From Sputnik to SpaceX®: 60 Years of Rocket Launch Acoustics

Caroline P. Lubert

Address:
Department of Mathematics &
Statistics
James Madison University
MSC 1911
Harrisonburg, Virginia 22807
USA

Email:
Lubertcp@jmu.edu

The field of rocket launch noise is 60 years old and has a lot to celebrate!

In the Beginning

At 7.28 pm (GMT) on October 4, 1957, the Soviet Union launched a 58-cm-diameter polished metal sphere into an elliptical Earth orbit at 29,000 kilometers per hour (kph), 800 km above the Earth's surface. The satellite was equipped with two pairs of external radio antennae that broadcast pulses from a one-watt, 3.5-kg radio-transmitting unit inside the sphere. Signals were emitted on two frequencies, 20.005 MHz and 40.002 MHz, spending 0.3 second at each (see bit.ly/2fSYJNl to hear these transmissions). The successful launch of Sputnik took the world by surprise at a time when the USSR and the United States were both desperately seeking to establish dominance over the new frontier, space.

Sputnik 1, where sputnik means "something that is traveling (the satellite) with a traveler (the Earth)," was the world's first artificial satellite. However, the language of rockets, the launch vehicles for satellites, goes back centuries. According to the Merriam-Webster Dictionary New Edition (2016), the first known use of the word rocket was in 1611. Deriving from the Italian word *"rocchetta"* meaning distaff, a rod used in spinning or weaving, it is defined in the Merriam-Webster Dictionary New Edition (2016) as "*a jet engine that operates on the same principle as the firework rocket, consists essentially of a combustion chamber and an exhaust nozzle, carries either liquid or solid propellants which provide the fuel and oxygen needed for combustion and thus make the engine independent of the oxygen of the air, and is used especially for the propulsion of a missile (such as a bomb or shell) or a vehicle (such as an airplane)*." Although we think of rockets as relatively new inventions, the first device to use the basic principles of rocket propulsion was probably a wooden bird, invented somewhere around 400 BC and propelled by escaping steam using the law of action-reaction (see bit.ly/2BNOi7F).

During the early days of the Space Race, the risk of rockets exploding during or just after liftoff was high and the technical focus was on improving rocket reliability. As the prospect of launch failure diminished (Martinez-Val and Perez, 2009), attention turned to other aspects of the liftoff process. At the time, very little was known about the acoustics of rocket launches, and at 300 m from the launch pad, peak levels could reach as much as 200 dB during liftoff (as far as 3 km from the launch pad, peaks of 140 dB, which is the threshold of pain in humans, were being observed). Such high acoustic loads are a source of vibration, and vibroacoustic interaction can critically affect correct operation of a rocket and its environs. Thus it was quickly realized that even a small decrease in noise could result in a significant reduction in both risk and cost, and the discipline of Launch Vehicle Acoustics was born.

And Then Came Sputnik...

Many important breakthroughs in rocket design were made between the 16th and 19th centuries. For example, the concept of a vehicle with multiple stages that

Figure 1. Dr. Robert H. Goddard before the flight of his first liquid-propelled rocket in Auburn, MA, on March 16, 1926. Photo available at go.nasa.gov/2MPRSCD.

could be used to lift rockets to higher altitudes, the so-called step rocket, was initially developed in the 16th century by a firework maker for enhancing firework displays (see bit.ly/2Ln7TLH). Its principles are still fundamental to the launch of orbital vehicles today. A significant breakthrough came in the 17th century when Sir Isaac Newton developed the scientific foundations for modern rocketry. His three laws governing physical motion explained how and why rockets work and could be used to inform future rocket design. However, improvements in rocket accuracy were not achieved for another two hundred years, until the technique of spin stabilization was developed. In spin stabilization, the exhaust gases strike small vanes, causing the rocket to spin as it travels. This is the same principle that bullets use today.

