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ABSTRACT
Flow over rectangular cavities can become unstable and excite the acoustic modes of the surrounding duct, resulting in severe noise and vibration. In this work, acoustic resonance excitation by two opposite and aerodynamically isolated rectangular cavities is experimentally and numerically investigated to identify the effect of the flow-acoustic coupling on the synchronization of shear layer instabilities. Compressible unsteady Reynolds-averaged Navier–Stokes simulation is used to model the self-excitation of resonance and characterize the fully coupled flow and acoustic fields. Moreover, the location and the strength of the acoustic sources and sinks are evaluated using Howe’s integral formulation of the aerodynamic sound. It is revealed that double symmetric cavities generate a higher rate of acoustic energy transfer due to the synchronization of the shear layer instabilities over the two cavities in an antisymmetric pattern, leading to a stronger acoustic resonance than all other cases. On the other hand, the two shear layers over two opposite cavities with different aspect ratios were mismatched in phase and vortex convection velocity. As a result, the net energy transfer in an asymmetric cavity configuration occurred at a similar rate to a single rectangular cavity, driving a weaker acoustic resonance excitation.

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I. INTRODUCTION
The excitation of acoustic resonance by fluid flow has recently attracted significant research attention due to its impact on many engineering applications. It can induce severe abrupt pressure oscillations leading to extreme noise or violent vibration. The excitation of acoustic resonance has been reported in multistage compressors, centrifugal pumps, solid rocket motors, heat exchanger tube bundles, air conditioning systems, combustion chambers, safety relief valves in nuclear power plants, architectural plates, pipelines and side branches, and several other applications. In these applications, the dynamic flow instabilities represent the source of excitation that gives rise to the onset of self-sustaining strong acoustic oscillations, causing undesirable noise and vibration and imposing significant dynamic loading that can cause damage and interrupt operation.

The mechanism that leads to the development of the coupled flow-acoustic field has been thoroughly investigated for the case of a single rectangular cavity attached to a rectangular duct. At moderately low Mach numbers, the sudden separation of the shear layer over the cavity results in negligible production of acoustic power due to the periodic flapping of the shear layer over the cavity mouth. As the shear layer impinges on the trailing edge of the cavity, pressure perturbations provide a modulating signal, sending feedback that organizes the separation of flow at the separation point. As a result, the shear layer produces pressure oscillations at a frequency that depends on the cavity length \( l \) and the flow velocity \( U_\infty \) as shown in the following equation:

\[
St_n = \frac{f_n l}{U_\infty} = \frac{n - \alpha}{M + \kappa}
\]

where \( St_n \) and \( f_n \) correspond to the Strouhal number and frequency of the shear layer \( n \)th mode, respectively. \( \kappa \) and \( \alpha \) are constants that correspond to the average convection speed of the vortex cores in the shear layer and a phase delay, respectively. If the flow over the cavity is confined in a rectangular duct of a height \( H \), the perturbations of the shear layer can excite the acoustic cross-modes by engaging in a fluid-resonant mechanism. The velocity perturbation of the shear layer is oriented in the same direction as the acoustic particle velocity of the cross-modes of the duct. Therefore,
the periodic flow instability can provide energy to the acoustic cross-mode in the case of frequency coincidence. The frequency of the acoustic cross-modes of the duct does not have significant dependence on the upstream flow velocity; consequently, the frequency coincidence occurs at particular flow velocities at which the acoustic pressure oscillations become significantly stronger. In turn, the stronger acoustic field organizes and modulates the shear layer separation and impingement. Therefore, the shear layer oscillations and the acoustic mode occur at the same frequency in a state of lock-in over a range of flow velocities. Acoustic oscillations sustained by the coupled field continue to grow limited only by the radiation and viscous damping losses and can reach extreme acoustic pressures. Experimental evidence indicates that periodic flow instabilities initiated by the separation and the development of unstable shear layers over cavities are capable of exciting the acoustic modes in shallow and deep cavities, cavities in tandem, and axisymmetric cavities. In these cavity geometries, unstable shear layer perturbations give rise to a self-sustained coupling of intricate flow and acoustic patterns.

