Acoustics Apps: Interactive simulations for digital teaching and learning of acoustics

Lennart Moheit, Johannes D. Schmid, Jonas M. Schmid, Martin Eser, and Steffen Marburg

Citation: The Journal of the Acoustical Society of America **149**, 1175 (2021); doi: 10.1121/10.0003438
View online: https://doi.org/10.1121/10.0003438
View Table of Contents: https://asa.scitation.org/toc/jas/149/2
Published by the Acoustical Society of America

JASA ARTICLE

Acoustics Apps: Interactive simulations for digital teaching and learning of acoustics

Lennart Moheit,[a] Johannes D. Schmid, Jonas M. Schmid, Martin Eser, and Steffen Marburg
Chair of Vibroacoustics of Vehicles and Machines, Technical University of Munich (TUM), Boltzmannstrasse 15, 85748 Garching, Germany

ABSTRACT:
This paper presents the Acoustics Apps, an e-learning platform that offers an interactive and playful environment for teaching and learning the principles of acoustics and vibration. The Acoustics Apps address the increasing demand for digitized teaching methods, which might be suitable for home schooling or as a complement to physical experiments by adding interactive simulation. The apps combine learning by experimenting, observing, and exploring using state-of-the-art scientific methods and numerical simulations. The ability to visualize and control acoustic phenomena facilitates understanding of the relevant physical principles. The apps are designed to be used intuitively and can be tailored to suit the existing knowledge of the user. As such, a wide range of users can benefit from this learning aid. It has been developed to allow barrier-free access to modern educational tools, requiring only a device with a browser and Internet access. The necessary computing power is provided by an external server using the COMSOL Server™ technology. The Acoustics Apps are freely available for academic and teaching purposes at apps.vib.mw.tum.de. https://doi.org/10.1121/10.0003438

(Received 23 October 2020; revised 7 January 2021; accepted 13 January 2021; published online 18 February 2021)

[Editor: James F. Lynch] Pages: 1175–1182

I. INTRODUCTION

The phenomena of acoustics and vibration are generally invisible to the human eye and, as such, often difficult to visualize. However, using suitable experiments, it is possible to illustrate their physical effects and elucidate the underlying theory (Angell *et al.*, 2004; Hodson, 1988). Feynman *et al.* elevate the experiment as *the test of all knowledge* to the principle of science and the *sole judge* of scientific "truth" (Feynman *et al.*, 2011, Chap. 1, p. 2). Experiments hint at physical theories and serve to confirm the laws derived from them. In education, experiments are primarily understood as "showing the theory in practice" (Angell *et al.*, 2004, p. 697) and indeed, they often help students to understand an underlying theory in greater depth. Furthermore, experiments create a vivid learning atmosphere and appear to many students as an interesting, "fun and easy" (Angell *et al.*, 2004, p. 697) element of their physics lessons.

However, despite these familiar benefits, there are certain barriers to the use of experiments in school and university teaching. Even though some experiments can be conducted with very basic equipment, experiments in the field of acoustics often necessitate large and expensive laboratories and measurement apparatus, such as an anechoic chamber, a reverberation room, transducers, and specimens. However, most schools and educational institutes do not generally have access to such professional equipment. Not only the experiment itself but the preparatory and follow-up activities are generally so time-consuming that teaching staff may choose to forego experiments in class due to the time restrictions of their tight curricula. As a result, many pupils and students are likely to have a limited understanding of the underlying theory.

Remote experiments (Cooper and Ferreira, 2009) facilitate access to laboratories at great distances to students, with limited space or low accessibility and especially for students with disabilities. Thanks to recent technological developments and the widespread availability of smartphones and tablet computers, experiments are now able to be conducted using the sensors available with such devices, rather than expensive measuring apparatus (Klein *et al.*, 2014; Kuhn and Vogt, 2015). It is also possible to use pocket calculators with graphics capability for the acquisition and evaluation of measurement values (Lampe *et al.*, 2015). Virtual reality is also applied in research and teaching, based on recent developments and the available technologies of the approach (ITA Aachen, 2020a; Shin, 2002). However, this may not be appropriate for computing and visualizing complex physical problems, which cannot be performed on standard user devices. Furthermore, a head mounted display or other device may be required for an optimum user experience (Shin, 2002), which brings back the barrier of high cost.

Computer-aided techniques are a powerful alternative and an effective enhancement to traditional experiments (Chang *et al.*, 2008; Holec *et al.*, 2004; Ortega and Bravo, 2000). There are several applications in which they can save time and money compared to real-world experiments. The simulations and the learning environments they create can

[a]Electronic mail: apps@vib.mw.tum.de, ORICID: 0000-0002-3081-3980.

be understood as *virtual experiments* or *virtual labs* (Haddad and Jurich, 2002). In the context of acoustics, virtual experiments enrich perception, as they enable visualization of ordinarily purely audible phenomena. A distinction should be made between applets, which calculate and visualize analytical solutions of simple problems, and numerical methods for solving more complex mathematical problems, for example, using the finite element method (FEM) (Ihlenburg, 2006), the boundary element method (BEM) (Marburg and Nolte, 2008), or ray tracing (Pierce, 2019). Several interactive applets for teaching and learning physical phenomena are freely available online, some of which include applications for acoustics and vibrations, such as "PhET" (Wieman *et al.*, 2008), "Interactive Apps" (Müller, 2020), and "ITApp" (ITA Aachen, 2020b). What these platforms have in common is that the complexity of the problems dealt with is tied to the existence of an analytical solution, i.e., highly complex problems can only be visualized as animations without interactive control. Other browser-based tools use animations but without the possibility of manipulating or controling them, such as the "ISVR Teaching Material on Waves and Acoustics" (Mary *et al.*, 2020) and "Dan Russell's Acoustics and Vibration Animations" (Leslie, 2001; Russel, 2020).

