Whistles: from toys to industrial devices and applications

By Ganesh Raman and K. Srinivasan

Whistles capture our fascination from the time we are children; the name and sound promptly rekindle fond childhood memories – toy whistle as a kid, boy/girl scout whistle, hoots of trains/ships, whistle of baseball/soccer coach/referees, lifeguards, sirens of factories, and musical instruments – the list is endless. Interestingly, beyond controlling people, as policemen/referees do, whistles can be useful control devices in industry, as this article explains. "Whistle" is a device that produces sound confined to discrete frequencies and their harmonics. Although such devices may be mechanical, electrical, or pneumatic, conventionally the name is refers to air-powered sound generators.

The name "whistle" has its origins as a musical wind instrument. Later, steam whistles used in rail engines and ships borrowed the name. The natural passion for the melody of whistles persists even though steam engines are now obsolescent, in the form of hobbies such as whistle collection*. Antique whistles still inspire memories about the industrial revolution and the steam age.

From prehistoric times, design of tunable cavities has interested researchers. They could produce acoustic tones by directing a fluid stream against a solid structure such as an edge or cavity – devices known by various relevant names, e.g., edge-tone, hole-tone, ring-tone, and impingement-tone [Fig. 1]. Devices that generate sound based on shear layer oscillations, impingement, edge-tone or vortex principles include an organ pipe, Galton whistle [1], (Fig. 2) Levavasseur whistle, and vortex whistle [2, 3]. The quarter wavelength of the cavity governs the frequency of such devices with cavities. In general, the amplitude of common whistles is inadequate for acoustic

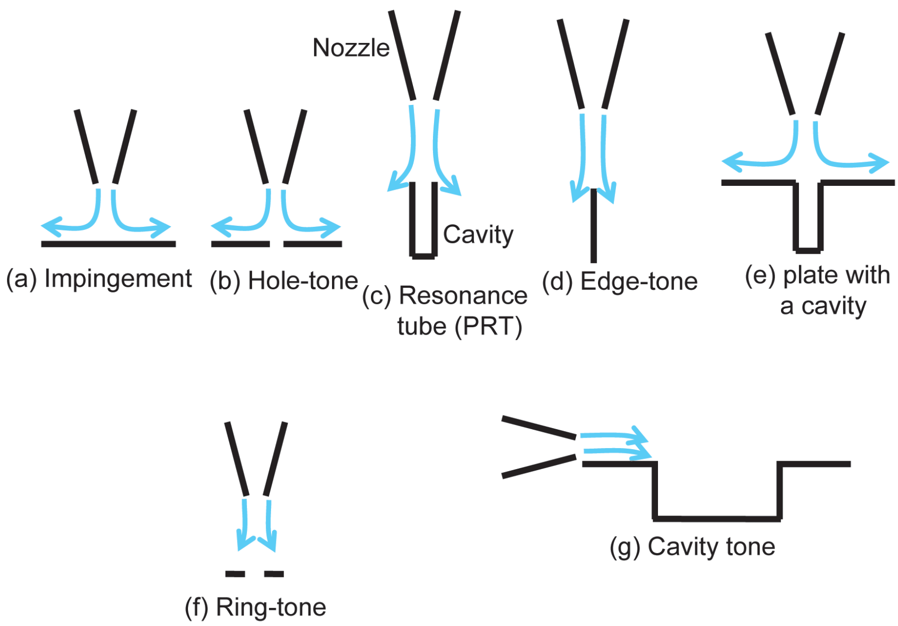

Figure 1. Various resonant situations

*See websites such as www.hornandwhistle.net and www.whistlegallery.com for interesting collections