To excite acoustic resonance, the shear layer over the cavity mouth has to become unstable, resulting in unsteady oscillations. The unsteadiness of the shear layer results from the pressure fluctuations caused by shear acting to force the flow streamlines to impinge at an angle into the trailing edge. Stallings and Wilcox identified the cavity length to depth ratio as the main parameter that defines the general dynamics of the flow inside a cavity. Tracy investigated the generation of acoustic tones by the flow over transonic and supersonic cavities. Results indicated that the spectral characteristics of the tone as well as its amplitude depend on the Mach number and the cavity length to depth ratio. Hirahara et al. experimentally investigated the aeroacoustic instability of a single rectangular cavity. The results showed that the cavity length-to-depth ratio did not have a significant effect on the modal characteristics of the excited modes, but indicated a remarkable difference in the sound source strength for a length-to-depth ratio of 1.0 and 2.0. Rockwell and Knisely showed that the organized two-dimensional separation of flow at the leading edge results in the formation of span-wise vortex cores with relatively weak three-dimensional effects. In agreement, Lafon et al. suggested that the resonance modulation effect for the fluid resonance mechanism ensures that the acoustic modes are two-dimensional and the acoustic oscillations are in phase along the span of the cavity. More recently, Islam confirmed that the excitation of acoustic resonance can organize the flow into a two-dimensional pattern due to the modulation by the strong acoustic field.

The effect of these parameters on the unsteady cavity flow has been also investigated using numerical methods. Rizzetta investigated the self-sustained aerodynamic oscillations within a rectangular cavity using the compressible three-dimensional Navier–Stokes equations along with a Reynolds-averaged turbulence model, indicating a fundamental two-dimensional behavior of the flow field. At subsonic upstream velocities, Henderson et al. used the two-dimensional unsteady Reynolds-averaged Navier–Stokes equations with the $k-\omega$ turbulence model to investigate the flow features over a rectangular cavity with a length-to-depth ratio of 5.0, achieving good agreement with experimental data in terms of the pressure distribution and the transient flow features. It was found that despite a deficiency to provide accurate representation of high-frequency intermittent time scales, unsteady Reynolds-averaged Navier–Stokes equations tend to accurately predict the larger scales associated with the lower frequency discrete acoustic tones. However, no effort has been made to numerically model self-excitation of acoustic resonance through coupled numerical simulation.

Moreover, hybrid numerical and experimental methods were used to investigate the mechanism of acoustic resonance excitation by cylinder configurations. Using a two-dimensional numerical model, Mohany and Ziada implemented the aeroacoustic analogy formulation of Howe to identify the spatial distribution of sound sources and sinks over a cycle of flow-excited acoustic resonance for the case of two tandem cylinders in cross-flow. Results showed a compact pattern of acoustic sources and sinks induced by the vorticity over the acoustic cycle, which provided a net generation of acoustic power. Accurate characterization of the net acoustic energy transfer and the spatial distribution of the aeroacoustic source and sink in the flow field are necessary to develop effective methods to control resonance excitation. However, the necessary experimental data required for acoustic source and sink analysis, including acoustic resonance strength and acoustic pressure distribution in double cavity configurations, are not yet available.

The configuration of two cavities facing each other arise in many engineering applications such as sudden expansions and contractions in ducts and pipes, wind flow in high rise building blocks, and flow in closely packed electronic components. For this configuration, available studies consider the fluid-dynamic excitation mechanism arising from a hydrodynamic feedback. A considerable attention was given to the cases with a small inter-cavity distances. Morel reported that two cavities facing each other on the walls of a chamber that has a passing jet can induce significantly powerful pressure oscillations at the Helmholtz frequency of the chamber. Rockwell and Naudascher suggested that this jet instability combined with alternating impingement can lead to the self-sustained instability of a fluid dynamic nature. More recently, Tuerke et al. investigated the effect of the distance between two identical cavities opposite to each other on the coupling of the shear layers that develop over both cavities. At a cavity spacing-to-depth ratio lower than 0.1, the shear layers over the cavities are merged together and an antisymmetric jet instability is observed. For a spacing-to-depth ratio higher than 0.2, the two shear layers separate anti-symmetrically along the cavity length. At separation distances higher than 0.4 of the cavity depth, no correlation between the two shear layers could be proven. On the other hand, Shaaban and Mohany measured the dynamic fluid forces on inline cylinders during acoustic resonance excitation and reported that the acoustic field can synchronize flow instabilities in the gaps between cylinders. It is not yet reported if the uncorrelated shear layers over two opposite cavities at large separation distance are capable of initiating a fluid resonant feedback mechanism and sustaining acoustic resonance. Moreover, the effect of the strong acoustic field on the phasing between the two shear layers and the effect of cavity symmetry need to be identified. The identification of the coupled field patterns has helped to develop different passive and active methods to control the excitation of acoustic resonance for a single cavity configuration. A rigorous understanding of the intricate and complex flow acoustic coupling excited by shear layers over two opposite cavities is necessary to effectively control structural and aeroacoustic excitations.