Some interactive learning aids are only available at a charge and are therefore not accessible to all students and teachers. This is also the case with most FEM applications, which are expensive and require extensive computing power. The model quality has to be estimated to ensure that both model results are physically meaningful and sufficiently accurate for their intended purpose. The problems have to be prepared, solved, and interpreted, which demands a high degree of personal effort and expertise and are therefore usually only used by experts in possession of costly software licenses.

This article presents the browser-based e-learning platform *Acoustics Apps*, which uses numerical methods. It aims to support teaching, understanding, and learning phenomena in the field of acoustics and vibration and to enable solutions to be found for complex physical and technical problems. The primary objective of the Acoustics Apps is to serve as a digital teaching aid that applies professional simulation tools in a meaningful and enjoyable way to support the learning process. The apps contain virtual experiments that are designed to be used intuitively by students and teachers without requiring any specialist knowledge or equipment other than a digital device with a web browser and an Internet connection. The project thus addresses the increasing demand for didactically meaningful, digital learning and teaching aids that enable independent preparatory and follow-up work in schools and universities. The Acoustics Apps create barrier-free access to knowledge, findings, and visualizations that were previously only available at considerable cost and therefore not accessible to all students.

II. CONCEPT AND TECHNOLOGY

A novel, simulation-based e-learning platform is being developed by the authors and is freely available for academic use from the website of the Acoustics Apps (Acoustics Apps, 2020). It is based on COMSOL Server™ (COMSOL, Inc., 2020) and calculations are conducted numerically, for instance, using FEM, BEM, or ray tracing. Calculations are performed on a remote server and the user's PC or mobile device (tablet or smartphone) is responsible for visualization and control in a standard web browser with Internet access.

For every problem there is a standalone app in the application library (see Fig. 1), which is regularly updated and enhanced as required. Problems are often explored from an engineering point of view, with an applied and technical focus, in which many of the numerous facets of acoustics and vibration are touched upon, from the physical principles of wave phenomena to the acoustics of musical instruments. Often, one app can deal with several problems or multiple apps can cover the same topic from different perspectives and can be regarded as complementary to each other. They either offer different views of a particular problem, have a different practical context or represent different levels of complexity. Some apps even enable the complexity of a problem to be examined at varying depths and thus address the needs of different user groups or levels of expertise. An example of this is the *impedance tube* app, which shows the basic effects of absorption, reflection, traveling and standing waves under simple boundary conditions as well as for complex porous materials. Another example is the *wind channel* app, which is used to investigate objects of diverse complexity in the flow.

The apps are aimed at both everyday users and specialists, ranging from school pupils and students to scientists and teachers. The aim is to provide learners with a supplement to traditional learning materials and to give teachers a helping hand in devising clear and practical teaching activities to suit the needs of their classes. The apps are designed to address important challenges encountered in teaching complex physical problems, such as complexity reduction, modeling, and visualization. The apps aim to provide clear presentation and encourage exploration to sustain a high level of interest and create a conceptual understanding of acoustics and vibration.

The apps can provide reference solutions with which analytical or measurement results can be compared. For example, the *beam and plate vibrations* app is used to visualize vibration mode shapes of beams (or, in higher semesters, plates) and to compare the bending eigenfrequencies from a simulation with analytical calculations of different beam models. The platform can be used to conduct comparative calculations or benchmark tests and thus offers a supplement to existing platforms on the Internet (Hornikx *et al.*, 2015).

To render them more intuitive in use, the apps are structured similarly according to design principles optimized through teaching experience. They create an open, enjoyable environment and encourage students to interact with them and explore them at their leisure. The *wine glass* app, for example, investigates vibrations and sounds associated with glasses, a phenomenon that is familiar to everyone and linking the concept of sound generation to daily life. The app aims to motivate users to perform experiments themselves