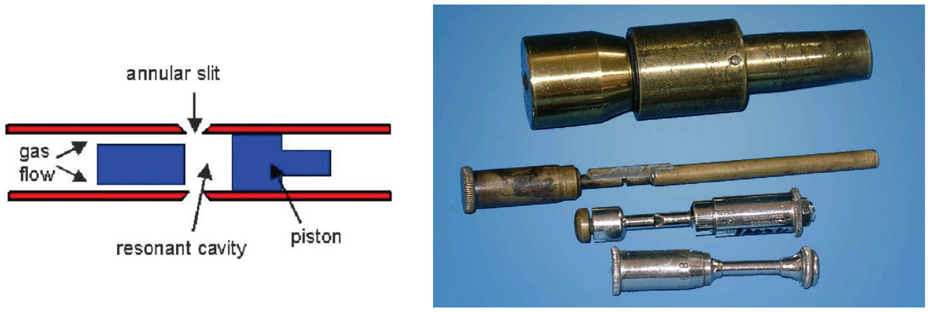

Figure 2. Galton whistle. (a) Principle of operation and (b) collection at http://physics.unl.edu/history/histinstr/wave_pix/10021_10022x.jpg

actuation. In addition to whistles, supersonic free jets also generate discrete tones called "screech" [4-6]. The Hartmann whistle differs from several tone generators in two ways: its high acoustic output and a different working principle.

While sound generation is intentional in certain circumstances (e.g., musical instruments, industrial whistles, industrial acoustic agitators, & actuators), it could be a consequence of some other process (e.g., cleaning processes, swarf removal, liquid/powder coating processes, rocket exhaust on launch pad, etc.). Wherever sound is undesirable, we label it "noise." While some researchers attempt to improve acoustic efficiency and tonal quality of useful sound, others find methods to fight unwanted noise.

The Hartmann whistle finds its place as a high efficiency acoustic device with numerous advantages cited earlier. Hartmann [7, 8] discovered that he could produce pressure oscillations by aiming a supersonic flow against a tube closed at one end. The device was initially known as a "Hartmann whistle." Another milestone in Hartmann tubes was Sprenger's 1954 [9] discovery of resonance-induced heating. The literature uses the terms 'Hartmann tube' and 'Hartmann-Sprenger tube' interchangeably, though researchers seem to prefer the latter term for resonance tubes with a thermal emphasis.

The primary advantages of the Hartmann whistle are:

- Sound generation is purely aeroacoustic; device has no moving parts; construction / fabrication is extremely simple
- Sound quality is high due to intense tonal content and high amplitude
- Device has a high directivity and thus provides positional flexibility
- Frequency of sound is tunable using the geometrical parameters
- Device cost is very low
- Device requires no special power and works on simple compressed air

THE HARTMANN WHISTLE IS BORN

Julius Hartmann discovered the Hartmann whistle resonance phenomenon when he conducted pitot pressure survey in a supersonic jet (1916-1918) [7, 8]. When an imperfectly expanded jet emanates from the nozzle, it shows spatially periodic cell structure with a periodic static pressure variation. Hartmann observed violent oscillations when he placed the pitot tube at certain locations in the shock-containing zone of the free jet, which he termed as "regions of instability" (Fig. 3). He recognized that the oscillation frequency had some relation to the longitudinal length of the pitot assembly. His experiments conducted over a wide range of cavity geometries including a large Helmholtz resonator ("Hartmann pulsator"), let him obtain frequencies as low as 1 Hz to 100 Hz and visualize the oscillations using schlieren or shadowgraph systems.