To fulfill that, this work provides an experimental and numerical investigation of the acoustic resonance excitation by shear layer
instabilities over the configuration of two opposite rectangular cavities at large separation. Investigations are carried out for the cases of a single rectangular cavity with a length-to-depth ratio of $L/D = 1.00$ and $1.67$, two opposite symmetric cavities with the same length to depth ratio of $L/D_1 = 1.00$, and two opposite asymmetric cavities with a different length to depth ratio of $L/D_1 = 1.00$ and $L/D_2 = 1.67$. For the opposite cavities cases, the two cavities are separated by a distance of $2.0L$. Aeroacoustic pressure measurements are used to identify the conditions for the excitation of the acoustic cross-modes. Moreover, phase-locked particle image velocimetry measurements for some selected cases are performed to validate the results of the numerical model and the sound source prediction algorithm. The two-dimensional compressible unsteady Navier–Stokes equations are solved in conjugation with the Reynolds stress transport turbulence model to investigate the coupled field behavior. The numerical model is able to capture the onset of the acoustic cross-mode by the flow instability, and the modulation effect of the strong oscillations on the flow field is presented. Finally, the aeroacoustic analogy method is used to characterize the development of the aeroacoustic sources and sinks over the acoustic cycle.

II. METHODOLOGY

A. Experimental methodology

Acoustic pressure measurements are carried out in an open-loop wind tunnel as shown in Fig. 1(a). Air flow is driven by a centrifugal blower at speeds up to 160 m/s. The test section is of 254 mm in height and 127 mm in width. The cavity configurations are attached at the top and bottom walls of the test section. The wind tunnel inlet is equipped with a parabolic bellmouth leading to the test section, and then, the air flows through a diffuser section that gradually increases in the cross-sectional area with an inclusion angle of less than $14^\circ$ to avoid flow separation at the walls. Finally, a flexible connection is used between the blower and the test section to prevent vibration transmission.

The different cavity configurations and the nomenclature used in the following discussions are shown in Fig. 2. Cavities of two different length to depth ratios $L/D_1 = 1.00$ and $1.67$ are tested. In the single cavity configuration, the cavity is mounted at the bottom wall, spanning the whole test section width of 127 mm. In the double cavity configuration, two cavities of the same length $L = 127$ mm are attached opposite to each other on the top and bottom walls, spanning the width of the test section. The parameters of the four investigated configurations are detailed in Table I. The table shows the dimensions of the cavities, the flow Reynolds number during excitation of acoustic resonance, and the frequency of the excited acoustic modes.

The acoustic pressure measurements are performed using a PCB pressure microphone model 377A12, with a diameter of 6.35 mm and a nominal sensitivity of 25 mV/kPa. The microphone is flush-mounted at the acoustic pressure anti-node of the first acoustic cross-mode, which is located at the cavity base. To characterize the aeroacoustic response of each configuration, acoustic pressure is measured for 60 s at upstream flow velocities between 10 and 160 m/s, with a step of 2.5 m/s. A sampling rate of 10 kHz is used. The frequency spectrum is obtained using Welch’s modified periodogram method with a resolution of 1 Hz. The dimensionless acoustic pressure amplitude $P^* = P/0.5\mu U_\infty^2$, and the reduced flow velocity $U_r = U_\infty/(f_\alpha L)$ are used to compare the measured acoustic pressure of different configurations, where $U_\infty$ is the upstream flow velocity, $f_\alpha$ is the acoustic cross-mode frequency, and $L$ is the cavity length.