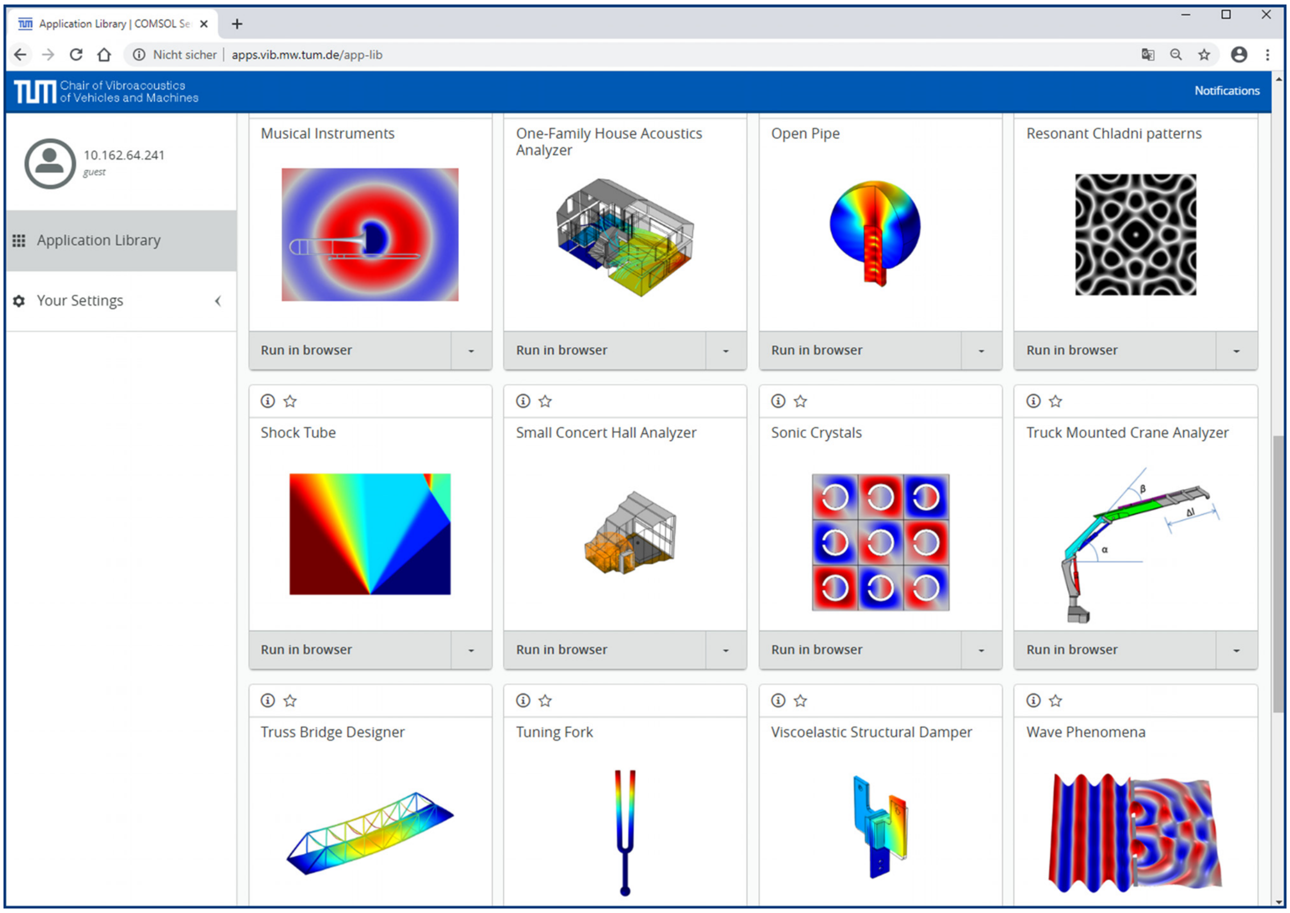


FIG. 1. (Color online) Selection from the Acoustics Apps library, as viewed in a web browser.

and to compare the tones they hear with the natural frequencies of a model of the same size and shape. Even bizarre shapes can be modeled and the influence of the level of liquid in the glass can be investigated. The *Helmholtz resonator* app is used to simulate not only the classic, spherical resonator shape but also the variation of sounds produced in bottles by altering the volume and level of the liquid. Users can experiment with blowing across the top of a bottle and compare the sound they hear with what the app shows.

All controls are kept simple and intuitive and can be operated by mouse or touch screen. The apps offer significantly more interactive control than applet platforms. In the *wind channel* app, for example, the user can upload a vehicle or object as a dxf file to study its aero-acoustic properties. The view can be varied as required between 2D and 3D and the resultant plots can be freely rotated and viewed from different angles, leading to a deeper understanding than would be possible with simple and fixed representations. The *room acoustics* app simulates several characteristic rooms, for example, a typical Munich subway car, which TUM students know from their ride to the campus. It also has a customizable classroom that learners can "enter". As they make their way through the simulated room, they audiovisually explore the spatial sound pressure minima and maxima that arise when a loudspeaker plays the corresponding natural frequency from the app.

Numerical methods generally require discretization, e.g., creating a volume or surface mesh of finite or boundary elements to introduce discrete, nodal degrees of freedom for which the numerical solution can be calculated. The quality and accuracy of the solution depend on the fineness of the mesh, which must normally be taken into account by the user. The apps provide appropriate default settings to overcome this need. Users interested in the numerical facets of acoustic simulations are referred to the app *convergence study in finite element discretization*.

Computationally highly intensive 3D simulations represent a limit to the usability in class, but the authors have endeavored, when selecting and creating the models, to keep calculation times low, namely, between a few seconds and a maximum of one minute. In case longer computing times cannot be avoided, solutions are usually already precomputed and available at startup, so the results can be immediately investigated. The visualization can often be downloaded as image or video files and used offline, e.g., in presentations. A detailed description of the respective problem, model assumptions and constraints is given in the individual documentation included within each app.

III. TEACHING AND LEARNING ACOUSTICS WITH INTERACTIVE APPS

Learning with Acoustics Apps is most successful when students are guided by the teacher during lectures and in the lab, or they are given detailed instructions that allow them to do the tasks at home. The range of possible applications is broad. Three examples are presented below along with suggestions and experiences on how the Acoustics Apps may be used effectively in different learning environments.

