On jet instability modes of a subsonic Hartmann whistle

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Abstract. Numerical experiments to understand the resonant acoustic response of a subsonic jet impinging on the mouth of a tube, known as the Hartmann whistle configuration, were performed as large-eddy simulations. The tube length was chosen so that its fundamental duct mode, for one end closed and one end open, would match the dominant mode in the exciting jet. When the tube mouth was placed in the path of a regular stream of vortex rings, formed by the instability of the jet's bounding shear layer, a strong resonant, tonal response (whistling) was obtained. At three diameters from the jet, OASPL was 150–160 dB. A tube with a thicker lip generated a louder response. When the tube was held closer to the nozzle exit, the impinging unsteady shear layer could not provoke any significant resonance. The simulations reveal that the tonal response of a Hartmann whistle operating in subsonic mode is significant.

Keywords. Hartmann whistle; jet-instability mode; subsonic flow; large-eddy simulation.

1. Introduction

A Hartmann whistle is a tube with one closed end, placed with the open end facing a free jet. In most studies the jet has been supersonic, including the one that led to Hartmann's discovery [1]. Often the jets have been sonic or at underexpanded supersonic conditions at the nozzle exit plane. High-intensity, narrow-spectrum sound (a whistle) is produced, and rapid heating of the gas is observed inside the tube, near its closed end. Whistling occurs for a wide range of pressure ratios, tube lengths and stand-off distances. A comprehensive, recent review is available [2]. Three modes have been identified, namely, the screech mode, the jet regurgitant mode and the jet instability mode. The screech and regurgitant modes are observed in supersonic jets, and the response to subsonic jets has been termed the instability mode. Whistles excited by supersonic jets have found various applications (industrial whistles, acoustic actuators, musical instruments, etc.), and have been the subject of many studies [3–8]. In these, numerical solutions were obtained from two-dimensional RANS models [4, 6] only. Here we report results of numerical experiments using a large-eddy simulation (LES) model (3-

d, unsteady) to understand the flow behaviour of a Hartmann whistle configuration excited by subsonic jets.

In many of the earlier experiments, tripping was considered essential to obtaining a strong response. These developments are discussed in the review by Raman and Srinivasan [2]. In supersonic streams, a ring or a wedge has served as a trip. By placing a thin nylon thread (diameter 10^{-3} cm) across the jet axis, Sprenger [9] was able to produce oscillating flow with low-Mach-number ($M = 0.52$) subsonic jets. Brocher *et al* [10] obtained a strong response even at $M = 0.12$ and suggested that it is essential to reduce the energy of the jet in the neighbourhood of its axis. They placed a thin cylinder axially in the jet nozzle, and produced a wake in the central region of the jet (region of lower mean kinetic energy). However, rather than any energetics processes, all these configurations cause vortex shedding that forces resonant oscillations in the tube. Borcher *et al* [10] proceeded to obtain theoretical relations for maximum amplitude and frequency for subsonic flows. Theoretical models to understand the oscillation mechanism were based on either wave or sound-speed diagrams, assuming isentropic, inviscid flow. Flow in the jet was assumed to be quasi-steady. In later experiments, Sarohia and Back [11] observed that the oscillations in the tube occur at the vortex-shedding frequency.

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Brocher and Duport [12] conducted experiments with resonance tubes mounted in a subsonic tunnel so that the upstream flow was uniform, and not that of a jet. Prismatic (wedge and square cross-section) bodies were mounted close to the tube mouth to trip the flow. The distance between the rear end of these trips and the tube mouth was varied from 10 to 34 mm. Tubes had a square cross-section of side 36 mm, and lengths 200 and 355 mm. The pressure at the closed end of the tube was measured. Below a critical velocity of the incident flow, pressure oscillations were small and irregular. As the critical velocity was approached, the pressure oscillation amplitude increased rapidly. They discuss the connection to organ pipe response, where, also, no sound is emitted below a critical velocity of the air stream that impinges on the pipe mouth. They argued that the strong, resonant response was a coupling between an instability wave in the shear layer separating from the tripping device and the standing acoustic wave in the tube. They concluded that ‘the device constitutes a very simple, powerful, sound source’ for use in applications or research [12].

Clearly, detailed, time-accurate, numerical simulations, which are now possible, can provide a better understanding of the mechanisms, especially the effects of ad hoc designs, like wires and stems, for enhancing the response.

