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Development of Hybrid Laboratory Sessions During the COVID-19 Pandemic

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ABSTRACT

This paper presents the hybrid delivery method of a laboratory experiment at the Stability Wind Tunnel of Virginia Tech to some 170 students during April 2020, which can be considered the early stages of the COVID-19 induced lockdown. The steps of converting the hands-on labs to hybrid labs are presented in detail. Namely, a videoconferencing tool was used to (i) stream the instrumentation used, (ii) provide live video feed, and (iii) to interact with the students. Labs began with a remote tour of the facility, whilst the presence of an expert-at-a-distance added key value to the labs as it enhanced students conceptual understanding via verbal interaction. The experiments were then performed by laboratory personnel while student's engagement was kept high via the teleconferencing session. At the end of the two-week laboratory campaign, the students provided feedback of the laboratory sessions via an open-ended and closed-ended survey. They highlighted the added value of expert-at-distance, the live video feed, and the ability of working with instructors. While their feedback was rather positive, students showed a strong preference toward hands-on laboratories. Overall, the methodologies presented here can be considered a relatively low-cost method to upgrade hands-on laboratories to hybrid or remote labs.

Key words: hybrid laboratory sessions; COVID-19; wind tunnel experiments

INTRODUCTION

Engineering laboratory sessions (labs) are a crucial element of undergraduate (UG) engineering education where students apply realistic physical environmental concepts they learn during courses.

Unfortunately, running laboratory teaching experiments have high expenses as they require university space, expensive instruments, and personnel support. UG labs also impose a high load on research laboratories because laboratories also need to meet research needs. While conducting research experiments involves the presence of a handful of people, experiments tailored for education often involve a large number of students conducting experiments in a strict schedule. Usually, universities must cover the overhead cost, the wage of the instructors, the equipment cost alongside its maintenance fees, and the laboratory preparation costs. *Remote* laboratory sessions offer a relief from some of these financial and workloads by separating the students from the laboratory environment while allowing the remote control of the experiment (M Ogot, Elliott, and Glumac 2003; Madara Ogot, Elliott, and Glumac 2002). *Simulated* experiments offer higher cost savings (Goodwin et al. 2011) by emulating the labs in a software environment, but they significantly compromise the interaction between the student and the instrumentation. More recently, (Ma and Nickerson 2006) suggested a new type of laboratory session, the *hybrid* approach where components of the different types of laboratory sessions (hands-on, remote, and simulated) are combined such that the strength of each approach is utilized.

Previous studies have shown (Ma and Nickerson 2006) that each laboratory delivery approach, namely, hands-on, remote, and simulated, have their own advantages and disadvantages. It was also reported that the nature of the laboratory session also dictates which approach is the most suitable solution to educate students. For example, hands-on labs are efficient in developing design skills, while simulated labs enable performing experiments that otherwise would impose health and safety concerns (e.g., using high-power lasers). Finally, remote labs can offer a similar level of conceptual understanding as hands-on labs (Lal et al. 2020; Herrington and Fields 2021; Niel, Mourey, and Bateman 2021; Wu et al. 2020). Each laboratory type has its drawbacks, too. During hands-on laboratories, students' interaction with the instrument is often limited to ensure the safety of the students and the equipment; remote experiments usually lack social interaction between instructor and student, and simulated experiments entirely separate the students from real-world experiences, therefore, often adversely affecting student's satisfaction. Based on the suggestions of Ma and Nickerson (Ma and Nickerson 2006), *hybrid* labs could potentially overcome the weaknesses of the different delivery methods by adequately combining features from the different approaches (Herrington and Fields 2021).

Over the past decades, remote labs became a suitable alternative to hands-on labs because even in the case of hands-on labs, students (and researchers) usually interact with a software environment to perform experiments. It has been shown that for conceptual understanding and education outcomes, remote labs can be a competitive alternative to hands-on laboratories (Madara Ogot, Elliott, and Glumac 2002; M Ogot, Elliott, and Glumac 2003; Nickerson et al. 2007; Leung et al. 2020).

Remote labs can also be used to advertise STEM education amongst high school students, deliver the curriculum to minorities or to students with motion disabilities (Carpenter et al. 2017; Ari-Gur et al. 2013). Remote labs, on the other hand, separate the instructor from the students, therefore, restricting the students from acquiring essential engineering laboratory skills (Lal et al. 2020). Remote labs can be considered as an extension of hands-on labs by adding the remote capabilities to the pre-existing experimental setups. Finally, remote labs open the possibility to perform experiments at a less strict schedule, and also they enable international collaborations (Nafalski, Milosz, and Considine 2020; Chen et al. 2020).

During the spring of 2020, the coronavirus pandemic brought a fundamental disruption to educational institutes. Universities were forced to transition their curriculum on-line to ensure the safety and wellbeing of their students and employers. By the end of March 2020, almost all universities across the world were operating over the internet, while only essential operations were permitted on campus. Thus, most laboratory-based education activities were canceled for the rest of the semester. In such a scenario, remote laboratory sessions are a suitable way to fulfill the curriculum from both student and university perspectives. While during the early months of the coronavirus pandemic, many assumed that everyday life would return to normal in a matter of months, by the summer of 2020 universities and governments came to realize that social distancing must remain in place for an extended period. Suddenly, these conditions impose a high demand on the development of remote and hybrid laboratory sessions as these laboratory types can be considered an upgrade to the existing experiments as opposed to simulated (or canceled) laboratories.

The Stability Wind Tunnel (SWT) at Virginia Tech (VT) (Devenport et al. 2013) fulfills important education responsibilities by accommodating undergraduate laboratories for several weeks during each semester. The SWT can be considered a large-scale, nationally important facility as it also serves as an important industrial test facility to external customers and it also accommodates high-fidelity research experiments (Clark et al. 2017; Murray et al. 2018; Alexander, Devenport, and Glegg 2017; Joseph et al. 2020). Most often, the facility accommodates studies of flow-induced noise, such as airfoil self-noise (Clark et al. 2017), propeller noise (Murray et al. 2018; Alexander, Devenport, and Glegg 2017) and surface roughness noise (Joseph et al. 2020), etc. Due to its large size on the scale of academic wind tunnels and the efficiency required by industrial tests, experiments at the SWT are remotely operated from a room adjacent to the test section. This creates a favorable condition to convert the hands-on undergraduate laboratory sessions held at the SWT to *hybrid* experiments.