A. Wave phenomena

The underlying physical principle of acoustics and vibration are wave phenomena that are taught in physics and engineering studies as well as in school physics lessons. They are frequently demonstrated by creating surface waves on water. Such experimental visualization can be combined with numerical simulation and visualization of the effects, which offers the advantage that amplitudes, wavelengths, velocities and frequencies can be artificially adjusted to achieve optimum learning. By way of example, the *wave phenomena* app was used in an elementary tenth grade[1] physics class to teach the characteristics of waves, see Fig. 2(a). For this purpose, waves were first defined in class as oscillations propagated in space through coupled and vibratory systems. The app was then used to demonstrate that wavelength is the distance between consecutive points in the same phase of the oscillation. Interactive control of the animated variables of wave propagation within the app result in a more effective learning process than is possible with motionless visual representations or simple video (Zollman and Fuller, 1994). The pupils then investigated the speed of wave propagation using the app and compared their observations in relation to the underlying equations taken from a collection of formulas.

The app covers such phenomena as interference in gratings and speakers, diffraction, reflection, refraction, and radiation of (sound) waves as well as the Doppler shift. Using the illustrations of the effects shown in Fig. 2(b), students learned about wave phenomena and where they can be encountered, e.g., why the sound of an ambulance alters as it goes past and why sound is audible in the shadow zone behind walls. The effects can be presented in frontal teaching or explored by students independently or in group work on tablet computers. Ideally, the apps are used by students to present the results of their own research to the class to consolidate their understanding of the material by explaining it.

Results, images and video sequences can be generated from different viewpoints for various frequencies, angles of incidence, source positions, speeds of sound, materials and domain sizes. It is possible to define the number and size of interference gratings, and the position and size of obstacles where waves are supposed to bend or edges where waves are refracted. The results can be displayed in terms of various physical quantities to enable a deeper understanding of the phenomenon, e.g., in terms of sound pressure and fluid particle velocity fields. Advanced users can plot the complex impedance of the monopole radiator to explain near-field and far-field effects. Since the effects are applicable in different physical disciplines, the app can be regarded as multidisciplinary in its scope, and is, as such, also suitable for use in explaining optics, electromagnetic radiation, and quantum physics.

B. Bell vibrations

Bells are very expressive objects for teaching vibrations and sound radiation. Their shape and their sound are strongly connected as the geometry of the bell implicitly determines mode shapes, which express how the structure is able to vibrate, and the corresponding natural frequencies in which the bell efficiently radiates sound. If structures are of slightly imperfect symmetry, which results from manufacturing uncertainties and generally applies to bells, some modes separate into virtually symmetrical partners with more or less the same natural frequencies. The resulting beat effect is perceived as an amplitude modulation with the beat frequency being equal to the difference of the two individual frequencies. It strongly characterizes the sound and thus influences the perception of bells. The effect can also be observed numerically in the case of imperfect symmetry of the finite element mesh. The app enables the influences of modeling and manufacturing uncertainties on the highly shape-dependent sound of idiophones[2] to be studied.

Furthermore, bells are interesting research objects from a psychoacoustic point of view. One reason for this, in the context of religion, is that people's expectations of sound have evolved historically and regionally, and any deviations, such as the sound of a major-third (Lehr, 1987; Roozen-Kroon, 1992; Schoofs *et al.*, 1987) or even harmonic bells (McLachlan *et al.*, 2003), are regarded as deviations from the norm. So, how are the shape and sound of bells related? This was investigated by taking students equipped with a tablet computer running the *bell* app into a belfry, see Fig. 3.

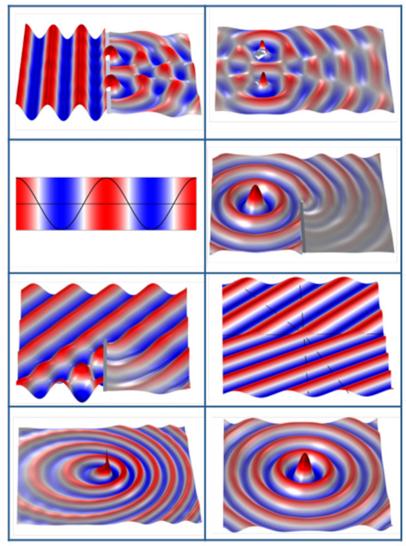
It has become apparent over several semesters that the practical experience of climbing the bell tower, touching the bells and experiencing their vibrations at nodes and antinodes is extremely valuable. This meets with an enthusiastic response from the students as a haptic experience is of great importance, which applies for many experiments. At the same time, it was confirmed that the *bell* app clearly reveals the connection between audible effects and underlying invisible vibrations. This considerably increases the learning benefit compared to photographic representations of vibrations. The virtual experiments in the Acoustics Apps should therefore be regarded more as a supplement to, rather than a substitute for, traditional experiments.

With the app it is easy to demonstrate that the location of excitation influences which modes dominate the vibroacoustic behavior of a bell. Campanologists make use of this when they excite a bell in certain areas with adjustable tuning forks to determine the individual tones by specifically bringing them into resonance.