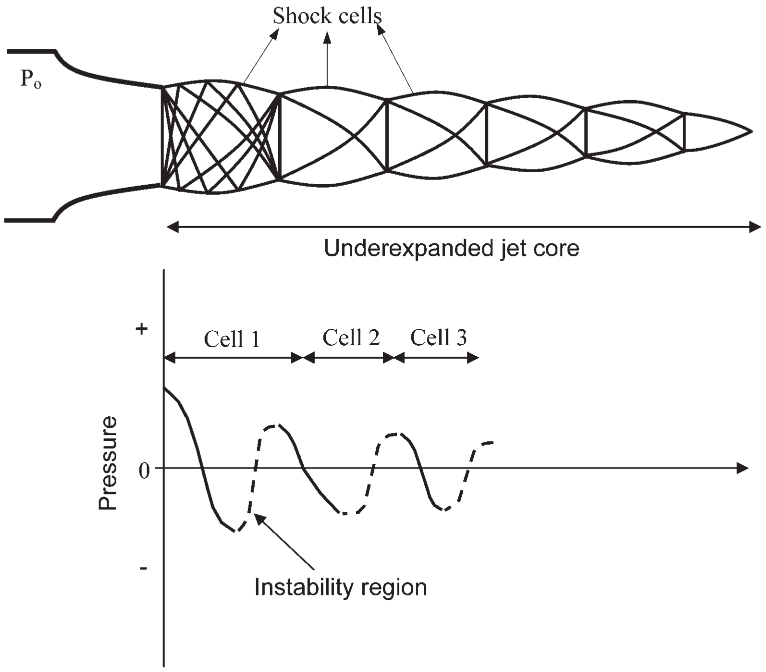

Figure 3. Regions of instability governed by accelerating and decelerating regions in a shock containing jet.

Hartmann's substantial contributions included careful experiments, providing minute details about the nozzle and tube geometries and their assembly for improving the efficiency and applications [10-12]. Using innovative experiments with a watch-maker's lathe, Hartmann explored the effect of varying the space between supply jet and resonance tube. His group published a continuous stream of papers from 1919 (initial discovery) to 1951 (application). Over time, the Hartmann whistle became known as a gas jet siren," "static siren," "air-jet generator," "jet-type vibrator," etc. [13].

WHY DOES IT PRODUCE INTENSE SOUND?

Based on flow visualizations, Hartmann explained that the cavity periodically swallowing and evacuating jet fluid caused the acoustic tone. The tone frequency corresponds to the quarter-wavelength mode applicable for tubes closed at one end and open at the other. Researchers later found that several other modes of resonance are feasible, some involving oscillations of the stand-off shock from the supersonic jet. Hartmann found that resonance occurred when he placed the cavity at certain regions of the supersonic jet's shock-containing region. When he placed the cavity in the regions of instability, where the static pressure shows an increasing trend ("zone of instability"), the detached shock oscillates, leading to resonance. If researchers locate the resonator tube mouth at the downstream limit of one unstable zone (Fig. 3), we can describe the physical phenomenon in these phases [13]:

1. Filling phase: detached shock is very close to cavity mouth, and jet fluid enters the tube [Fig. 4(a)]
2. As the tube fills, its pressure increases, which tends to push the stand-off shock into the unstable region upstream. Since pressure continues falling during upstream movement, the shock is forced upstream until it reaches the stable region [Fig. 4(b)]. Due to the static pressure bump, this movement of the shock happens impulsively.
3. This upstream motion of the shock lowers the pressure near the tube

mouth, initiating outflow from the tube, which is diverted radially outward; outflow makes the shock retract back in the downstream direction [Figs. 4 (c & d)]

4. As pressure distribution regains its original value, the shock resumes its downstream quasi-stable position, and the jet refills the resonator tube, completing one cycle

Later, researchers identified other oscillation modes, termed "jet instability mode," "jet regurgitant mode," and "jet screech mode." Jet instability mode occurs only for subsonic jets, where large periodic toroidal vortices produced at the jet exit amplify as they convect downstream and result in weak compression waves inside the tube. In the jet regurgitant mode, the resonance tube periodically completely swallows the jet as mentioned above. In the screech mode, the shock between the nozzle and the tube undergoes violent oscillations. Depending on geometrical parameters (spacing to diameter ratio and flow parameters such as nozzle pressure ratio), modes can switch.

AFTER HARTMANN'S DISCOVERY

Early research following Hartmann's discovery develop in several directions. Some delved deep into the physical