The experiments conducted as undergraduate labs at the SWT often perform research-level investigations, while simultaneously serving educational purposes. This unique combination of efforts offers a deeper insight for UG students to cutting-edge research while also serving educational goals. In April 2020, wind tunnel experiments were scheduled at the SWT as part of the “Experimental methods" junior-level course (Aerospace and Ocean Engineering curriculum). Within the course, the students learn the fundamental terminology of experimental work and testing in aerospace and ocean engineering in a combination of classroom and online lectures, along with laboratory work. Students are exposed to various flow measurement techniques, displacement, and strain measurements of simple structures in both static and dynamic settings, analog and digital instrumentation, data acquisition systems and appropriate software. Through teamwork they design, prepare, and conduct several experiments, and document their results and findings in logbooks and lab reports. Students perform data analysis using basic statistic concepts and validate their result through uncertainty quantification.

The scheduled experiments at the SWT investigated the trailing edge noise (Amiet 1976; Brooks, Pope, and Marcolini 1989) generation of a NACA0012 airfoil (Ayton et al. 2021). This study was a collaborative work between VT, University of Southampton (UK) and University of Cambridge (UK). The experimentation included the use of a state-of-the-art particle image velocimetry (PIV) system to capture the velocity field in the vicinity of the airfoil trailing edge (TE), while the airfoil was equipped with TE add-ons that are intended to reduce the self-noise of the airfoil. To quantify the noise reduction efficiency of the add-ons, surface pressure transducers (miniature microphones) were embedded in the TE add-ons, while the self-noise of the airfoil was also captured using a far field microphone array consisting of 251 microphones. Such a complicated experimental setup is rarely used even in research studies; therefore, the level of complexity and the detail of the experimentation was far beyond common UG laboratories.

These experiments at the SWT were converted (VT News, 2020) to a *hybrid* delivery method in response to the COVID-induced lockdown to sustain educational needs. The remotely controlled nature of the wind tunnel was utilized by streaming the displays of instruments to the UG students, and a live and interactive video feed was also streamed to the students during the laboratory sessions. In addition, faculty and graduate students took an active role in keeping the students engaged during the sessions by providing a live walkthrough of the facility. Streaming the instrumentation displays to students enabled the remote execution of the labs, while the remote presence of faculty and graduate students provided a hybrid delivery. This novel combination of efforts delivered a near in-person virtual immersion of the UG students and can be considered a *hybrid* laboratory type (Ma and Nickerson 2006).

This paper presents how the hybrid delivery of the laboratory sessions was developed at the SWT during the early phase of the coronavirus pandemic. The overview of all components that were necessary to the successful delivery of the hybrid laboratory sessions are presented, in particular, all computers, streaming devices, participants in the on-line laboratory sessions are introduced and discussed. After the two-week-long experimental campaign, all 175 participating students were asked to fill a survey, from which results are shown and analyzed in detail. Most of the components used at the SWT to deliver the laboratory sessions are readily available at other universities, therefore, the effort presented here can be a good basis for transitioning to remote or hybrid laboratory delivery at other institutes.

DESCRIPTION OF THE LABORATORY SETUP

Experimental Facility

The Stability Wind Tunnel at Virginia Tech (Devenport et al. 2013) is a low-speed closed-circuit wind tunnel used for a mix of commercial testing, research, and educational experiments on the campus of Virginia Tech in Blacksburg, Virginia, see Figure 1. The facility can generate speeds of up to 80 m/s (180 MPH) through its 7.3 m (24 ft.) long, 1.85 m x 1.85 m (6 ft. x 6 ft.) square test section. The flow through the empty test section is closely uniform and of very low turbulence intensity. Two interchangeable test sections are available in the wind tunnel. The hard wall “aerodynamic” test section has walls formed from a sequence of aluminum panels. Test objects, such as airfoils, are mounted 3.56 m downstream of the test section entrance. The Kevlar-wall “aeroacoustic” test section replicates the same interior dimensions as the hard wall test section, and it is primarily used for aeroacoustic testing as it has two anechoic chambers flank the test section. The Kevlar walls enable acoustic investigation of test objects as this material is near-impermeable to flow and acoustically transparent. The Kevlar-walled aeroacoustic test section was used in this study to enable the measurement of the far field self-noise emitted by the NACA0012 airfoil.

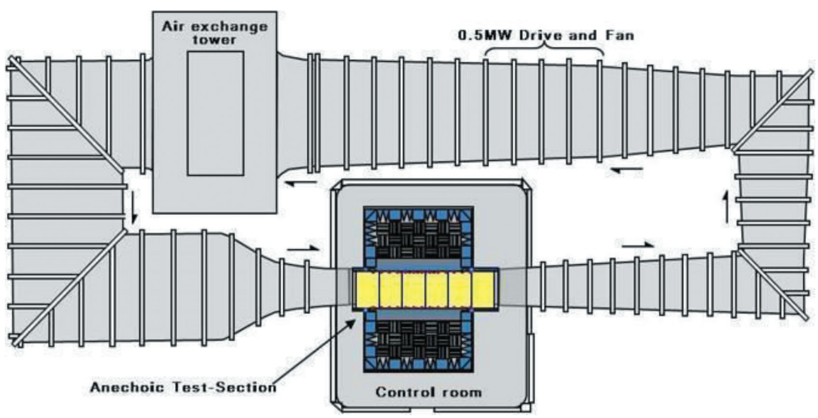

Figure 1. The schematic view of the Stability Wind Tunnel.