Particle image velocimetry measurements were carried out for the case of a single cavity. The Particle Image Velocimetry (PIV)
measurements are performed using a LaVision PIV system, shown in Fig. 1(b), equipped with a double-head Nd:YAG laser generating two laser beams of wavelength 532 nm at a maximum frequency of 15 Hz and peak power of 200 mJ. A double frame 12-bit CMOS camera with a resolution of 2752 × 2200 pixels, equivalent to a field of view of 165 mm × 114 mm, is used to capture pairs of images in synchronization with the laser beam. An aerosol generator is utilized to seed the flow using Di-Ethyl-Hexyl-Sebacat (DEHS) as seeding material with a maximum particle size of 1 µm to ensure a homogeneous distribution of seeding particles among the flow field, settings described in detail by Shaaban and Mohany.\(^{48}\) The signal from the microphone attached to the base of the cavity is used to trigger the PIV system in order to perform phase-locked PIV measurements.\(^{49}\) The measurements were taken at eight equally distributed phases over the period of the acoustic pressure cycle. For each phase, 150 instantaneous pairs of images are acquired. PIV measurements were phase-locked to provide an ensemble-averaged phase instant of the acoustic pressure cycle during acoustic resonance excitation at an upstream flow velocity of \(U_\infty = 37.5\, \text{m/s}\). Due to the size of the domain, particle image velocimetry measurements were limited to the shear layer development over the mouth of the cavity.

### B. Numerical Methodology

The coupling between the flow and acoustic fields over an axisymmetric cavity is investigated by means of a two-dimensional compressible unsteady Reynolds-averaged Navier–Stokes (URANS) equations. A schematic of the computational domain used in the case of opposite rectangular cavities is shown in Fig. 3. The mesh used for the other cases has the same characteristics and are structured in an identical manner. The numerical domains consist of inlet, outlet, and cavity zones. The domains extend 2.5 \(L\) in the upstream and downstream directions in order to allow for adequate flow development, prevent any significant effect of the inlet and exit boundary conditions on the cavity region, and reduce the effect of acoustic radiation from the test section ends.\(^{50}\) The dimensions of the cavity and the wall separation are identical to the cases selected for experimental investigation to identify the flow patterns associated with the experimental observations. A fully coupled transient solver for compressible turbulent flows is used to directly solve the two-dimensional unsteady Reynolds-averaged Navier–Stokes equations in order to model the flow dynamics and the aeroacoustic response. The pressure-implicit with splitting of operator algorithm is used to resolve the pressure-velocity coupling.\(^{51}\) The second-order bounded Crank–Nicolson scheme is used for temporal discretization.\(^{52}\) A Gauss linear-upwind scheme is used for the spatial discretization of the convective terms in the momentum equation, and a Gauss linear gradient differentiation scheme is used for the diffusive terms.\(^{53}\) All the implemented schemes have second order accuracy, necessary to capture self-initiation and fine resolution of the transient and periodic flow structures.\(^{54}\)

The Reynolds stress model was used to model the turbulence by solving transport equations for the Reynolds stresses, together with an equation for the dissipation rate, as it provides accurate predictions in flows with high anisotropy similar to the separating and impingement flows under high pressure amplitudes.\(^{55}\) The anisotropic total stress tensor is modeled to satisfy the transport equation:

\[
\frac{D\rho\overline{u_i'u_j'}}{Dt} = \Gamma_{ij} + \Gamma_{Lij} - P_{ij} + \Phi_{ij} - \epsilon_{ij}.
\]

The molecular diffusion \(\Gamma_{ij} = \frac{\partial}{\partial x_k} [\rho \overline{u_i'u_j'}] \) and the stress production \(P_{ij} = \rho \left( \overline{u_i'u_k'} \frac{\partial u_j}{\partial x_k} + \overline{u_j'u_k'} \frac{\partial u_i}{\partial x_k} \right) \) are obtained from the solution of the coupled continuity and momentum equations. However, the turbulent diffusion term \(\Gamma_{Tij}\), the pressure strain \(\Phi_{ij}\), and the dissipation \(\epsilon_{ij}\) are modeled to close the equations. The scalar dissipation term \(\epsilon_{ij}\) is calculated by solving a transport equation

\[
\frac{\partial (\rho \epsilon)}{\partial t} + \frac{\partial (\rho u_i \epsilon)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \mu_t \frac{\partial \epsilon}{\partial x_j} \right] + C_{t}\frac{\epsilon}{k} \left[ 2\mu_l E_{ij} E_{ij} - C_{2} \rho \frac{e^2}{k} \right].
\]

The two-dimensional simulation of the Reynolds stress model is performed by solving for four components of the Reynolds stresses tensor. As the mean velocity \(\overline{u_i}\) is not included in the formulation, the Reynolds stress \(\overline{u_i'u_j'}\) is solved for as it constitutes part of the turbulent