Owing to the well-known strong response in supersonic streams, the subsonic whistle has not received much attention. The focus of our studies was to determine the response of a Hartmann whistle-like configuration placed in a subsonic stream. The whistle is then excited by the jet instability mode. Two qualitatively different types of responses were obtained by placing the tube at two locations in a subsonic jet—close to the nozzle exit where the jet’s bounding shear layer experiences instability and provides an unsteady excitation at the tube mouth, and secondly, further downstream where the excitation is by a train of vortex rings that have developed from the shear layer. A strong resonant response was found in the latter case. This is consistent with conclusions on whistle designs that incorporated stems or wires to promote vortex shedding that have been discussed earlier. The paper begins with the numerical method for LES and a relevant validation with a round jet, followed by results of whistle simulations in the two configurations.

2. Numerical method

The flows considered are governed by the Navier–Stokes equations for compressible flow:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0, \quad (1)$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j}, \quad (2)$$

$$\frac{\partial \rho E}{\partial t} + \frac{\partial}{\partial x_j} [(\rho E + p)u_i] = \frac{\partial q_i}{\partial x_i} + \frac{\partial u_j \tau_{ij}}{\partial x_i}. \quad (3)$$

Here ρ is the density, u_i are Cartesian velocity components, p is pressure, E is the energy, $\rho E = (\rho u_k u_k)/2 + p/(\gamma - 1)$ and q_i is the heat flux. The Prandtl number was set to a constant value of 0.71. Shear stress is

$$\tau_{ij} = \mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \left[\frac{\partial u_k}{\partial x_k} \right] \delta_{ij} \right), \quad (4)$$

where μ , the dynamic viscosity, was calculated from Sutherland’s law

$$\mu = \frac{1.458 T^{1.5}}{(T + 110.0)}. \quad (5)$$

Since the flows considered are not laminar, the numerical solution was found as an LES using the explicit filtering method of Mathew *et al* [13]. Essential requirements for this method are the use of a high-resolution numerical method along with a high-resolution, low-pass spatial filter applied to transported variables after every time step. This approach to LES has been used successfully, for several types of flows, by at least two other groups [14, 15]. Here, a Cartesian grid was used with an 8th-order compact difference formula for spatial derivatives, split into a forward and a backward step, extending the method of Hixon and Turkel [16]. Time-stepping was by a 2nd-order Runge–Kutta scheme. A one-parameter fourth-order compact filter [17] was applied with filter parameter $\alpha = 0.475$ in the stream-wise direction and 0.498 in the cross-stream directions. Partially non-reflecting, characteristic boundary conditions were specified at boundaries [18]. A constant time-step estimated from a maximum CFL number of 0.075 was used. The numerical method including boundary treatments, combining non-reflecting conditions, stretched grid buffer zone and anchoring inflow variables to target values was developed and tested for jet aeroacoustics studies. Ganesh [19], who developed the initial version of this code, provides a detailed discussion.

2.1 Validation

LES of a subsonic round jet is provided as a relevant validation before performing whistle simulations. The method (and core components of the code) has also been used for wall-bounded flows such as impinging flow [19]. The whistle simulations were performed using the same round jet with a tube placed downstream. Hence, the accurate simulation of the round jet also provides guidelines for setting up the whistle problem. The round jet of mean radius r_j was defined by the radial profile of its axial velocity at the inflow plane. Its mean value

$$U = \frac{U_j}{2} + \frac{U_j}{2} \tanh\left(\frac{r_j - r}{2\delta_2}\right) \quad (6)$$

defines a jet of roughly uniform velocity U_j bounded by an annular shear layer, and emerging into a quiescent region; shear layer momentum thickness $\delta_2 = r_j/20$ [20]. Mean inlet pressure $p_j = 1823.85$ Pa. Inlet density is determined using the Crocco–Busemann relationship. Ambient density $\rho_a = 0.022$ kg/m³ and inflow density $\rho_j = 0.02564$ kg/m³.

To induce breakdown to turbulence, fluctuations are added to the axial velocity in the shear layer as

$$u'(\theta, t) = \frac{U_j}{1000} A \left[\sum_{m=1}^6 \sin(m\theta + \alpha_m + 2\pi f_m t) + \sum_{m=7}^8 \sin(\psi_m t) \right] \quad (7)$$

with

$$A = \exp\left(-128 \left[\frac{r-R}{R}\right]^2\right).$$

Here θ is the azimuthal angle, f_m are frequencies with random phases α_m and $R = 0.875r_j$. The frequencies correspond to Strouhal numbers $St = 2fr_j/U_j = 0.2, 0.27, 0.31, 0.39, 0.45$ and 0.53 , as in Bodony and Lele [20]. The perturbation u' was added at both stages of the time-stepping.