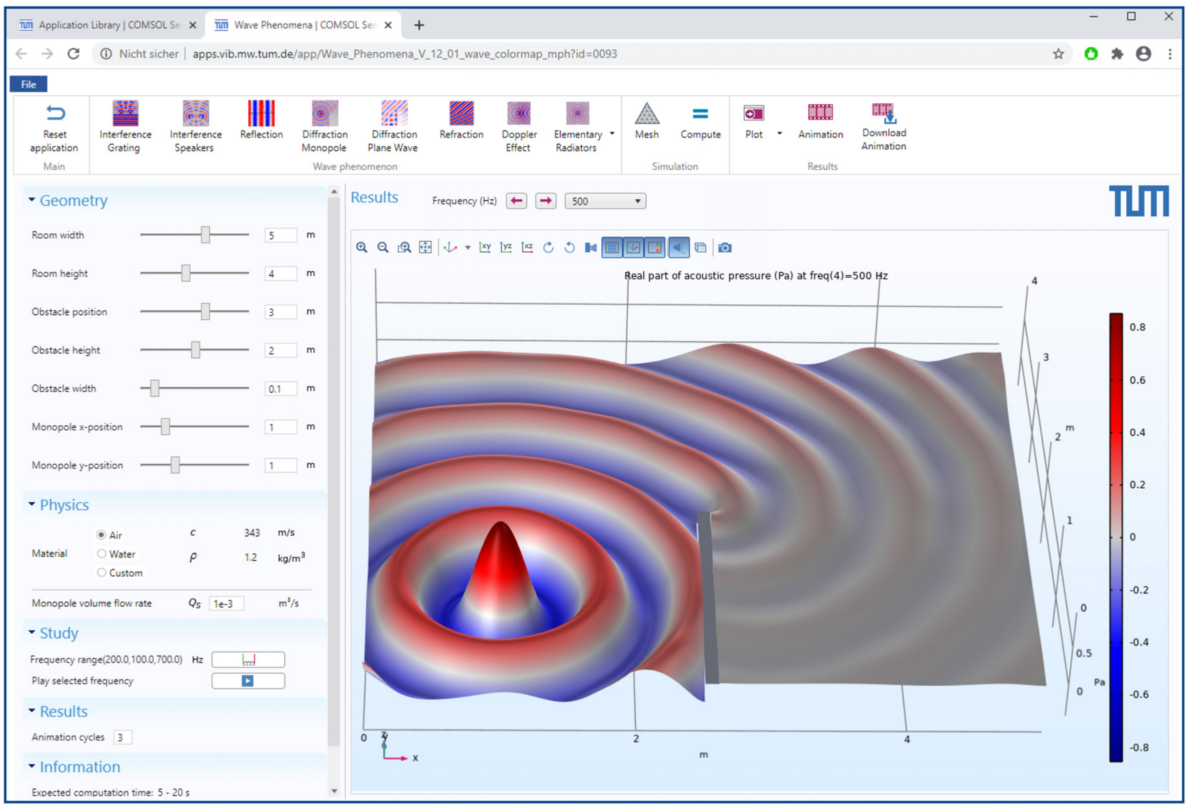
C. Musical instruments

Music is a very important area of application in the field of acoustics and vibration and one with which everyone is

(a)



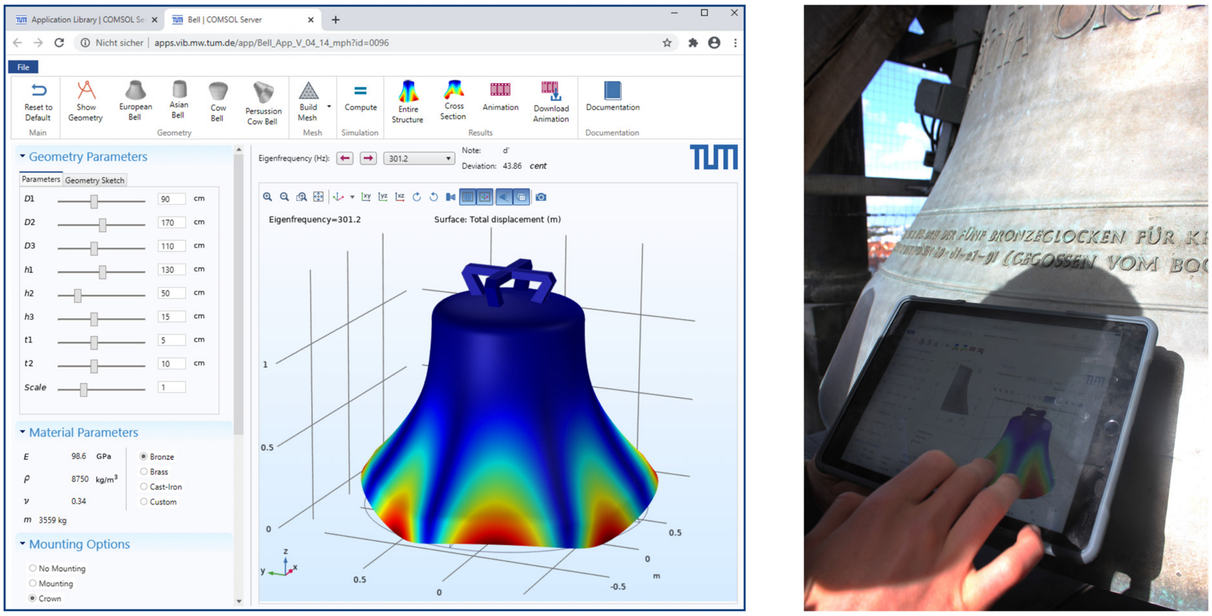
(b)