Experimental Description

The main objective of the experiments was to capture the trailing edge noise (Amiet 1976; Brooks, Pope, and Marcolini 1989) generated by a NACA0012 airfoil and to analyze the trailing edge noise reduction performance of different trailing edge serrations. A series of physical quantities were measured during each laboratory session, namely, the far field trailing edge noise was acquired using a far field microphone array, the surface pressure fluctuations were measured in the vicinity of the airfoil trailing edge using flush-mounted miniature microphones, and the flow field was obtained in the vicinity of the trailing edge using a high-speed PIV system (Szőke et al. 2021). The schematic view of the experimental setup is depicted in Figure 2, where the 3-ft chord NACA0012 airfoil is shown in the test section of the SWT. The far field microphone array, comprising of 251 microphones, is not shown in the schematic, but it was present inside the starboard side anechoic chamber adjacent to the test section with the chambers and flow field separated by tensioned Kevlar walls.

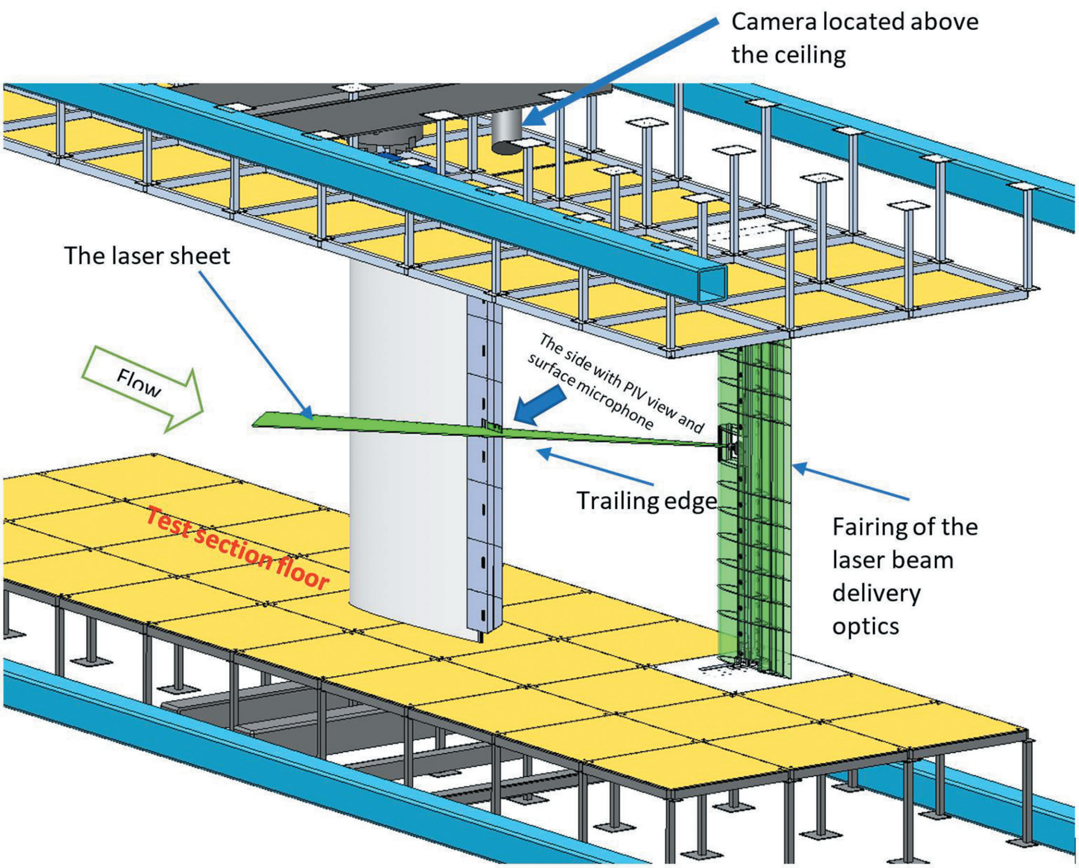

Figure 2. The overall schematic view of the experimental setup.

From a data analysis point of view, the students were provided the time-series signal of a surface pressure microphone, the time-series signal of a far field microphone taken from the 251-element microphone array. In their laboratory report, the students were responsible to present the Fourier transform of these data. In addition, the time-resolved PIV system was used to capture and visualize the instantaneous velocity field around the trailing edge add-ons. From the PIV measurements, the mean velocity profile was provided to the students to determine the properties of the boundary layer present on the surface of the airfoil.

The students were provided two, pre-recorded lectures discussing the fundamentals of frequency domain analysis and the underlying physics of trailing edge noise generation. The student's understanding of the underlying physical phenomena of trailing edge noise generation was challenged during the laboratory sessions. A surface add-on was prepared in the laboratory that disturbs the flow over the surface of the airfoil, hence it can enhance the trailing edge noise generation. The student teams were given the task to determine a position and orientation for the add-on on the surface of the airfoil such that the noise generation was enhanced at the highest possible rate. At this step, the UG students had to work as a team to identify the condition from a set of options that fulfills this goal.

Laboratory Session Procedures

This section presents all components used to deliver the laboratory sessions in a hybrid manner. The structure of the labs alongside with the participants are listed first, followed by a detailed technical description of each component's educational aspect.

The overall structure of the laboratory sessions is shown in Figure 3. The laboratory sessions were conducted using Zoom® teleconferencing software to maintain social distancing and to provide access to the labs to all 175 participating students. This also enabled student access to the labs conducted at the SWT regardless of their geolocation. To help students navigate within the teleconferencing software during the lab sessions, a tutorial video of how to use the relevant features of the teleconferencing software was recorded and made available to the students prior to the labs. In terms of participants, the teleconferencing sessions contained two wind tunnel operators, six students (two groups of three), an expert-at-a-distance, the screens of the various instrumentation devices, and two sets of cameras, see Figure 3. The expert was either a faculty member or a graduate student working from home, hence the name "expert-at-a-distance". Overall, there were two wind tunnel operators present throughout each 1.5-hour long lab session with an expert-at-a-distance remotely present for the first 30-min of each session. In addition to these regular participants, research collaborators from University of Southampton and University of Cambridge were also present at selected laboratories, all of whom could participate in the labs despite the pandemic and their geographic separation.