<table>
<thead>
<tr>
<th>L/D1</th>
<th>D1 (mm)</th>
<th>D2 (mm)</th>
<th>ReL</th>
<th>fExp (Hz)</th>
<th>fCFD (Hz)</th>
<th>fsnomflow (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single L/D1 = 1.00</td>
<td>127</td>
<td>127</td>
<td>0</td>
<td>3.1 × 10^5</td>
<td>481</td>
<td>490</td>
</tr>
<tr>
<td>Single L/D1 = 1.67</td>
<td>127</td>
<td>76</td>
<td>0</td>
<td>3.6 × 10^5</td>
<td>597</td>
<td>600</td>
</tr>
<tr>
<td>Double symmetric</td>
<td>127</td>
<td>127</td>
<td>127</td>
<td>2.9 × 10^5</td>
<td>424</td>
<td>422</td>
</tr>
<tr>
<td>Double asymmetric</td>
<td>127</td>
<td>76</td>
<td>127</td>
<td>2.9 × 10^5</td>
<td>458</td>
<td>464</td>
</tr>
</tbody>
</table>
kinetic energy scalar $k = \frac{1}{2}(\overline{u^2} + \overline{w^2} + \overline{\epsilon}^2)/2$. As a result, the continuity and momentum equations are solved along with five transport equations for $\overline{u_x}, \overline{u_y}, \overline{u_z}, \overline{\epsilon}$, and $\epsilon$.

The simulation is performed at a range of Reynolds number between $R_e = 2.9 \times 10^5$ and $3.6 \times 10^5$ based on the cavity length $L$. The properties of air are fixed at their values at 20 °C, and the density is calculated from the ideal gas equation. A sensitivity analysis was carried out on the flow domain, shown in Fig. 4, to ensure that the results have no dependency on the domain length, time step, or the mesh node count. The data in Fig. 4 show the predicted frequency of the first acoustic cross-mode at an inlet flow velocity equivalent to Reynolds number value of $3.1 \times 10^5$ for different domain lengths, meshes, and time steps. The length of the domain was adjusted to avoid any influence of the location of the boundaries on the value of the generated acoustic pressure frequency. Using number of nodes less than $3.3 \times 10^5$ or a time step higher than $2 \times 10^{-5}$ s results in an increase in the predicted acoustic pressure frequency. A number of hexagonal structured grid elements of $1.2 \times 10^6$ and a time step of $5 \times 10^{-6}$ s are used to achieve a value less than 1, and 4 for the convective, and acoustic Courant numbers, respectively, to capture the details of the transient flow and to resolve the flow-acoustic coupling and predict self-excitation of resonance.

The inlet boundary condition is set as a velocity inlet with uniform velocity $U_{in}$. The outlet boundary is specified to ensure no pressure gradient normal to the wall, while preventing any back flow. The pressure boundary condition on the inlet and outlet boundaries follows a nonreflecting wave-transmissive condition based on the characteristic wave relations derived from the Euler equations, so that the pressure at the boundaries relaxes gradually toward the imposed pressure in the far field. Pressure monitor points $p_{in}$ and $p_{out}$ are located at the middle of the base of the top and bottom cavities, respectively, to capture the amplitude and phase characteristics of the excited resonance for comparison with the experimental observations. For each cavity configuration, the simulation is initialized at a constant flow velocity and pressure run until a steady-state periodic flow pattern is achieved. In all cases, the coupled numerical model was capable of capturing the coupled dynamics of the flow over the studied cavity configurations, and the feedback cycle was initiated. As the solution progresses, the pressure field starts to fluctuate around its mean component at an increasing amplitude until it reaches a steady amplitude. At the steady state, the frequency of the acoustic fluctuations is within 2% of the experimental value, as seen in Table I.

**C. Quantification of acoustic energy exchange**

To investigate the influence of the cavity geometry on the acoustic power transfer during acoustic resonance excitation, Howe’s integral formulation of the aerodynamic sound55 is implemented. For incompressible flows at low Mach numbers, Howe29 showed that the sound generation by the fluctuating fluid forces caused by a vorticity field can be modeled as a dipole source. For an unsteady flow field with a vorticity field $\omega$, acoustic particle velocity field $u_a$, and flow velocity field $\vec{U}$, the instantaneous acoustic power $\Pi$ can be approximated by the first-order form of the aeroacoustic analogy, as in Eq. (4):

$$\Pi = -\rho \iiint_{V} \vec{\omega} \cdot (\vec{U} \times \vec{u}_a) dV. \quad (4)$$