Simulations were performed on multiple grids and at different Reynolds numbers. Here we show results of a case where the Reynolds number based on reference quantities from the jet at the inflow $Re = 2\rho_j U_j r_j / \mu_j = 88,000$, corresponding to an aeroacoustics reference case. In the following, all lengths are scaled with the nominal jet radius r_j . There were $386 \times 201 \times 201$ points in the axial and transverse directions on a Cartesian grid on the domain of extent $0 < x < 100$ and $-16 < y, z < 16$. The grid spacing is uniform in the near field and is then stretched. In the cross-stream directions, grid spacing $\Delta y = \Delta z = 1/10$ for $0 < |y|, |z| < 10$. Beyond this there is 1.5% stretching in geometric progression. In the axial direction $\Delta x = 0.25\Delta y$ for $0 < x < 75$. Then there is 2% stretching till 90 and 5% beyond till the outflow plane; the latter region serves as a buffer zone where, due to the aggressive stretching, small-scale structures are diffused.

Figure 1a is a visualization of the jet with contours of vorticity magnitude at an instant. The roll-up of the initial annular shear layer into vortex rings and sudden breakdown around $x \approx 12$ terminating the potential core are evident. Further downstream, the flow is turbulent and becomes self-preserving.

Figure 1b shows the decay of the centreline velocity U_c . The reciprocal of U_c is expected to grow linearly in self-preserving round jets. This is a sensitive test of LES. It is our experience with several types of coarse-grid

Figure 1. (a) Contours of vorticity magnitude on the plane $z = 0$ at an instant. (b) Centreline velocity decay. (c) Turbulent fluctuation development for the round jet simulations. (d) Turbulent kinetic energy spectrum at $x = 14$. A dominant mode occurs at $St = 0.334$ (for the results presented, $M = 0.9$ and $Re = 88000$).

simulations that when the scale range simulated is not adequate, a parabola-like curve rather than a straight line is obtained. The slope of the straight line $B = 6.28$ is comparable to the value 6.06 obtained in the benchmark experiments of Panchapakesan and Lumley [22] for a low-speed jet at $Re = 11000$. The slightly larger value is expected as jet Mach number is increased, as in our case [23]. The close agreement with another simulation [20], which was performed over a shorter length (useful region $x < 30$), is evident. The development of turbulent fluctuations also agrees well with previous simulations, see figure 1c. Results of simulations for $Re = 3, 600$ and $400,000$ are available [24, 25]. A dominant frequency can be identified in the spectra of signals taken near the end of the potential core with a Strouhal number $St = 0.334$ (figure 1d); the reported range is 0.3–0.4 [21, 26]. For the whistle simulations, the tube length will be chosen so that the duct mode frequency is close to that of this jet instability response.

3. Hartmann whistle studies

For the Hartmann whistle configurations, the exciting round jet was taken to be that in the validation discussed earlier. The grid spacing in this region was identical, but the Reynolds number was lower at 16,000 and the Mach number was 0.3 at inflow. Thin annular shear layers can be expected to have stability characteristics similar to those of plane shear layers. The perturbations added to the shear layer at inflow have Strouhal numbers $St = 0.2, 0.27, 0.31, 0.39, 0.45$ and 0.53 , as in the free jet simulation described earlier and in Bodony and Lele [20]. In tubes that are not too short, standing acoustic modes can be excited. In a tube of length L , with one closed end and one open end, the fundamental frequency is

$$f = \frac{a}{4L} \quad (8)$$

where a is the sound speed. In one configuration the tube was placed just downstream of where the jet shear layer had rolled up into vortex rings but the potential core had not broken down. Since the free jet exhibited a mode with $St = 0.34$, the tube length L was chosen so that the duct mode was at $St = 0.33$. Distance between jet inflow plane and tube opening, the stand-off distance, scaled with jet radius r_j is $S = 20$. This is labelled as the S1 simulation. In the second simulation (S2), the tube was placed upstream $S = 7.5$, where the annular shear layer had not broken up into distinct vortex rings; duct length was chosen so that the duct mode is at $St = 0.31$, which is the dominant response of the initial shear layer. We can then expect resonant, large amplitude, excitation of the duct—whistling.