In terms of execution order, each laboratory session comprised of three major components, namely, each session began with the *tour of the facility*, followed by *data acquisition* and the final step was *data processing and visualization*. During the tour of the facility, the students were provided a live tour of the SWT using a cell phone camera operated by a wind tunnel operator. The purpose of the tour was to familiarize students with the facility and instrumentation by providing a live walkthrough of the laboratory. At this stage, the expert-at-a-distance was responsible to ensure that the UG students have adequately prepared for the lab session. The students could also interact with the expert as well as with the tunnel operator. Introducing the expert at a distance and a tour of the facility brought the *hybrid* sessions closer to that of a hands-on lab by allowing interaction between instructors and students that usually present only in hands-on labs. The students had the opportunity to take screen-shots during the facility tour, and to record the entire videoconference session on their own computer for later use, both of which were in support of their graded laboratory report.

At the end of the tour, the expert-at-a-distance left the teleconferencing session. The facility personnel present in the laboratory then began the streaming of experimental apparatus screens to the students, namely, the wind tunnel camera system, the wind tunnel conditions, the surface microphone data acquisition software (Surf. Mic. DAQ), the PIV software (PIV PC) and the far field microphone array software (Beamforming PC), see Figure 3. While each student was assigned to monitor a specific instrument for laboratory report writing purposes, they also had the opportunity to freely choose which instrumentations screen to follow during the data acquisition and processing step. Next, the experiments were performed by the wind tunnel personnel while they also guided the students throughout the data acquisition procedure. Although the students were not provided remote control of the facility and instruments, they could observe the data acquisition and were able to ask questions and initiate discussions throughout the entire session. After the first round of experiments, the students were responsible to identify which location and what orientation to place the surface add-on onto the surface of the airfoil to enhance the generation of trailing edge noise. To answer this question, they must have understood the experiments as well as the underlying physics, therefore, this step challenged their conceptual understanding and communication skills as they had to decide as a team on how to proceed. The measurements were then repeated with the surface add-on placed on the airfoil by the wind tunnel personnel. Once data has been gathered, it was uploaded to the cloud and therefore was made accessible to the students using a URL link for further processing and laboratory report writing.

Overall, the lab procedures discussed in this section were developed to support the following important educational goals:

- The student's ability to develop and conduct appropriate experimentation, analyze, and interpret data, and use engineering judgment to draw conclusions.
- The students were required to communicate effectively with a range of audiences, namely, with expert-at-a-distance, wind tunnel personnel, and fellow students.

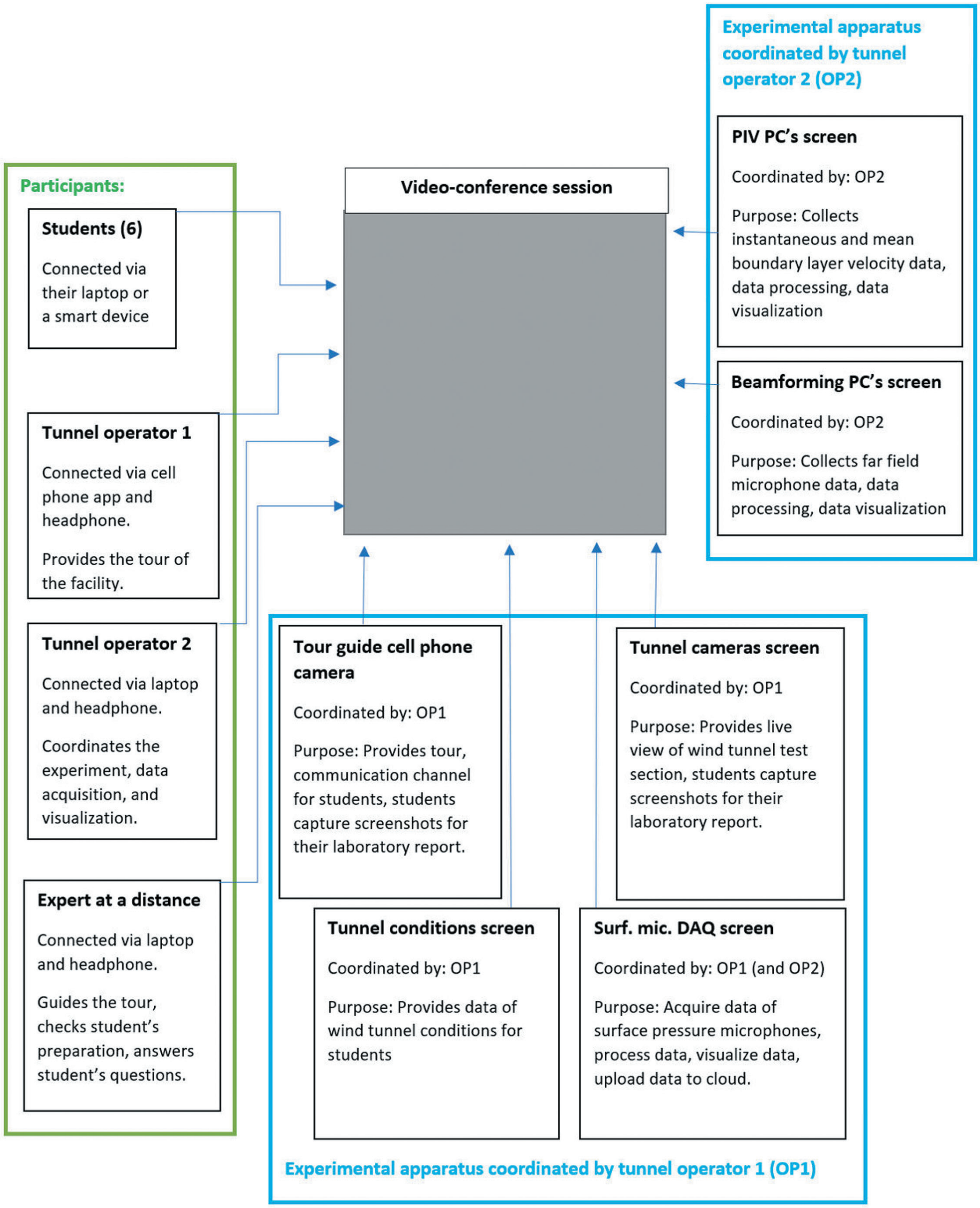

Figure 3. The technical structure of laboratory sessions.