An algorithm is developed to compute the transient acoustic energy transfer rate over the two dimensional cavity field. The acoustic particle velocity and the flow velocity and vorticity fields are obtained through numerical simulation and interpolated to the same hexagonal mesh, with a minimum element size of 0.1 mm. The acoustic pressure amplitude from the experimental measurements is used to scale the normalized acoustic pressure field for each configuration. During self-
excitation of acoustic resonance, the time variation of the acoustic pressure is modeled as a simple harmonic motion \( p(t) = P_0 e^{i(\omega t + \phi)} \). The spatial distribution of acoustic pressure \( P \) for the excited mode is calculated using a finite element analysis of the three-dimensional domain for the four cases discussed in Table I. An eigenvalue modal analysis is performed to obtain the acoustic pressure and the vectors of acoustic particle velocity for the first acoustic cross-mode by solving the Helmholtz equation [Eq. (5)]

\[
\nabla^2 \phi + k^2 \phi = 0, \tag{5}
\]

where \( k = 2\pi f_a/c \) is the wavenumber and \( \phi \) is the complex potential scalar function. A three-dimensional tetrahedral mesh with a maximum element size of 1 mm is used to discretize the acoustic domain, which has the same dimensions of the test section.

The Euler’s equation [Eq. (6)] relates the acoustic particle velocity distribution with the distribution of the acoustic pressure in the domain

\[
\rho \frac{\partial \vec{U}_a}{\partial t} = \nabla p(x, y, z). \tag{6}
\]

The integral of the Euler’s equation is used to calculate the field of acoustic particle velocity \( \vec{U}_a \)

\[
\vec{U}_a(x, y, z) = \frac{P_{\text{exp}} \nabla p(x, y, z)}{2\pi \rho \cdot f_a}, \tag{7}
\]

where the measured acoustic pressure \( P_{\text{exp}} \) is used to scale the normalized pressure \( p(x, y, z) \) for each case. The acoustic particle velocity of the resonant mode lags the acoustic pressure by a phase of \( \phi = \frac{\pi}{4} \) at resonant conditions and therefore is adjusted to obtain the instantaneous distribution corresponding to the phase of the acoustic pressure cycle as

\[
\vec{u}(x, y, z, t) = \vec{U}_a \sin (2\pi f_a t + \phi). \tag{8}
\]

The obtained flow and acoustic quantities are then used in Eq. (4) to calculate the instantaneous energy production \( \Pi(x, y, z, t) \) at all phase instants. The field of spatial acoustic power net source is obtained by algebraically integrating the instantaneous fields over a complete acoustic cycle.

**III. CHARACTERISTICS OF THE FLOW-ACOUSTIC COUPLING**

In order to validate the model accuracy in capturing the flow-acoustic coupling details, velocity profiles across the shear layer are compared to PIV measurements at several streamwise locations over the cavity. First, Fig. 5 shows the profiles of the average flow velocity at different locations along the cavity mouth for the case of a single cavity with \( L/D_1 = 1.0 \), where the numerical predictions show a good agreement with the experimental results. The upstream flow velocity is 37.5 m/s equivalent to a Reynolds number \( Re = 3.1 \times 10^5 \), which resulted in the excitation of acoustic resonance. Figure 5 shows that the velocity profile at the upstream edge prior to separation is well predicted by the numerical model, resulting in an accurate profile of the boundary layer. This particular profile is vital to the topology and dynamic instability of the shear layer as it separates over the mouth of the cavity. Moreover, in the vicinity of the cavity mouth \(-0.05 \leq y/L \leq 0.05\), this deviation does not exceed 1.5%. A deviation reaching up to \( u/U_\infty = 0.5 \) m/s occurs at \( x/L = 0.25 \) and \( y/L \leq -0.1 \). As will be shown next, the deviation had no significant effect on the dynamic characteristics of the shear layer nor on the coupling of the acoustic and flow fields as the profiles are well predicted close to the impingement point, where the feedback is initiated and the acoustic sources are strongest.

Second, Fig. 6 shows a comparison between the predictions of the numerical simulation with the experimental results for the case of a single cavity with a length to depth ratio of 1.0. The numerical results show that instantaneous vorticity field and the streamlines over the cavity mouth are well predicted when compared to the experimental measurements. In both cases, the location and size of the cores and the vorticity value are in good agreement. The flow fields in both cases are used as inputs to the acoustic analogy algorithm to calculate the acoustic power production, which is well predicted when compared with the experimental results. As the acoustic source field is the integration of the acoustic power field over the acoustic pressure cycle, the algorithm was capable of providing a comparable prediction using the numerical and experimental results.