Still, modern rocketry belongs to the 20th century. Although early rockets were propelled by solid fuels, modern scientists thought (Tsiolkovsky, 1903; Goddard, 2002) that they could achieve greater speed and range by using liquid fuel. American rocketry pioneer Dr. Robert H. Goddard (see **Figure 1**) achieved the first successful liquid-propelled rocket flight in Auburn, MA, on March 16, 1926 (see bit.ly/2Lr9FeI for video of the first liquid-fueled rocket launch). The outbreak of World War II caused attention to shift almost exclusively to the development of rockets for use as weapons. They became such important elements of warfare that had research advanced more quickly on Germany's V-2 rocket, designed by Wernher Von Braun, the course of the war would almost certainly have been significantly changed. Similarly, it was the military as well as the scientific uses of rocket technology that made Sputnik such a historic event. Its successful launch caused great anxiety for the Americans who feared a widening technological gap between the two so-called superpowers, the United States and USSR.

In December 1957, American scientists made their first attempt to launch a satellite into orbit. The Vanguard TV3 ignited and began to rise but immediately lost thrust and fell back to the launch pad (see bit.ly/1bvmJxp to view the unsuccessful Vanguard TV3 launch). Finally, in early 1958, the United States successfully launched its first satellite, Explorer 1, which returned data for nearly four months and which remained in orbit until 1970 (see bit.ly/2P5dQPy that shows the US (National Aeronautics and Space Administration [NASA]) Space Explorations of 1958, including the first five US satellites). Following Explorer 1, satellite technology developed quickly and by the mid-1960s, satellites were prevalent and were being widely used for digital telecommunications. To date, more than 6,600 satellites have been launched from 40 countries. There are currently approximately 3,600 in orbit, 1,000 of which are operational.

And We Have Liftoff...

Rocket "launch" is the liftoff phase in a rocket's flight. Orbital launch vehicles, rockets that are capable of placing payloads into or beyond Earth orbit, typically lift off vertically (or near vertically) before progressively leaning over as they use gravity to steer the vehicle onto the required trajectory in order to exit Earth's atmosphere. Once rockets have completed the transonic climb phase through the atmosphere, they reach the desired altitude by angling slightly below the horizontal. This maneuver also increases their horizontal speed until it reaches orbital speed, at which point the engine cuts out. Because single-stage orbital rockets require an excessive amount of fuel, all current rockets are multistage vehicles, meaning that they jettison hardware (stages) on the way to orbit. The jettisoned stages are either lost or recovered and reused as in SpaceX's recently developed Falcon rockets.

The launch environment, which typically lasts only a few minutes, is the most severe dynamic environment that a spacecraft will endure during its normal life (Martinez-Val and Perez, 2009). The acoustic environment of a launching rocket is two-phase. During hold-down, which lasts a matter of seconds, the first stage engines are firing and building thrust, but the rocket is restrained by the transporter erector launcher (TEL). The second phase is entered once the TEL releases and the rocket lifts off, initially moving very slowly. During both phases, a dynamic load is produced on the surrounding infrastructure and personnel by sound pressure waves that fluctuate and generate structural vibrations that, if they are strong enough or at the "right" frequency, can cause damage or injury (Hess et al., 1957).

Since the late 1950s, engineers have been concerned about the acoustic environment generated by rockets. During the development of the Saturn V launch vehicles, still the tallest, heaviest, and most powerful rockets launched to date (see bit.ly/2P7N09E for the Apollo 8 Saturn V launch), there was a great deal of concern about the acoustic impact their launch from Cape Canaveral would create. A novel solution was suggested, namely, moving the launch site offshore to a remote structure built in a deepwater location. Three radar facilities off the east coast of Texas (the Texas Towers) had already been used during the Cold War as surveillance stations, and it was suggested that one tower be repurposed for use as a launch pad. However, after a 1961 storm destroyed one of the towers, the idea was abandoned (Teitel, 2016).

The eventual ground launch of NASA's Saturn V rocket was, at 204 dB, one of the loudest sounds ever recorded. This focused attention on improving predictions of liftoff noise so as to affect rocket design and thereby reduce damage from launch-generated noise (Guest and Jones, 1967). However, the upcoming launches of SpaceX's Interplanetary Transportation System (ITS) and NASA's Space Launch System (SLS), extremely large rockets with big acoustic impacts, are likely to generate renewed interest in offshore launches.