- Finally, the students were responsible to work as a team to generate their lab report, which required them to function effectively as a member or leader of a team that establishes goals, plans tasks, meets deadlines, and create a collaborative and inclusive environment.

LABORATORY EVALUATION

After the two-week-long campaign of laboratory sessions, the students were asked to respond to a questionnaire tailored to assess the laboratory sessions from a variety of aspects. The questionnaire contained a set of *closed-ended statements*, to which students could respond quantitatively, and a set of *open-ended questions*. The response rate was rather high, namely, 170 responses were received out of the 175 students enrolled in the class, thanks to the small credit value (2% of the overall class grade) offered in response to filling the questionnaire. This section provides the methods used to evaluate the student's responses before evaluating the survey results.

Quantitative Evaluation

The closed-ended questionnaire focused on the quantitative assessment of the labs from three aspects, namely, the students' experience *during the labs*, the *interaction* between students and other lab participants, and finally, a few statements targeted the student's *overall* impressions of the laboratory sessions. The following responses were available for the closed-ended questionnaire: Strongly Agree, Agree, Neutral, Disagree, and Strongly Disagree.

Statements related to student experience *during the labs* targeted the students' experience during the laboratory sessions. The statements posted under this category aim at understanding the efficacy of the lab tour, the importance of the expert-at-a-distance, and the student's conceptual understanding of the generated and visualized data.

The second category within the closed-ended questionnaire targeted students' *interaction* between the different components of the labs (see Figure 3) and the students. These statements aim at quantifying the ease of use of the Zoom® teleconferencing tool, student's interaction with wind tunnel staff, and the efficacy of transferring data to the students via the cloud.

Finally, a few statements targeted the students' *overall impressions* of the laboratory sessions. Student's responses to the closed-ended questions are presented in percentages for each statement within the Results section.

Qualitative Evaluation

In addition to asking closed-ended questions on a five-point scale, students were also asked a series of open-ended questions to solicit more detailed responses than the fixed-choice questions. In this paper, we present the results of two of these questions. The specific questions were:

1. List a few aspects of the remote experimentation that were better than a regular lab.
2. List a few aspects of the remote experimentation that were lacking compared to a regular lab.

Similar to the closed-ended questions, there was a high response rate (97%) for each question.

To analyze responses, we combined two approaches: (i) a traditional thematic coding process (Braun and Clarke 2006; Clarke and Braun 2017) and (ii) a novel natural language processing (NLP) approach to help scale the processing of the more than 1,100 text responses (170 students x 7 questions - two of which are presented here). The NLP approach involved a series of steps. First, the text response from each student was embedded into a high dimensional vector space using pre-trained sentence transformers that have been fine-tuned from language models like Google's Bidirectional Encoder Representations from Transformers (BERT) (Devlin et al. 2019) and Facebook's RoBERTa model (Liu et al. 2019). These embeddings in abstract vector spaces are designed to convert the student responses from textual representation to numerical representations that can then be transformed with standard mathematical operations. Ideally, these transformations enable faster pattern recognition (identification of similar themes across responses) without losing the original meanings. The original embeddings take the raw text and place the numeric representations in a high-dimensional vector space. The embeddings themselves are simply arrays of numbers, which themselves convey little meaning. The meaning in our application here primarily comes from which samples are close to other samples.

From this high-dimensional space (e.g., 1,024-dimensional), we then projected those representations down to a 50-dimensional space with a linear projection method (principal component analysis, PCA). From here, we then used a nonlinear projection method (uniform manifold approximation and projection, UMAP) (McInnes et al. 2018) to obtain a two-dimensional representation of the original sentences that students wrote. These steps basically convert the arrays of 1,024 numbers (for each response) to two numbers (again, for each response). The goal of these intermediate dimension reduction steps was to enable clustering while circumventing the curse of dimensionality (where everything tends to be far from everything else in high dimensions and thus clustering can be less meaningful). Finally, we used agglomerative clustering of these two-dimensional, embedded text representations. This clustering helps to identify similar responses. With these clusterings, we then reviewed each cluster to identify similarities in the responses. For example, when answering what the students liked about the remote lab, one student said, "I liked being able to wear my pajamas" and another said, "I enjoyed not getting dressed up". This NLP method takes those two responses, embeds them in the original high-dimensional vector space, and eventually clusters them together, thereby suggesting the responses share similar semantic meaning. In the instance of these two sentences, it was the theme of comfort and convenience. Overall, we performed this same process for each of the questions that we present here, taking the raw text, passing it through this process, obtaining clustered responses, and then thematically coding these different groupings to identify themes in students' responses. We present a graphical distillation of students' comments in Figures 7 and 8.

RESULTS

Quantitative Results

Figure 4 presents students' experiences during the laboratory sessions. Results are shown as the percentage of the number of student choices per statement. Overall, the results reveal that the student's experience during the labs was rather positive as most of the responses (70–90%) fall into the agreed or strongly agreed category.

The lack of students' physical presence can significantly compromise their laboratory experience. This drawback of the remote labs was successfully compensated with the tour of the facility while the interactions between the students and instructors (expert-at-a-distance and wind tunnel staff) also added key value to the sessions, see statements A)–F) in Figure 4. The SWT is a rather large, nationally significant facility on the scale of university-owned wind tunnel facilities. Based on students' feedback, the tour of the facility provided a good estimate on the scales of the facility, see statement C) in Figure 4.