To study the effect of the different cavity configurations on the aeroacoustic response, Fig. 7 shows the spectral characteristics of the acoustic pressure signal over a range of upstream flow velocities up to \( U_\infty = 160 \) m/s. The acoustic pressure signal at the cavity wall has a significant dependence on the flow velocity and the cavity configuration. The frequency of the acoustic cross-modes is presented as constant-frequency vertical dashed lines. The acoustic cross-mode fundamental frequency strongly depends on the furthest distance between the side walls, and therefore is slightly different for each configuration. According to the Rossiter formula, Eq. (1), the theoretical shear layer mode frequencies have a strong dependence on the length of the cavity and the upstream flow velocity. Therefore, the first four shear layer modes are approximated as lines in Fig. 7. At an intersection of a cross-mode line with a shear layer mode line, frequency coincidence provides a potential for acoustic resonance excitation. It is clear from Fig. 7 that acoustic pressure of extremely high amplitudes is detected in a few frequency coincidence events. Moreover, the acoustic pressure at coincidence varies in strength and in the range of flow velocities over which it persists, demonstrating that the mechanism of acoustic resonance excitation in this configuration is strongly dependent on the geometry and flow velocity.
The excitation of the first acoustic cross-mode \( n = 1 \) by the first acoustic shear layer mode \( St \approx 0.5 \) resulted in acoustic resonance with sound pressure levels in excess of 140 dB for all cases. Nonetheless, the range of flow velocities over which acoustic resonance was observed at a constant frequency due to the state of lock-in changed with the change in geometry. For a single cavity at \( L/D_1 = 1.00 \), strong acoustic oscillations at a frequency \( f_a = 481 \) Hz were observed at upstream velocities between \( U_1 = 110 \) m/s and 145 m/s. However, for a double symmetric cavity, acoustic resonance was excited at flow velocities as low as 90 m/s. This different range can be partly attributed to the slight change in the acoustic mode frequency, which results in coincidence conditions at lower flow velocities for double cavities. On the other hand, lower upstream flow velocities imply that the supply of kinetic energy available for the acoustic field is lower for the double cavity cases, leading to a weaker acoustic resonance excitation. Meanwhile, results in Fig. 7 clearly show that the acoustic resonance excited by double symmetric cavities is the strongest, compared to the other cavity configurations, at 170 dB and persistent over a wide range of flow velocities, indicating that the symmetric geometry of the double symmetric cavity provides a particularly high enhancement to the acoustic resonance excitation.

The distinct dominance of the double symmetric cavity configuration can be verified by examining acoustic resonance excitation with the different shear layer modes. Figure 8 shows the normalized acoustic pressure for different cavity configurations at three ranges of reduced velocities at which excitation by the first three shear layer instability modes takes place. At reduced flow velocities \( Ur/C20 \approx 0.5 \), no acoustic resonance excitation events were detected. At the lowest range of reduced flow velocities \( 0.5 \leq Ur/C20 \leq 0.8 \), the third shear layer mode was able to excite the first acoustic cross-mode. The acoustic pressure at the cavity floor reaches a maximum value then drops again to background noise levels as the reduced flow velocity is increased. Figure 8(a) shows that although it occurs at a different flow velocity for each configuration, the peak acoustic pressure for the double symmetric cavity is about four times higher than the other three cases, which have nearly the same magnitude. This shows that the symmetry...
of the double cavity plays an important role in the excitation mechanism of the shear layer. This is an interesting behavior as the shear layers at the wide separation distance of $2L$ are aerodynamically isolated.

In the case of asymmetric cavities, the two shear layers over the opposite cavities have the same length between the separation and impingement points, while the different depth means that the acoustic mode is not completely symmetric about the streamwise axis. The significant increase in acoustic pressure for the case of the double symmetric cavities suggests that the feedback mechanism is further strengthened by the symmetry of the acoustic cross-mode. Figure 8(b) and 8(c) shows that the same conclusion holds during the excitation of acoustic resonant modes, which occur at higher flow velocities. In the following discussion, the dynamic flow characteristics for these four configurations are presented to demonstrate the effect of the configuration symmetry on the resonance excitation mechanism.