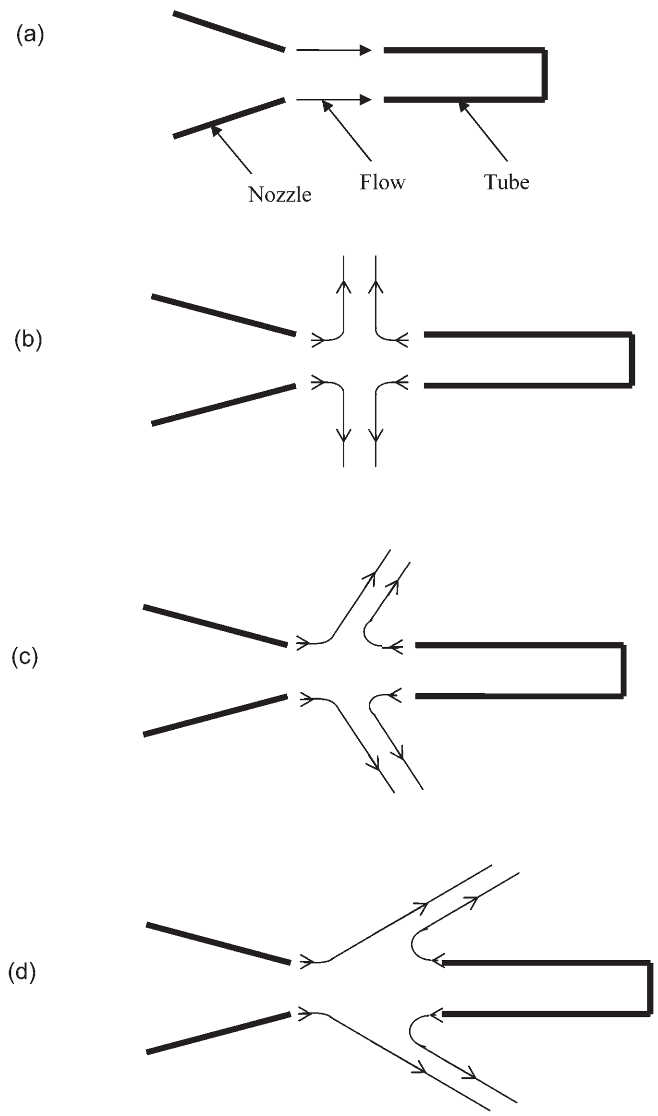

Figure 4. Schematic of the flow geometry during various phases of an oscillation cycle.

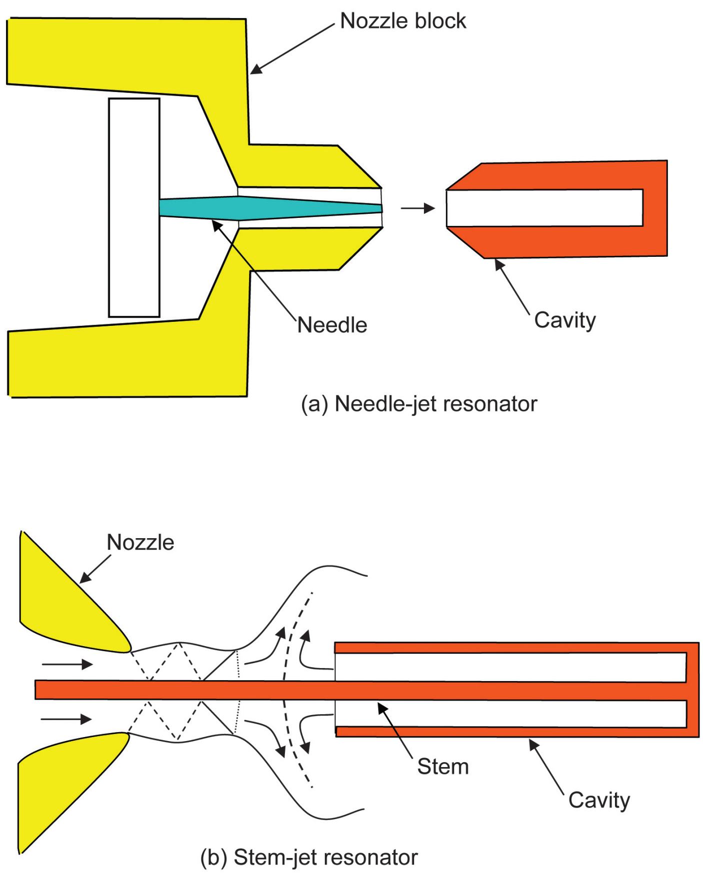

Figure 5. Destabilization devices. (a) Needle-jet resonator and (b) stem-jet resonator.

mechanism of resonance and ways to sustain it over a larger range of operating parameters. For instance, Savory [14], Hartmann, and Trusdo [15] showed that when a stem passing through the nozzle axis supports the resonator (Fig. 5), oscillations occur even at subsonic Mach numbers. Others modifed the device to enhance efficiency while yet another group adapted it for practical applications.