(c)

FIG. 2. (Color online) Wave phenomena app: (a) diffraction from a double-slit is taught in frontal teaching in a high school physics class; (b) the individual phenomena covered by the app at a glance; (c) view of the diffraction of waves emitted by a monopole source, which can be used, for example, to explain the effect of noise barriers along traffic routes.

familiar. The theory of musical instruments provides a vivid and tangible means of exploring and understanding physical wave and sound phenomena. Musical instruments' versatility arises from the way they produce sound and how musicians interact with them, which can involve bowing, plucking, striking, or blowing. Although the *musical instruments* app describes only a fraction of the many possible instruments so far, it offers very revealing insights into how they generate sounds. With the interactive control and clear visualizations of otherwise invisible acoustic behavior, the



(a) (b)

FIG. 3. (Color online) Bell app: (a) in a web browser and (b) during a lecture in a belfry.

3D models in the app establish clear connections between the cause and effect of various parameters. Being fun to use, it serves as an additional way of emphasizing the importance of physics in everyday life and helping students to develop a lasting conceptual understanding by exploring scientific relationships.

The app is aimed equally at musicians, physicists and engineers and it combines a variety of disciplines. For instance, it can help musicians to explore the physics behind the way their instrument generates sound by establishing a connection between physical principles and artistic perception. The app can be used in an instructional course, to explain, for example, how a trombone works. Depending on the students' previous knowledge, the necessary physical principles can be taught beforehand using other apps, e.g., simple sound propagation and standing waves in a cylindrical tube (using the *impedance tube* app) or the effects at the tube end and the influence of a bell on sound radiation efficiency (with the *open pipe* app).

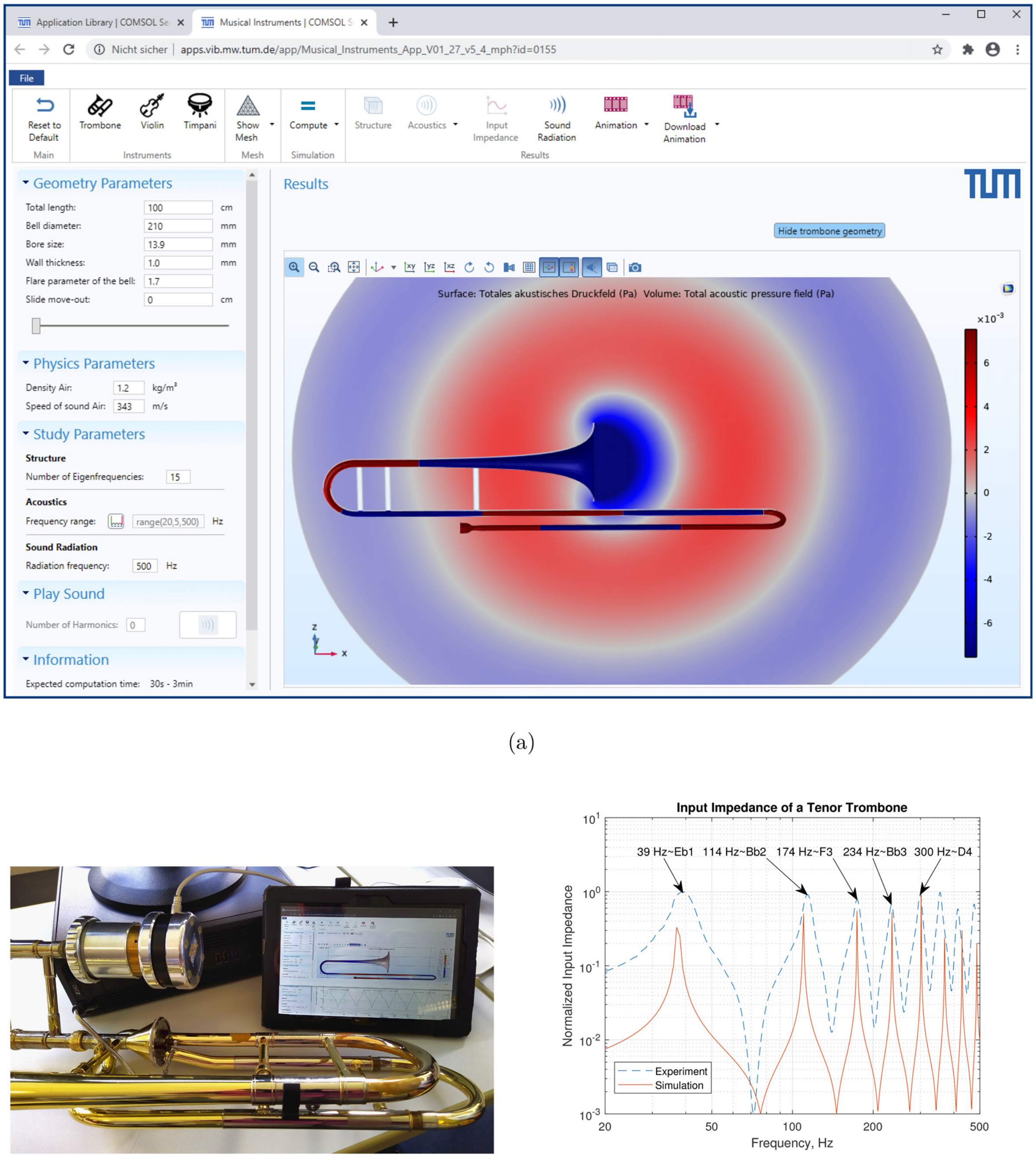
The *musical instruments* app [see Fig. 4(a)] is a useful tool with which the teacher can explain why a brass instrument resonates at certain frequencies depending on the tube length and on the buzzing of the lips. Figure 4(c) illustrates the frequency spectrum of the input impedance with musical notes at the peaks of the harmonic series of the trombone. The app is ideal for self-study, e.g., by comparing the simulation results with the effects that can be observed with the instrument itself. The user can investigate how the slide position of a trombone determines the resonant frequencies of the air cavity inside the instrument. The tone of the harmonic series which is ultimately excited depends on the frequency of the player's lip vibrations and the embouchure.[3] Using the trombone as an example, the authors have compared the results of app simulations with measurements of input impedance in the mouthpiece of a real trombone and obtained very good matches between the resonant frequencies, see Figs. 4(b) and 4(c). In this way, the *musical instruments* app can help musicians and students expand their knowledge of the physical sound generation principles of their instrument, perhaps even helping them improve their musical ability.