Launch Vehicle Acoustics: An Overview

Rocket launches generate a significant amount of acoustic energy. The primary source of rocket noise is due to the high jet exhaust velocity required to boost the launch vehicle during takeoff. Shock waves are formed by the collision of the supersonic exhaust plume with the ambient air, and the acoustic intensity of these waves depends primarily on both the size of the rocket and its exhaust velocity. Typical near-field peak noise levels are around 170-200 dB and are concentrated in the low- to midfrequency range, namely 2 Hz to 20 kHz. This is exactly the range where the transmitted energy and power can cause damage to buildings and humans (Teitel, 2016). Turbulent boundary layer excitation, separated flows, and wake flows also contribute to an extremely inhospitable acoustic environment that can cause structural vibrations during the climb through the atmosphere. Once the vehicle is supersonic, the rocket exhaust noise becomes less than the turbulent flow noise excitation. When stages separate, pyroshocks (the transient dynamic structural shock that occurs when an explosion or impact takes place on a structure) occur, causing additional vibration problems. However, it is the launch phase (characterized as a random, nonstationary, short-duration transient) that is the most problematic in terms of generating a potentially damaging vibroacoustic profile (Arenas and Margasahayam, 2006).

There are three types of supersonic jet noise: turbulent mixing noise (TMN) and two types of shock-associated noise (SAN): broadband shock-associated noise (BBSAN) and discrete screech tones (Allgood et al., 2014). TMN is always present and is generated by the large-scale turbulence structures/instability waves of the jet flow. However, the two types of SAN only occur in jets where there is a mismatch between the pressure at the jet exit and the ambient pressure (so-called imperfectly expanded jets). In this case, pressure equalization takes place through a series of compression and expansion cells or shock cells that form in the jet plume. BBSAN is then caused by the interaction of turbulence in the jet shear layer with this shock-cell structure and is primarily directed back toward the jet nozzle. Under the right conditions, BBSAN can also lead to the formation of narrowband tones, known as screech tones.

Not surprisingly, accurate prediction of the overall sound and vibration fields emitted by a rocket jet based on the rocket engine design is extremely difficult because it comprises several different, complicated noise-generating mechanisms (see **Figure 2**) and requires a detailed knowledge of the associated thermodynamics, aerodynamics, and acoustics (Koudriavtsev et al., 2004). Further complications occur when the effects of the launch vehicle and payload, launch pad design, and surrounding infrastructure are taken into account. Consequently, much rocket launch noise work to date has focused on noise mitigation, on experimental work, or the development of models that combine experimental data and theoretical assumptions.

Noise Mitigation

In many engineering applications, noise mitigation can be achieved by the control of vibration boundaries and unsteady flow phenomenon. Such techniques can be divided

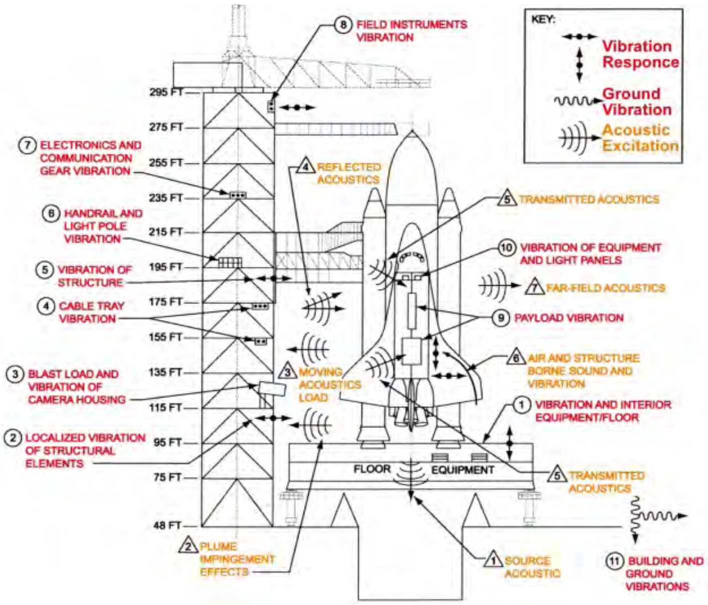

Figure 2. *Rocket launch-induced noise and related vibration-induced response of structures.* ***Numbers in circles*** *are related to those effects of vibration response that need to be considered as potential problems during the operation of the shuttle. These include structure-borne wave transmission.* ***Numbers in triangles*** *are related to the acoustic radiation, such as airborne sound waves. Reproduced from Arenas and Margasahayam (2006, Figure 8).*

Figure 3. *Water from an acoustic suppression system test soaks the mobile launcher platform at the Kennedy Space Center Pad 39A with 350,000 gallons of water. Photo available at bit.ly/2P1W93e.*

into active noise control, which results in achieving sound reduction in real-time using a power source, and passive noise control, which incorporates sound reducing measures into the original system design or retrofits them. Passive treatments are most commonly used to mitigate rocket launch noise.