While several investigators enhanced the amplitude of the sound generated and the device's acoustical efficiency, they made little effort to control device frequency or to make it tunable. On the application front, early applications included coagulation and precipitation of dust/smoke, atomization, and ignition. Sprenger's pioneering discovery of resonance heating effects led to a chain of studies on thermal effects. This idea was very attractive since researchers could achieve substantial heating without combustion, fuel, or moving parts. Studies on heating enhancement, and thermal applications soon followed; using the resonance tube in flow control emerged much later.

Raman and Kibens [16] demonstrated use of the device as an actuator for flow control, ushering in a new era of resonance tube applications. This method of flow control is "active control," since external energy is supplied to the control device, so in actuator applications, this is conveyed appropriately by the "powered resonance tube" (PRT). Although a simple free jet could resonate or "screech" under certain conditions, it is extremely difficult to use as an actuator: the free jet is not tunable (screech frequency is discontinuous with Mach number) and some frequencies are impossible to generate. Further, the only variable parameter available for varying frequency is the nozzle supply pressure. In contrast, the PRT has several parameters (e.g., tube aspect ratio, depth, spacing, pressure ratio, etc.) for controlling acoustic properties such as frequency and amplitude. So, it is possible to identify appropriate parameters satisfying all practical constraints in practical applications. For example, in applications where supply pressure is limited, we can meet the application challenge using other flexible parameters. Also, in the presence of needle/stem type devices, resonance occurs over a large frequency range in a continuous manner, rendering it fully tunable over the frequency range.

THERMAL EFFECTS – HARTMANN SPRENGER TUBE

Initially, researchers did not observe thermal effects such as resonance heating since the thick tube walls and surrounding apparatus resulted in heat dissipation. For instance, Hartmann observed only a 7^{o}C temperature rise. Sprenger was the first to observe significant thermal effects in resonance tubes – e.g., distortion of resonance tube material; he reported melting of tubes made of German silver. In fact, it is fairly easy to demonstrate Hartmann-Sprenger tube heating effects in a shop floor. If we blow air into a hole the same size as the jet hole drilled in a piece of wood, the wood ignites.

Non-isentropic flow in the tube causes the heating mechanism that an oscillating flow promotes. In his Guggenheim memorial lecture. Ackeret [17] emphasized the importance of entropy in the heating, reporting resonant heating up to 1000 K. Thermal effects are enhanced when the gas in the tube gets partially trapped inside the resonance tube unable to exchange heat and mass with the jet flow, accumulating the heat inside the tube. Heating effect is more pronounced when the resonance generates high amplitude pressure oscillations. However, tuning parameters for heating effects may be different from those for acoustic effects, so "tuning" depends on the desired PRT function.

When the Hartmann tube is long enough, it provides sufficient distances of shock travel back and forth, increasing entropy generation inside the tube, which enhances temperature increase at the closed end of the tube. Such a configuration is commonly referred to as the "Hartmann-Sprenger (H-S) tube," named after Sprenger who discovered this effect (noted earlier). If the resonance tubes are shorter, the compression fronts moving across the tube have no chance to coalesce to form strong shocks, so researchers do not observe thermal effects in shorter tubes. Iwamoto [18] explained the detailed mechanism behind the flow oscillations in a H-S tube, based on in-flow and out-flow time measurements and shock dynamics.

GEOMETRIC VARIANTS OF THE HARTMANN WHISTLE

Motivations behind various geometrical resonance tube forms include enhancement of acoustic efficiency, thermal effects; or adaptation to practical situations. Simplest geometric modifications (Fig. 6) include stepped tubes, conical tubes, nonlinearly varying tube profiles, and Helmholtz resonators. In general, we may classify variants based on jet nozzle geometry, tube geometry, the combination of jet and tube, external augmentation such as with a horn or a reflector (Fig. 7) (based on the destabilizing device), and unconventional geometries such as twin whistles excited by a single jet, secondary resonators, etc. Smith and Powell [13] point out geometrical/operational differences between various resonance tube geometries and emphasize the fact that