A longitudinal section of the computational domain is shown in figure 2a. A round jet of unit radius enters the domain through the plane $x = 0$. Flow was simulated in the

region $0 < x < 50$ and $-16 < y, z < 16$. In the cross-stream directions, grid spacing $\Delta y = \Delta z = 1/10$ in $0 < |y|, |z| < 10$; beyond this, grid spacing is increased at 1.5% in geometric progression. In the axial direction, $\Delta x = 0.25\Delta y$ for $0 < x < 40$. Then there is 2% stretching till $x = 45$, and 5% beyond till the outflow plane. A tube with a square cross-section, closed at one end, was placed with tube axis on the jet axis as shown. Tube walls coincided with grid points. For computational efficiency, the computational domain was divided into 3 blocks. The discretized equations were solved to advance the state at interior points in each block in parallel using MPI. Within each block, code segments were executed in parallel using OpenMP. At block interfaces, grids overlap. At the solid boundaries of the tube, one-sided differences were used. Pressure time series were collected at several points. Signals used in the analyses are for 10 flow-through times; flow-through time was estimated as the duration for a particle to travel from nozzle exit to tube end with particle velocity falling linearly. There were $224 \times 201 \times 201$ points in the axial and transverse directions, but of these, no calculations were done at points within the tube walls. No-slip boundary conditions were enforced at tube walls.

Dimensions of the tubes in the simulations are listed in table 1. T2 is a tube with twice the wall or lip thickness compared with T1, and tube T3 has increased inlet area. The four simulation cases are listed in table 2, with labels that are a combination of tube type and duct mode.

3.1 Tube excited by ring vortices

The flowfield at an instant for case S1T1 is shown in figure 2b with contours of the velocity magnitude on the midplane $z = 0$. The open end of the tube was at $x = 20$. The impinging jet is deflected by the tube. Inflow perturbations grow on the shear layer and roll up into vortex rings. These rings impinge on the jet and expand rapidly around the tube. Time series of pressure inside the tube at the closed end ($x = 24.5, y = z = 0$) and near the tube lip ($x = 20, y = \pm 2.25, z = 0$) are shown in figure 2c. The amplitude of oscillations is larger at the closed end (cavity end wall), and more regular; it is more broadband near the tube lip (top/bottom – shedding region). Figure 3a shows spectra at these same locations. The inset figure shows the tonal components more clearly; the dominant tone is at $St = 0.33$. The simulation with a tube with thicker lip, S1T2, is qualitatively similar. The spectra are shown in figure 3b. The dominant frequency excited is still $St = 0.33$ as can be expected for a resonant duct mode, and the amplitude is about the same. There are other tones of smaller amplitudes; those at lower frequencies have relatively larger amplitudes. These tones are not harmonics or sub-harmonics and do not represent waveform distortion. We shall refer to these as secondary modes. The lower frequency secondary modes have a larger amplitude with the thicker tube wall. It should also be noted that the power

Figure 2. (a) Schematic of computational domain on the plane $z = 0$, showing boundary conditions, axis, nomenclature and interface communication zones. (b) Axial velocity field at an instant on midplane $z = 0$. (c) Pressure time history for simulation S1T1. (d) Axial velocity field at an instant on midplane $z = 0$ (zoomed) for simulation S2T1.

Table 1. Dimensions of square cross-section tubes. All dimensions are scaled with jet radius r_j .

Tube type	Dimensions of outer wall			Dimensions of inner wall		
	Length	Breadth	Width	Length	Breadth	Width
T1	4.25	2.125	2.125	4	2.0	2.0
T2	4.25	2.250	2.250	4	2.0	2.0
T3	4.25	2.750	2.750	4	2.5	2.5

Table 2. Configurations of tube simulations.

Simulation cases	S	Tube type
S1T1	20	T1
S1T2	20	T2
S2T1	7.5	T1
S2T3	7.5	T3

of the oscillations is quite small compared with the power of oscillations achieved by placing the tube in supersonic flow field. For tubes placed in supersonic jets, Narayanan *et al* [27] measured the maximum power to be on the order of $10^6 \text{ Pa}^2/\text{Hz}$, whereas for these subsonic flows, maximum power observed is on the order of $10^3 \text{ Pa}^2/\text{Hz}$. The

effect of the stand-off shock as a source of periodic forcing is stronger than that of the vortex rings.

To establish a causal connection between the jet's ring vortices and tube oscillations, coherence was calculated between the upper lip and tube end wall pressure signals. Coherence between two signals ($x(t)$, $y(t)$), is a real-valued function in the range of [0–1] defined as

$$C_{xy}(f) = \frac{|\phi_{xy}(f)|^2}{\phi_{xx}(f)\phi_{yy}(f)}$$

where ϕ_{ij} , ϕ_{ii} are cross-power spectral density and auto-power spectral density, respectively. When $C_{xy}(f) \approx 1$ the signals are perfectly related, whereas $C_{xy}(f) \approx 0$ when they are uncorrelated. Figure 3c shows the close connection (high coherence levels) between excitation at the lip and the end wall at the dominant frequency and for secondary modes for case S1T1. Results for case S1T2 are similar.