While the tour of the facility was proven to be a successful way to overcome students' lack of physical presence in the facility, the interaction between the students and instrumentation was a more challenging task to resolve because the direct control of the instrumentation could not be made available to the students due to the short period of time available for laboratory preparation. Figure 5 presents students' feedback on the interaction-specific statements of the closed-ended questionnaire. Overall, the responses were still positive on average, with most of the responses still

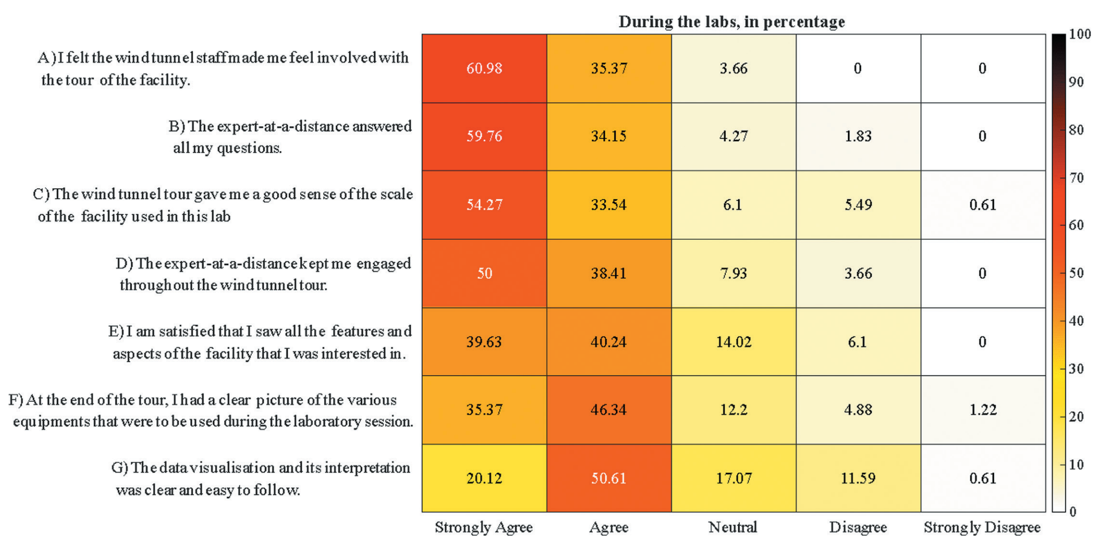

Figure 4. Results of the closed-ended questionnaire: Students experience during the labs.

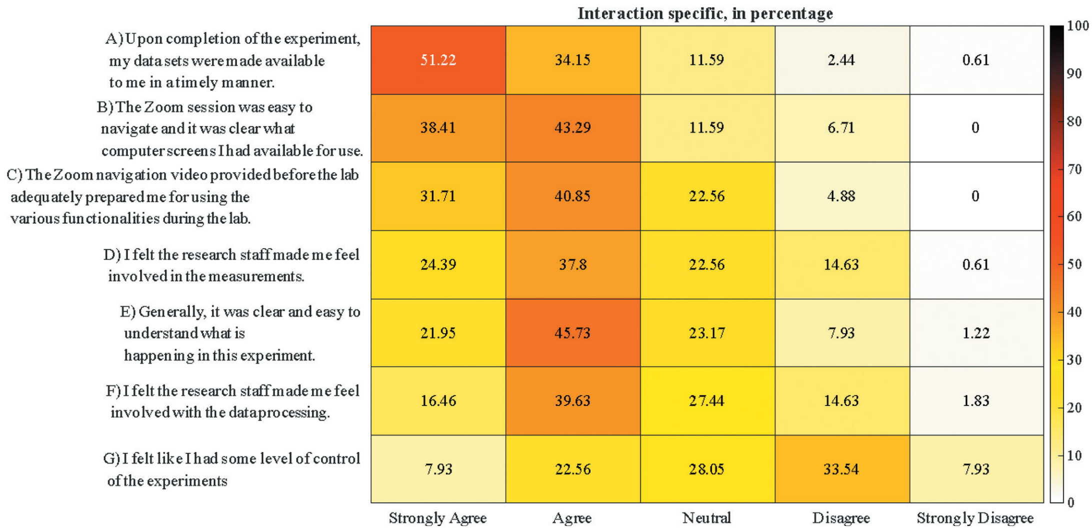

Figure 5. Results of the closed-ended questionnaire: Interaction specific metrics.

registered under the agree or strongly agree categories. Based on the results, uploading files to the cloud was an efficient way to transfer the acquired data to the students (statement A in Figure 5). Students were provided a video tutorial prior to the labs focusing on how to navigate and operate within the Zoom® teleconferencing software. Their feedback suggests that they observed some difficulties using the software (statements B, C in Figure 5). A possible explanation for this is that when the laboratory sessions were conducted (early April 2020), the Zoom® teleconferencing software was relatively new to the academic community and students were still in the adopting phase. Similarly, the evaluation of the data acquisition process and data visualization process was positive and most of the responses were observed in the agree category (statements E, F in Figure 5). The possible reasons for the drop in the percentage of students with strongly agree responses can be explained with the difficulty of navigating within the Zoom® sessions and the lack of direct student control over the instrumentation. The latter is clearly indicated by the responses observed to statement G in Figure 5, where the level of students' control over the experiments was targeted. While some control could be given to the students, for example determining the location and orientation of the surface add-on, they still seem to prefer an entirely remotely controlled experiment over a wind tunnel operator performed one. Due to the lack of time and the large-scale nature of the facility used here (i.e., for safety reasons), the complete remote control of the instrumentation could not be made available to the students for this experimental campaign.

Finally, Figure 6 presents the results of the student's overall impressions. While most of the feedback is still rather positive, some shift to the disagree responses can be observed. Based on

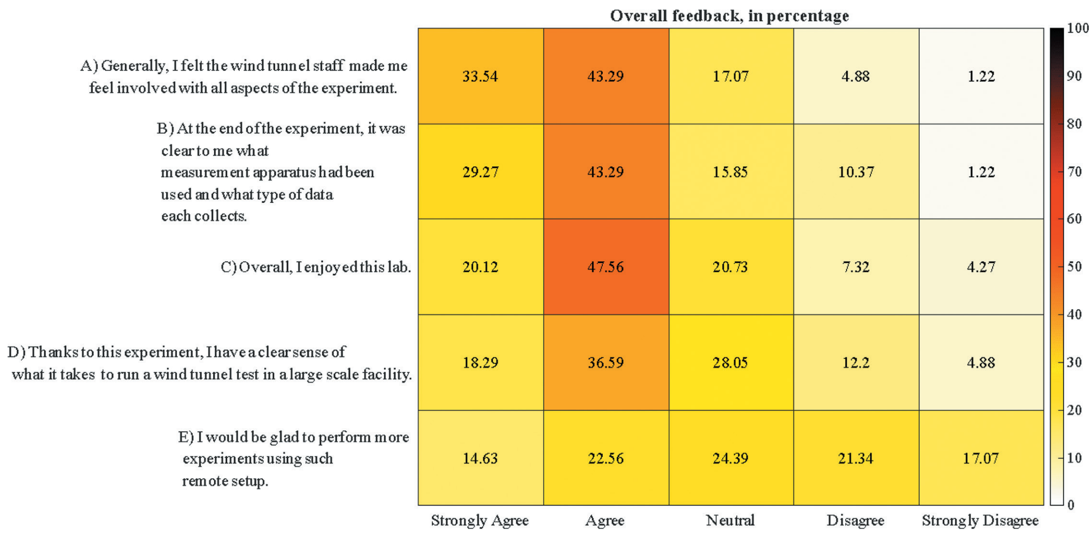

Figure 6. Results of the closed-ended questionnaire: Students overall impressions.