IV. CONCLUSIONS

Thanks to its interactive, simulation-based approach, the Acoustics Apps represent a new kind of e-learning concept using the latest computer-aided methods. The underlying COMSOL Server^{TM} (COMSOL Inc., 2020) technology enables both control and visualization of numerical simulations in standard web browsers, while the computing operations are performed on a remote server that is independent of the user's device.

This article outlines the concept of the Acoustics Apps as an innovative supplement to traditional teaching and learning media. It explains and provides examples of how the apps can give teachers more flexibility and possibilities in their teaching and to better respond to individual needs of the students. As for their use by school pupils and students, it is shown how the apps are suitable as a supplement to class, preparation and follow-up activities as well as a support for homework and research. It is shown how the interactive and playful approach can enhance understanding and encourage students to develop enthusiasm for the subjects.

A central aspect of the platform is that it enables numerical simulations for academic purposes at no charge. The flexibility and efficiency of these state-of-the-art numerical



(b) (c)

FIG. 4. (Color online) Simulation of the sound pressure distribution inside a trombone and sound radiation in the far field at a frequency of 500 Hz as viewed in the *musical instruments* app (a). Measurement setup for the input impedance of a tenor trombone using the BIAS 7 (Artim GmbH, 2017) system (b). Comparison of measured and simulated (*via* app) input impedance at the initial slide position (c).

methods and their revealing presentations are available to a broad user group, without the need for in-depth prior knowledge and without resorting to expensive hardware and software. It is now possible to supplement or replace complex or expensive experiments with computer-based techniques, for instance, in home schooling.

For the future, it is planned to further quantify the learning success through evaluations and discussions with students. The aim is to find out which topics are of particular interest and how the apps can be specifically improved to support students in their learning. The authors hope that this e-learning concept will be a useful tool for teachers and students and might inspire similar projects and new developments beyond the field of acoustics and vibration. As new apps are constantly being developed, any feedback, suggestions and inquiries for possible cooperation with schools and research institutes worldwide is very welcome.

ACKNOWLEDGMENTS

For their support in this project, the authors would like to thank all the student developers who have contributed to the Acoustics Apps so far: Michael Buba, Sarath Devanand, Lukas Erdt, Lukas Greiner, Johannes Harth-Kitzerow, Tanjina Laila, Akshaya Shri Natarajan, Manuel Scholl, Julian Stang, and David Wawrzyniak. Thanks are also expressed to the Technical University of Munich for funding, Ralf Grauer and his pupils for allowing us to visit their physics class at Primonth-Levi High School, Lucas Heidemann from the Oscar Walcker school of instrument making for performing the trombone measurements and providing us with the data, as well as to Marion Burgess and to Nicole Kessissoglou for their valuable feedback.

[1]In the German school system this corresponds to pupils aged around 16 years.
[2]An idiophone is any musical instrument in which sound is produced mainly by the vibration of the instrument (Cambridge Dictionary, 2008).
[3]Embouchure is the way in which a player uses their lips and face muscles to produce sound from a brass or wind instrument (Cambridge Dictionary, 2008).

Acoustic Apps (**2020**). apps.vib.mw.tum.de (Last viewed 7/23/2020).

Angell, C., Guttersrud, Ø., Henriksen, E. K., and Isnes, A. (**2004**). "Physics: Frightful, but fun. Pupils' and teachers' views of physics and physics teaching," Sci. Educ. **88**(5), 683–706.

Artim GmbH (**2017**). "BIAS 7 brass instrument analysis system," https://www.artim.at (Last viewed 7/23/2020).

Cambridge Dictionary (**2008**). *Cambridge Advanced Learner's Dictionary* (PONS-Wörterbucher, Klett Ernst Verlag GmbH, Stuttgart).