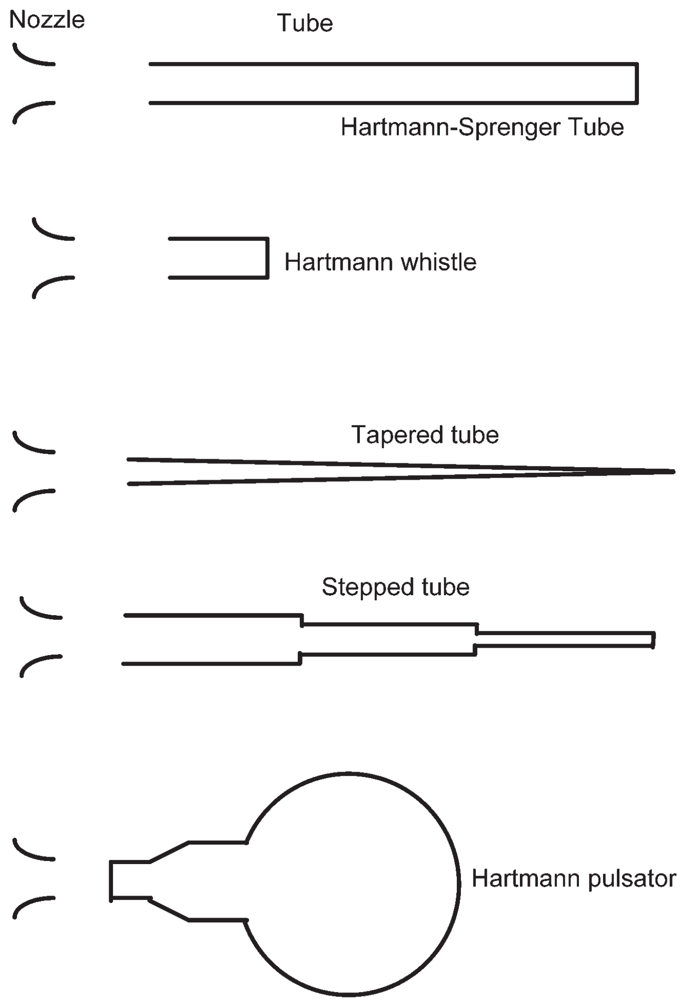

Figure 6. Geometric variants of the Hartmann whistle

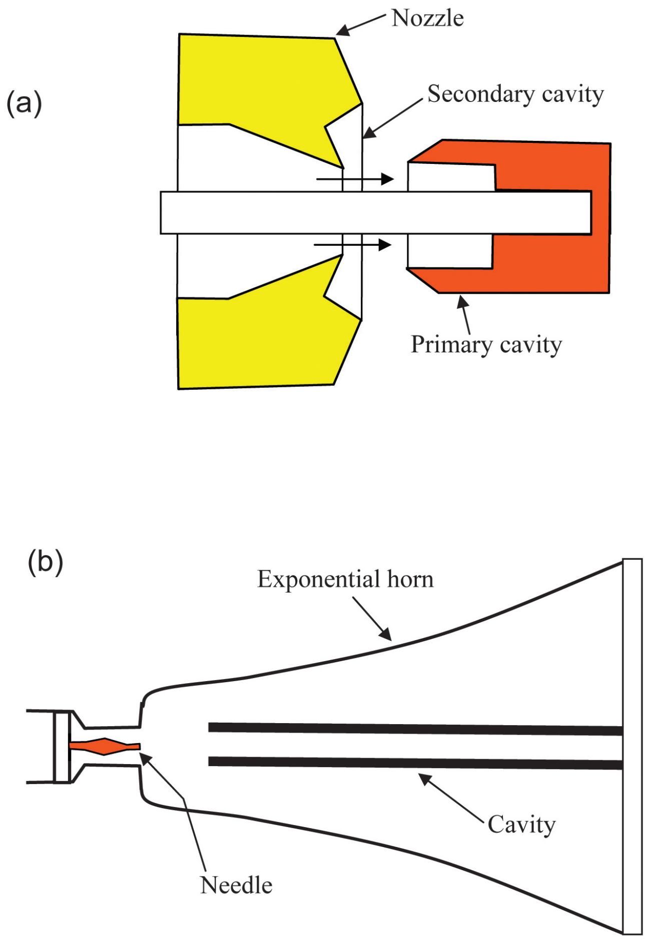

Figure 7. Performance augmenting modifications. (a) secondary resonator and (b) horn-augmented resonator

even small geometry changes could lead to a different sound-generation mechanism.