OASPL curves along the line $y = 6$, $z = 0$ have been plotted in figure 3d. On this line, the levels of 150–165 dB are quite large. Even in a subsonic jet, the Hartmann whistle is a significant sound source. The minimum is obtained at sideline angles from the tube lip. Sound produced with the thicker tube (S1T2) is generally higher everywhere, slightly more upstream of the jet than downstream. Peak levels occur at about 22° upstream and 13° downstream with respect to the tube lip. Narayanan *et al*

Figure 3. Frequency characteristics comparison: (a) lip thickness, $0.125r_0$, (b) lip thickness, $0.250r_0$ and (c) coherence analysis for simulation S1T1. (d) Overall sound pressure level (OASPL).

[27] showed that directivity of Hartmann whistle is found to be around $35^\circ - 40^\circ$ for cavities placed in supersonic jet flow.

3.2 Tube in potential core region

In the second configuration, the open end of the tube was at $x = 7.5$. Here, the annular shear layer has fluctuations responding to the forcing in the inflow plane but does not roll up into vortex rings. Figure 2d is a visualization at an instant with contours of the velocity magnitude. The jet is deflected outward by the tube and the jet boundary breaks up. Within the tube there are pressure fluctuations, but of very small amplitude. OASPL along $y = 6, z = 0$ for the two cases S2T1 and S2T3 are shown in figure 3d. Clearly there has been no significant resonant response, even though the fundamental mode of the tube was matched with the dominant shear layer frequency. Increasing tube width (S2T3 simulations) did not change the response. Hence, the excitation by an unsteady shear layer is not sufficient to evoke a resonant response. The periodic impingement of the vortex rings seems to be crucial.

4. Discussion and conclusions

A computational study of a Hartmann whistle arrangement in a low subsonic round jet was conducted. The length of the tube was selected such that its fundamental duct mode was close to the dominant mode in the impinging jet. It was found that even a subsonic jet can provoke a strong resonant response if the tube is excited by the regular train of vortex rings that result from the instability of the jet's bounding shear layer. At a distance of 3 diameters from the jet, the OASPL is 150–160 dB. A thicker tube lip was found to support larger SPL due to increased response at frequencies lower than the fundamental. These lower frequencies were not subharmonics. Although the Hartmann whistle in a supersonic stream exhibits power levels that are $O(1000)$ times larger, the response in a subsonic stream is not insignificant. If the tube is placed closer to the jet exit, where the jet shear layer is unsteady but has not broken up into vortex rings, the excitation does not provoke any significant response at all. A direct comparison of these computational results with other published results is not

feasible due to the lack of any other experimental or computational studies in subsonic regime. However, our simulations are qualitatively similar to simulations of an impulsive subsonic jet actuator [8], and experiments reviewed in the introduction [9, 10].

The resonant response provoked by the train of vortex rings demonstrates that the actions of stems or wires on the axis are due to the vortex shedding that they produce. In this case, these impinging vortices were generated without such devices as the end result of shear layer instability.

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List of symbols

A	area of the tube inlet (m^2)
a	speed of sound (ms^{-1})
f	frequency (Hz)
L	length of the tube (m)
M	Mach number
p	static pressure (N/m^2)
p_0	total pressure (N/m^2)
R	nozzle pressure ratio (p_0/p_∞)
Re	Reynolds number
r_j	jet radius (m)
S	stand-off distance (m)
St	Strouhal number ($fU_j/2r_0$)
U_j	jet velocity at nozzle exit (ms^{-1})
x	reduced length (no unit)
x_{in}	value of variable x at nozzle exit
x_∞	value of variable x at ambient conditions
ρ	density (kg/m^3)
θ	polar angle (degrees)
$\phi_{ij}(f)$	cross-power spectral density (Pa^2/Hz)
$\phi_{ii}(f)$	auto-power spectral density (Pa^2/Hz)
τ_{ij}	shear stress tensor
μ	dynamic viscosity (Nsm^{-2})
PSD	power spectral density (Pa^2/Hz)
SPL	sound pressure level (dB), $p_{ref} = 20 \times 10^{-6} \text{ Pa}$
OASPL	overall sound pressure level (dB)

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