Water-based acoustic suppression systems are commonly used on launch pads (see **Figure 3**), where they offer typical noise reductions of 3-5 dB (depending on frequency) in the overall sound pressure level at most frequencies of interest (Krothapalli et al., 2003; Norum, 2004; Houston et al., 2015). Interestingly, the technology on which these suppression systems are based was originally developed to help submarines avoid detection. Naval engineers designed the exhaust of submarine engines to emit bubbles, which have the ability to absorb an amazing amount of sound. As sound waves encounter the bubbles, the bubbles compress and convert the acoustic energy into heat, thereby shrouding both the noise emitted by the submarine, and incoming sonar waves.

In a water-based launch pad acoustic suppression system, water molecules sprayed into the air begin to vibrate on contact with a sound wave, converting the acoustic energy into heat. Additionally, any air bubbles present in the water will be compressed by sound waves, again converting the sound energy into heat energy. At the same time, below-deck (that is, under the launch pad) systems inject water into the exhaust plume with the aim of reducing far-field noise by more rapid dispersion of the rocket exhaust (Allgood et al., 2014). Moreover, above-deck systems, so-called rainbirds, inject water around the top of the pad as well as into the plume (Houston et al., 2015) that, in addition to suppressing the noise, helps cool the launch pad and environs. Care must be taken, however, not to deluge the pad, degrade materials and structures (Pico et al., 2016), or adversely affect performance of the diffuser (Allgood et al., 2014), which is a device used during sea-level rocket tests to simulate the effects of altitude. Water injection helps to reduce the SAN (Norum, 2004), and the extent of the reduction depends on where in the plume the water is injected and how great the injection pressure is (Gely et al., 2000, 2005; Lambare, 2016). To achieve any significant noise reduction, the quantity of water injected must be at least three times the jet flow rate; for the new acoustic suppression system on the mobile launcher platform at the Kennedy Space Center (KSC) Pad 39A, this means that the water flow rate exceeds 900,000 gallons a minute at liftoff. See bit.ly/2o9FEa7 for a recent test of the water suppression system (using about 450,000 gallons of water) at the KSC Pad 39B, from which the SLS will launch.

A key component of any launch pad is a flame deflector (FD), which is a trench used to channel the rocket exhaust away from the pad (see **Figure 4**). Flame deflectors are generally not specifically designed for acoustic purposes but nonetheless can have an important effect on the noise. Although the impingement of the plume on the FD generates noise that propagates away from the vehicle, the unsteadiness of the plume flowing along the FD emits the dominant noise that is directed toward the vehicle. As a consequence, factors such as trench cover and shape have a significant effect on the ability of the deflector to reduce noise (Gely et

Figure 4. *The Antares launch pad at the Wallops Flight Facility, Virginia. The rocket is attached to the pad by the rocket launch mount, which is the large white ring that can be seen in the* ***middle*** *of the figure. The (square) rocket flame trench exit is shown at* ***right****.*

al., 2005; Pico et al., 2016). Preliminary work (Tsutsumi et al., 2009) has indicated the possibility of substantial noise reduction, particularly if the initial inclination of the FD is steep and it is covered. The longer the trench, the greater the noise reduction (Gely et al., 2000).

Rocket nozzle configuration and shape also impact launch noise emission (Humphrey, 1957; Viswanathan et al., 2012), and tailored nozzles can provide a reduction in the directional noise by providing a low-speed layer around the outside of the primary jet that partially blocks sound transmission. This layer can be further modified by the use of wedges, pairs of vanes, and flaps (Viswanathan et al., 2012). Finally, flat concrete (reflecting) surfaces are predominant on launch pads, and recent studies have indicated that the inclusion of perforations in these surfaces is effective at reducing noise (Natarajan and Venkatakrishnan, 2016).

