzadeh:** Writing – original draft. **Olga Umnova:** Writing – original draft. **Anton Krynkin:** Writing – original draft. **Kiril Horoshenkov:** Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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