EARLY APPLICATIONS OF THE HARTMANN WHISTLE

In the early 1940s, applications started in Europe for ultrasonic testing of alloys using specially shaped cavities [13], with output reaching 220 kHz. Other early applications were aerosol coagulation, gas cleaning, precipitation of dust, smoke/fumes, acoustic agitation, industrial drying of solid materials (mostly dehydration), dispersion of fog in runways, textile fiber processing, and degassing high viscosity oils. Greguss [19] surveyed available acoustic generators and their relative merits and demerits in terms of acoustic efficiency, air consumption, etc. The resonance tube phenomenon also plays a role in related research areas: aircraft intake and propulsion systems, combustion chambers, diffuser design, and supersonic buzz suppression efforts.

APPLICATIONS OF THERMAL EFFECTS

Researchers used heat generated inside the resonance tube to ignite propellants inside rockets: they dubbed the device a "fluidic ignitor" or "flueric initiator." They obtained temperatures on the order of 1200°C using PRT-based fluidic actuators and minimized ignition times. Among the resonator geometrical shapes examined stepped, conical, tapered, cylindrical, the stepped tube achieved higher temperatures and faster heating rates. There were even attempts to convert heat inside the resonator tube to electricity by placing magnetohydrodynamic generators in the tube; researchers concluded that they could convert about 21% of the jet energy into electricity. Investigators also integrated the Hartmann-Sprenger tube in the flow path of injectant gases in a scramjet engine to passively heat them before admitting them into the combustion chamber.

THE POWERED RESONANCE TUBE (PRT) ACTUATOR IS BORN

Active flow control (AFC) methods modify flow dynamics to achieve flow objectives such as mixing enhancement, delay of flow separation, resonance suppression. AFC applications require actuators that can produce high-amplitude unsteady fields. High frequency actuation was beneficial for AFC, so the search for such actuators followed. Several ideas emerged: fluidic oscillators, piezoelectric wedge actuators, acoustic drivers, loudspeakers, etc. However, most suffered limitations. For instance, acoustic drivers and oscillating flaps do not perform well in the high frequency regime. The novel piezo-electric wedge actuator consisted of a piezo-ceramic wedge embedded on a slender wedge supported at two points. The wedge was designed so the desired frequency matched the wedge's second bending moment. Although the device was successful in edge-tone suppression, its fragility and very narrow range of operation restricted its use. Sometime later, researchers evaluated the Hartmann whistle as a high frequency actuator, which proved successful [20, 21]. The success of the resonance tube actuator in suppressing impingement tone is evident in Fig. 8. The advantages of the PRT – simple construction, absence of moving parts, high tonal amplitude, narrow band spectra, directivity, tenability, low cost, and obviation of special power requirements – paved the way for this promising device's success. Investigators have not yet achieved the PRT's full potential, research in this direction continues.

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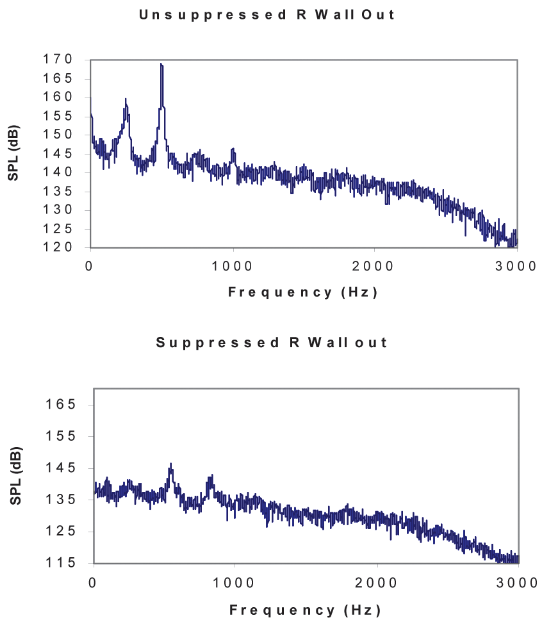