To control the vibration levels on launch structures, their dynamic characteristics need to be thoroughly understood, and a significant amount of recent work has focused on this (Caimi and Margasahayam, 1997; Margasahayam et al., 2002). Whereas previous pad configurations have been designed based on reducing liftoff peak acoustic load, Caimi and Margasahayam's (1997) work indicates that the duration of plume impingement is a far more damaging and crucial design parameter. However, it should be noted that the feasibility of utilizing such modifications in practical launch pad design still remains to be determined.

Theoretical Work and Scale-Model Experiments

Noise mitigation techniques have been fairly successful and in some cases decrease peak acoustic levels by up to 5 dB. However, to achieve further reductions, much greater understanding of the mechanisms by which rocket launch noise is generated and propagated is necessary. Although the importance of acoustic loading in causing structural failure has been known for 60 years (e.g., Hess et al., 1957), only relatively recently have significant advances in sensors, data acquisition, and processing techniques, along with huge improvements in numerical simulation ability, allowed the measurement and prediction of launch noise with any degree of accuracy.

The main issue in accurately predicting rocket launch noise is determining the relationship between the aerodynamic characteristics of the flow and the spatial characteristics of the sound field. Most rocket noise models are semiempirical and based on the classic NASA SP-8072 methodology (Eldred and Jones, 1971) in which the rocket plume is the primary noise source throughout launch. A major problem with this method is that it is not consistent with Lighthill's (1952, 1954) generally accepted jet noise theory because the initial approach to the aerodynamics was far too simplistic. Nevertheless, modified versions of the NASA model continue to be used. Revisions typically focus on improving the estimate of the laminar core length (Varnier, 2001) or on amending the acoustic efficiency by a factor that significantly improves the fit to the experimental data while accounting for the launch pad and FD geometry as well as for shielding (Plotkin et al., 2009).

Other empirical or semiempirical methods based on historical data, engineering judgment, and/or acoustic measurements have also been used extensively (Arenas and Margasahayam, 2006; Fukuda et al., 2009). For example, data were recently collected by the Japan Aerospace Exploration Agency (JAXA) during two static-firing tests of a solid rocket motor. The data were then compared with the results of the classical NASA SP-8072 empirical prediction method and a computational fluid dynamics (CFD) calculation (Herting et al, 1971). The former overestimated the sound pressure level at certain angles from the jet axis, although the prediction at other angles was reasonable. The CFD model was effective for prediction of both the near- and far-field acoustic profiles.

Once the acoustic load generated by liftoff has been predicted, it is then used to predict internal vibration responses of the vehicle, its payload, and the launch pad. Due to the