Chang, K.-E., Chen, Y.-L., Lin, H.-Y., and Sung, Y.-T. (**2008**). "Effects of learning support in simulation-based physics learning," Comput. Edu. **51**(4), 1486–1498.

COMSOL, Inc. (**2020**). "Comsol Server™," http://www.comsol.com/comsol-server (Last viewed 7/23/2020).

Cooper, M., and Ferreira, J. M. (**2009**). "Remote laboratories extending access to science and engineering curricular," IEEE Trans. Learn. Technol. **2**(4), 342–353.

Feynman, R. P., Leighton, R. B., and Sands, M. (**2011**). *The Feynman Lectures on Physics, Vol. I: The New Millennium Edition: Mainly Mechanics, Radiation, and Heat* (Basic Books, New York).

Haddad, W., and Jurich, S. (**2002**). "ICT for education: Potential and potency," Technologies for education: Potential, parameters and prospects," UNESCO and Academy for Educational Development, pp. 28–40.

Hodson, D. (**1988**). "Experiments in science and science teaching," Edu. Philos. Theory **20**(2), 53–66.

Holec, S., Pfefferová, M. S., and Raganová, J. (**2004**). "Computer simulations in mechanics at the secondary school," Inf. Educ. **3**(2), 229–238.

Hornikx, M., Kaltenbacher, M., and Marburg, S. (**2015**). "A platform for benchmark cases in computational acoustics," Acta Acust. Acust. **101**(4), 811–820.

Ihlenburg, F. (**2006**). "Finite element analysis of acoustic scattering," Vol. 132 of *Applied Mathematical Sciences* (Springer, Berlin).

ITA Aachen (**2020a**). "Virtual Acoustics – A real-time auralization framework for scientific 500 research" http://www.virtualacoustics.org/ (Last viewed 7/23/2020)

ITA Aachen (**2020b**). "ITApp – Interactive Teaching in Acoustics" http://gershwin.akustik (Last viewed 7/23/2020).

Klein, P., Hirth, M., Gröber, S., Kuhn, J., and Müller, A. (**2014**). "Classical experiments revisited: Smartphones and tablet PCs as experimental tools in acoustics and optics," Phys. Educ. **49**(4), 412–418.

Kuhn, J., and Vogt, P. (**2015**). "Smartphones & Co. in physics education: Effects of learning with new media experimental tools in acoustics," in *Multidisciplinary Research on Teaching and Learning* (Springer, Berlin), pp. 253–269.

Lampe, H.-U., Liebner, F., Urban-Woldron, H., and Tewes, M. (**2015**). "Innovativer naturwissenschaftlicher Unterricht mit digitalen Werkzeugen" ("Innovative natural science teaching with digital tools"), MNU Deutscher Verein zur Förderung des mathematischen und naturwissenschaftlichen Unterrichts e.V.

Lehr, A. (**1987**). "A carillon of major-third bells. III. From theory to practice," Music Percept. **4**(3), 267–280.

Leslie, M. (**2001**). "Visualizing acoustics," Science **293**(5535), 1563.

Marburg, S., and Nolte, B. (**2008**). "A unified approach to finite and boundary element discretization in linear time–harmonic acoustics," in *Computational Acoustics of Noise Propagation in Fluids—Finite and Boundary Element Methods*, edited by S. Marburg and B. Nolte (Springer, Berlin), pp. 1–34.

Mary, C., Wright, M. C. M., and Nelson, P. A. "ISVR Teaching Material on Waves and Acoustics" http://resource.isvr.soton.ac.uk/spcg/tutorial/tutorial/StartCD.htm (Last viewed 6/1/2020).

McLachlan, N., Nigjeh, B. K., and Hasell, A. (**2003**). "The design of bells with harmonic overtones," J. Acoust. Soc. Am. **114**(1), 505–511.

Müller, G. (**2020**). "Interactive Apps" https://www.bgu.tum.de/bm/lehre/interactive-apps/ (Last viewed 7/23/2020).

Ortega, M., and Bravo, J. (**2000**). *Computers and Education in the 21st Century* (Springer, Berlin).

Pierce, A. D. (**2019**). "Ray acoustics," in *Acoustics* (Springer, Berlin), pp. 427–486.

Roozen-Kroon, P. J. M. (**1992**). "Structural optimization of bells," Ph.D. thesis, Technische Universiteit Eindhoven, Eindhoven, the Netherlands.

Russell, D. A. "Acoustics and Vibration Animations" https://www.acs.psu.edu/drussell/demos.html (Last viewed 6/1/2020).

Schoofs, A., Van Asperen, F., Maas, P., and Lehr, A. (**1987**). "A carillon of major-third bells. I. Computation of bell profiles using structural optimization," Music Percept. **4**(3), 245–254.

Shin, Y.-S. (**2002**). "Virtual reality simulations in web-based science education," Comput. Appl. Eng. Educ. **10**(1), 18–25.

Wieman, C. E., Adams, W. K., and Perkins, K. K. (**2008**). "PhET: Simulations that enhance learning," Sci. **322**(5902), 682–683.

Zollman, D., and Fuller, R. (**1994**). "Teaching and learning physics with interactive video," Phys. Today **47**(4), 41–47.