the results of Figure 6, students reported to have a general understanding of what experimental apparatus was used (statement B), they felt involved in the experiments (statement A) and they also reported to gain a sense of what it takes to perform wind tunnel experiments at a large-scale facility (statement D). In contrast, statement E in Figure 6 received a rather wide-spread responses. These responses were most likely based on the interpretation of this statement; hence this statement is underdetermined for the following reasons. Considering a pandemic situation, remote experiments are clearly a far superior alternative to canceling the laboratory sessions. In this interpretation, the students were presumably more likely to favor a remote laboratory session over canceling the labs. On the other hand, at the time of the questionnaire (April 2020), many assumed that the next semester (i.e., Fall 2020) would be conducted in a regular, in-person fashion. Under regular circumstances, students most likely would prefer in-person laboratory sessions. Overall, the remote labs discussed in this paper can be considered a successful and efficient way to ensure the laboratory delivery of wind tunnel experiments to the students.

Qualitative Results

Improvements Compared to Traditional Lab Settings

In response to which parts of the remote lab were better than traditional labs, students identified 13 different elements, as shown in Figure 7. The most common comments were the advantage of seeing the live camera feeds and to work and interact with experts, see the first two rows in Figure 7.

These comments justify the advantages of the currently presented *hybrid* labs over conventional remote labs. First, the live camera feeds and the tour of the facility provided a live, interactive student access to the facility, regardless of the student's geolocation. Again, the wind tunnel used in this study is a nationally significant research facility, which is not necessarily accessible to students from areas not well served by research capabilities. Second, the expert-at-a-distance could be present in a remote manner hence could interact with the students providing key conceptual learning value to the labs. In conventional remote labs, this usually is not a possibility. Also, the current approach enabled the expert to work from home. In addition, the collaborators from other institutions can also be considered experts, and the interaction between students and external collaborators are a novelty presented in this setup. The expert-student interaction also provided an easier way for the students to understand the experiments, see the 5th row in Figure 7. The remote aspect of the *hybrid* labs was found to be advantageous by the students, see the 7th row in Figure 7, since this way they could be present in the labs regardless of their location. There was also a non-trivial number of

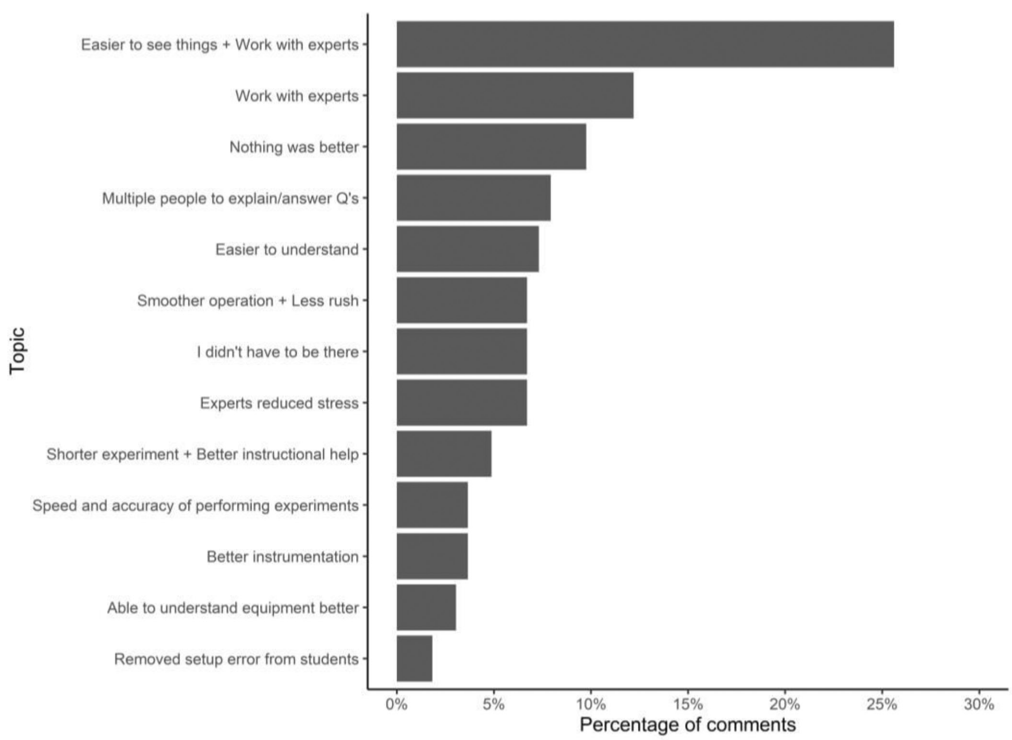

Figure 7. Results of the open-ended question: "List a few aspects of the remote experimentation that were better than a regular lab".