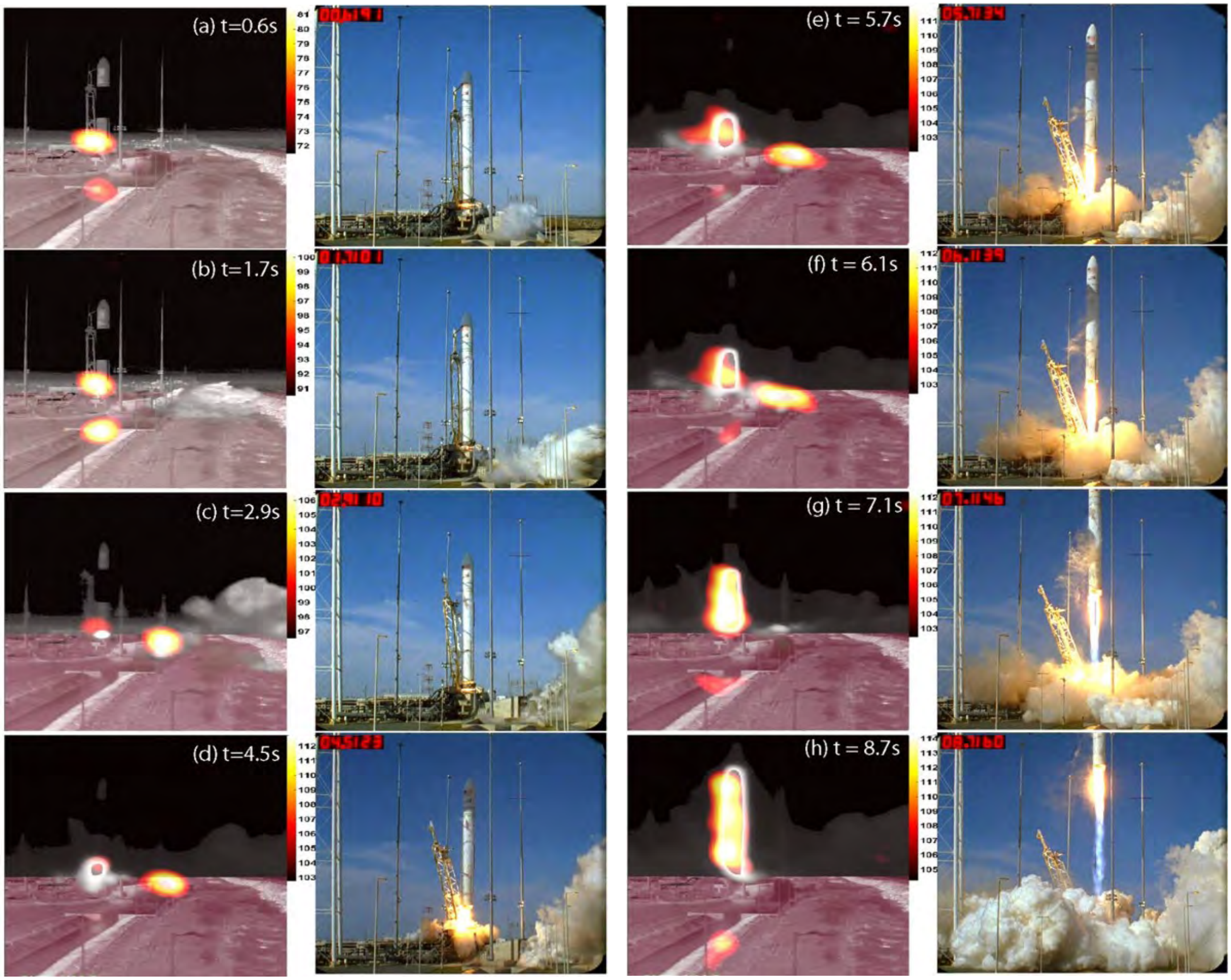

***Figure 5. Left, a-h**: noise maps superimposed on frames from an infrared camera, conventional beamform at 2 kHz; **right**: corresponding frames from a high-speed camera. Reproduced from Panda et al. (2013, Figure 11). See text for further explanation.*

obvious difficulties in full-scale experiments, launch vehicle design is heavily reliant on scale-model testing, where the results can prove invaluable (Bies and Franken, 1961). A recent comparison between full-scale and model-scale data shows good correlation, indicating that scale data can be used with confidence (Giacomoni and Kenny, 2016). Indeed, a source localization and reconstruction technique has lately been employed to successfully analyze wall pressure measurements on a model launch vehicle (Casalino et al., 2012). Similarly, aerovibroacoustic methods are currently being developed for predicting the response of a rocket to the intense acoustic environment inside the nose cone used to protect the payload (Tsutsumi et al., 2016). Such research is of great importance in rocket design.

Recent efforts have also focused on collecting acoustic data from static-fire rocket tests in an attempt to characterize the full-scale rocket plume noise environment. The acoustic temperature has been measured in a rocket noise field and found to contribute significantly to the total temperature variations (Giraud et al., 2010). Near-field vector intensity measurements on a model rocket motor indicate that as the frequency increases, the dominant source region contracts and moves upstream, with peak directivity occurring at greater angles from the plume axis (Gee et al., 2010). The noise source, conventionally assumed to be the rocket plume, is known to be directional and distributed and can be modeled by line arrays of monopoles that mimic the partially coherent nature of jet noise (Morgan et al., 2012). Recent work has shown that including source correlation and atmospheric turbulence in the model improves the predictions (Gee et al., 2014).

The first beamforming experiment conducted during an actual launch, in which microphones were placed on the rocket itself, confirmed the source distribution found during a model-scale static-fire test (Gely et al., 2000). However, the first time a ground-based beamforming experiment was conducted during an actual launch was not until the 2013 launch of Orbital ATK Antares rocket from the NASA Wallops Flight Facility in Virginia (Panda et al., 2013). Results from these experiments provided unprecedented and unexpected insights into rocket launch noise sources (see **Figure 5**). In contrast to previous static-fire tests, they indicate that the primary noise source changes with time and that the source distribution is actually very different from the traditional model assumption of the plume as the primary noise source throughout launch (Eldred and Jones, 1971).