Figure 8. Impingement tone suppression by PRT

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About the Authors:

Dr. Ganesh Raman is Associate Dean for Research at the Illinois Institute of Technology in Chicago (Raman@iit.edu). Dr. K. Srinivasan is Associate Professor for Mechanical Engineering at the Indian Institute of Technology, Madras, India (ksri@iitm.ac.in)

DADE CITY APPROVES NEW NOISE ORDINANCE

The Dade City Commission has approved a new noise ordinance that will make it easier to prosecute violators. The ordinance was written to limit "the making and creation of excessive, unnecessary or unusually loud noises within limits of the city." It revises ordinances written in 1956 and 1973, which City Attorney Karla Owens has described as impossible to enforce. Owens said the city has received 52 noise complaints from residents since Jan. 1. Owens also said the new ordinance was not written to focus on a specific organization or business, and that she did not think it would be appropriate for enforcement officers to test for noise violations unless a complaint was filed. For residential areas, sounds measuring at or less than 60 decibels between 7 a.m. and 10 p.m. and at or less than 55 decibels between 10 p.m. and 7 a.m. will be permitted. The levels will be measured from the closest adjacent property line. The noise ordinance includes exceptions for emergency signals (such as horns and sirens) and the ability to file for a waiver from the commission for other exceptions. Cultural, historical and community events and educational activities during school hours are also exempt. The ordinance would prohibit noise pollution, including limits on sound provided by instruments, drums, radios, televisions and other audio visual equipment. It also limits loading, unloading, opening, and otherwise making noise with garbage cans and similar containers between 11 p.m. and 6 a.m. and limits the decibel level of construction work in residential areas from 10 p.m to 7 a.m.

NOISE COMPLAINER ARRESTED

A 53-year-old man who police said called dispatchers over 20 times in a five-minute time frame to complain about neighborhood noise, will face a judge later this month. Palm Bay Police said Dawson Giles made the barrage of calls as officers were investigating an unrelated shooting incident, telling dispatchers that he would continue to call the non-emergency line until police responded to his call, reports show. Giles, was charged with giving false information to law enforcement officers after police turned up but did not hear the loud music he complained about, officials reported.

SEATTLE CITY COUNCIL VOTES TO EASE NOISE RULES FOR BETTER ENFORCEMENT

A recent meeting about Seattle's new noise ordinance grew so contentious that the City Council president threatened to have The Quiet Alliance representative thrown out for making too much noise. The council sought to simplify noise rules as construction continues on big public projects such as Sound Transit light rail. Currently, construction projects can get two-week variances from Seattle's noise ordinance, for example, if work is going to be louder than the rules allow. That means that during an extended project, construction companies might apply for dozens of variances. Council members, who voted 9-0 to pass the new regulations, said it will be cheaper and less cumbersome for construction companies to apply just once for an exception to the noise rules. Under the new rules, variances would require a public hearing before being approved and a review after one year. The new regulations are supposed to make enforcement easier, clarifying, for example, that the city can shut down a project that is violating the noise ordinance. "The noise ordinance changes are a great step toward stronger noise enforcement, and a serious effort to lower the cost of public projects," Council member Tim Burgess said by text message after the vote. Council members disagreed sharply over a proposal by member Nick Licata to require more reviews — and an annual opportunity for residents to appeal variances. Council member Jan Drago called Licata's proposal "public process run amok." Others questioned whether it was too complex. But Licata said it would be better than the current, every-two-week system, which he called "a total mess." Before voting 5-4 against Licata's proposal, the council allowed an attorney from Sound Transit to speak. That angered Chris Leman, of The Quiet Alliance, a neighborhood group that says the rules are too lax. Leman said it was inappropriate for Sound Transit, the agency being regulated, to have an opportunity to speak during the meeting. "It's a devastating setback for any kind of fair public process," he said.