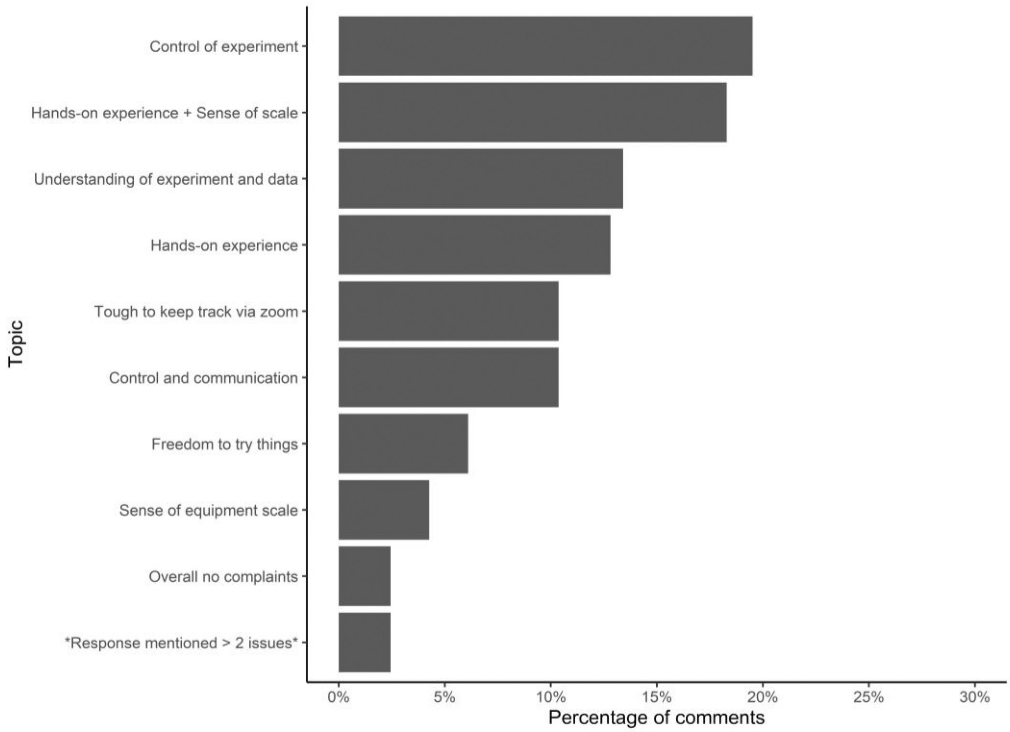

Figure 8. Results of the open-ended question: "List a few aspects of the remote experimentation that were lacking compared to a regular lab".

comments stating that nothing was better with the hybrid experiment compared to the traditional, in-person experiment. Other comments dealt with the convenience of not needing to physically be present in the lab and feeling less rushed compared to traditional lab settings.

Aspects Lacking Compared to Traditional Lab Settings

As with other questions, student comments highlighted different aspects where the hybrid labs were lacking compared to a hands-on lab, see Figure 8. In response to the question of what students thought was lacking compared to traditional labs, the most frequent comment was about the lack of direct control over the experiment. Associated with that, students more generally wanted hands-on experience. Another popular theme in comments responding to this question dealt with the lack of an ability to directly sense the scale of the experimental apparatus. Each of these three might be difficult to address in future remote labs at the SWT but can be addressed at smaller-scale facilities using simpler experimental setup. The fourth most common response was the difficulty in understanding the experimental data and purpose of the lab, although it is unclear how much of that is actually connected with the remote lab and how much of that would persist regardless of the lab modality and the instrumentation used. The next most common comment was about general issues following along on Zoom®. This may also be related to the aforementioned lack of control that students highlighted in their comments.

CONCLUSIONS

This paper presents the hybrid delivery of laboratory experiments (labs) performed during the early stages of the coronavirus pandemic. The labs presented here were conducted during April 2020 at the Stability Wind Tunnel of Virginia Tech and they were originally scheduled as in-person laboratory sessions. The laboratory sessions assessed the aeroacoustic noise reduction efficiency of various trailing edge serrations on the generated trailing edge noise of a NACA0012 airfoil. In their laboratory reports, students were responsible for performing a Fourier analysis of the gathered acoustic data. After the laboratory sessions, some 170 students provided feedback on the efficacy of the laboratory sessions via a questionnaire comprising open-ended and closed-ended questions.

All necessary components that ensured the successful delivery of the laboratory sessions are presented and discussed in detail. A widely available and commonly used teleconferencing software was used to stream the screens of various equipment to the students, while a set of cameras provided a visual immersion of the students to the facility. Each laboratory session consisted of three main parts, namely, tour of the facility, data acquisition and data visualization. During the tour of the facility, an expert-at-a-distance (faculty member or graduate student) was also present in the teleconferencing session and interacted actively with the students to ensure they have a good understanding of the underlying physics and they gain a clear view of the experiment. During the data acquisition and data visualization process, the students closely followed the displays of all instruments used during the experiments. Finally, the acquired data was made available to the students via a cloud service. The gathered data was also visualized and discussed at the end of each laboratory session.

Students' feedback via the closed-ended questionnaire revealed that the remote delivery method of the laboratory sessions presented here is an efficient and successful way to perform undergraduate laboratory experiments during the coronavirus pandemic. Students reported that the tour of the facility provided a clear sense of the scale of the facility, and the instrumentation used in the experiment. The teleconferencing session was also proven to be a sufficient method to deliver the screens of various instruments to the students. Overall, students reported that they were satisfied with the laboratory sessions, but the responses also revealed that their preference is still biased toward in-person laboratory sessions. Through the open-ended questions, students indicated that the presence of the experts added a key value to the labs and the interaction between experts and students contributed to their conceptual understanding of the experiments. Students also highlighted that performing experiments from their homes was comfortable. Finally, they also communicated a strong preference toward in-person labs as navigating over the teleconferencing session restricted their understanding of the scales of the experiment and their control of the instrumentation.

The present study demonstrates that standard video conferencing tools are already sufficient for effective delivery of remote experiments in an educational setting. It also demonstrates that such experiments are perfectly practical in a large-scale facility and, indeed, in some ways improve upon the experience that can be gained in an in-person setting. A particular advantage was presented here in the framework of a collaborative research undertaken between a US and two UK high-educational institutes. There is great scope for expansion here. Properly designed remote laboratory experiences have the potential to place unique and internationally significant facilities in the hands of students and professionals wherever they are located. This can be performed at comparatively low cost and in a setting that preserves the security and integrity of the facility while eliminating the geographic and economic barriers that ordinarily prevent such sharing.

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