Figure 5, *left*, shows the sound sources, with lighter colors indicating higher noise levels, as identified by the beamforming experiments. **Figure 5, *right***, shows selected frames from a high-speed camera and are courtesy of the NASA KSC imaging group. From **Figure 5, a** and **b**, it is clear that during initial engine ignition, the primary noise source (***left, bright yellow/white areas***) was the launch mount and its accompanying ground reflection. However, once the engines come to full power during hold-down, the hot exhaust plume exits the deflector and the FD exit becomes the primary source (see **Figure 5, c** and **d**). This effect is mitigated to some degree by the duct water. The TEL then releases the launch vehicle and pitches away from it while the launch vehicle simultaneously fires at a slight angle to the vertical away from it. This so-called "TEL avoidance maneuver" causes the hot exhaust plume to spill out from the FD inlet and spread across the launch pad, causing a large area on the surface of the pad to become a loud, distributed acoustic source, in addition to the FD exit (see **Figure 5, e** and **f**). Thus, contrary to assumptions made in many traditional rocket noise models, it is not until the plume finally emerges fully from the duct (see **Figure 5, g** and **h**) that it becomes the primary noise source.

These data indicate that, contrary to the traditional model assumptions, a thorough understanding of the changes in acoustic source location with launch phase (time) is of fundamental importance in accurate launch noise modeling. For example, within the Antares flame trench, the Coanda effect is present. In the Coanda effect, a jet of fluid passing over a curved (Coanda) surface bends to follow that surface, simultaneously entraining large amounts of air as it does so. Because this flame deflector is the primary noise source as the engines come to full power (see **Figure 5, c, d** and **e**), it may prove to be a significant source of launch noise. Thus, recent work focuses on applying results obtained previously concerning turbulent Coanda jet flows (Lubert, 2008, 2017) to modeling the noise generated within this deflector.

The Future

Expendable launch vehicles have been used in the vast majority of the approximately 5,700 launch attempts since Sputnik. Now, however, the trend is for reusable rockets (Klotz, 2017). Indeed, the US Air Force and NASA, the two biggest customers for US launch services, both predict using reusable rockets in the near future. For example, SpaceX's Falcon 9 rocket is designed to have a recoverable and reusable first stage. See bit.ly/1Jq9EjT for the historic first landing of a Falcon 9 first stage on December 21, 2015. Much of this effort is cost driven because typically about 70% of the cost of the rocket is related to the first stage. It should be noted that this is not the first attempt at reusability. The Space Shuttle (see go.nasa.gov/2r8E4aH) had reusable parts, the three main engines, which were removed between flights for extensive checking. This process was expensive and took several months, whereas SpaceX's current goal is to go from recovery to relaunch in 24 hours. However, as yet very little is known about how the launch acoustics change when reusing hardware or how the vibroacoustics might potentially be more damaging to hardware that has already been used and structurally stressed.

Finally, rockets are getting larger and louder. NASA's latest rocket, the SLS (see go.nasa.gov/2365V9K), will be the most powerful they have ever built, with 20% more thrust at liftoff than the Saturn V. That is, at liftoff, the SLS will generate more than 30 times the total thrust produced by a 747 airplane! Such extremely high fluctuating acoustic loads are a principal source of structural vibration, and this vibroacoustic interaction critically affects the correct operation of the rocket and its environs, including the vehicle components and supporting structures. Even relatively small reductions in the rocket launch noise level can result in substantial savings by reducing unexpected repairs, operating costs, and system failures. These benefits are spurring the development of novel and effective acoustic suppression methods, new experimental data-gathering techniques such as acoustic beamforming, and a plethora of mathematical modeling tools aimed at accurate noise prediction.

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BioSketch

Caroline P. Lubert is a professor of mathematics at James Madison University, Harrisonburg, VA. She obtained her degree in mathematics and her PhD in engineering from the University of Exeter, Devon, UK. Her aeroacoustics laboratory focuses on the noise emitted by turbulent Coanda wall jets, which are used in a multitude of industrial applications but, unfortunately, also often produce unwanted and harmful noise. Her research has recently focused on modeling the turbulence-generated noise emitted during liftoff of the Antares rocket, which resupplies the International Space Station and launches from Wallops Island, VA.

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