**IV. EFFECT OF DOUBLE CAVITY SYMMETRY**

Figure 9 shows the acoustic pressure amplitude distribution of the first acoustic cross-mode for the four configurations under investigation. Contours of the acoustic pressure amplitude normalized by the maximum pressure amplitude show distinct features of the fundamental acoustic mode that is subject to excitation by flow instability. Negative pressure amplitudes refer to a phase angle of $180^{\circ}$ out of phase with the maximum pressure. First, the fundamental cross-mode has a two-dimensional topology in all cases, with the pressure contours extending across the span-wise direction. For the case of two opposite cavities of the same aspect ratios, the local pressure amplitude maxima are located at the middle of the opposite cavity floors. Figure 9(c) indicates that the acoustic mode is antisymmetric about the streamline direction, with the phase between the two halves at $180^{\circ}$. The predicted frequency of this mode is 417 Hz. In Fig. 9(d),...
the different depth of the cavities distorts the symmetry of the pressure contours, leading to different pressure amplitudes near the cavity mouth, and a frequency of 450 Hz. It is expected that this variations would lead to different behaviors when the cavities are subject to the potential coupling with the instabilities of the shear layer separation.

The characteristics of the periodic flow cycle are presented to demonstrate both the instantaneous and the average flow behavior at the conditions of the self-excitation of acoustic resonance. The numerical model was able to accurately simulate the feedback mechanism in all cases, and the acoustic resonance was self-excited in form of a fluctuating pressure field. Figure 10 shows the oscillating pressure component over one complete cycle for the different configurations recorded at the pressure antinodes of the first acoustic cross-mode. For the case of the single cavities shown in Figs. 10(a) and 10(b), the pressure reaches its maximum value inside the cavity. At the antinode located at the wall opposite to the cavity, the acoustic pressure reaches nearly half of its value inside the cavity. The two antinodes are 180° out of phase with each other similar to the first acoustic cross mode pattern shown in Fig. 9.

For double symmetric cavities, the acoustic pressure cycle shown in Fig. 10(c) indicates that the acoustic pressure at the two antinodes has the same value and is exactly 180° out of phase. This suggests that the symmetry of the configuration reinforces the acoustic mode so that it is mirrored in the two opposite cavities, and this symmetry would have an effect on the dynamics of the shear layers. The significance of this symmetry becomes clear when contrasted with the case of double asymmetric cavities. Figure 10(d) shows two different amplitudes for the acoustic pressure at the antinodes, which are located at the opposite centers of the two cavities. Not only that, but there is a slight shift in the phase of the acoustic pressure, which is 165° out of phase. This asymmetry in the acoustic pressure field can have significant consequences on the transfer of energy between the flow and the acoustic cycles, which is sensitive to the phase between the periodic cycles of the two fields.

Figure 11 (Multimedia view) shows the instantaneous acoustic pressure at a phase lag of $\phi = 90°$ from the start of the acoustic pressure cycle. At this instant, the acoustic pressure reaches its maximum value at the center of the bottom cavity. For the double symmetric cavity in Fig. 11(c) (Multimedia view), the acoustic pressure field at this instant is symmetric around the streamwise direction $y/L = 1$. The pressure amplitude is symmetric and higher than 0.5 $p_{\max}$ inside the two cavities. The pressure fluctuations associated with the vorticity field are insignificant compared to the acoustic mode amplitude. Outside the two cavities, the acoustic pressure amplitude falls rapidly. For the other three cases, the acoustic pressure distribution is not symmetric due to the geometry of each configuration. The cavity with $L/D_1 = 1.00$ exhibits higher acoustic amplitudes, and a more rapid decay in the acoustic pressure, showing that the acoustic mode energy is trapped inside the cavity, resulting in high acoustic amplitudes. In contrast, the cavity with $L/D_1 = 1.67$ has a lower acoustic pressure and the acoustic pressure amplitude is spread out of the cavity. For the cases that lack symmetry, the pressure fluctuations due to the vorticity are more significant.

In order to study the interaction between the flow field and the acoustic field, Fig. 12 (Multimedia view) shows the shear layer vorticity fields and the acoustic particle velocity at two instants in the acoustic...
pressure cycle. At $\phi = 0$, the acoustic particle velocity vectors reach their maxima, and at $\phi = 180^\circ$, the acoustic particle velocity vectors reach their minima. In all cases, three vortex cores are observed over the cavity mouth for both instants regardless of the cavity depth. This is characteristic of the excitation of the third shear layer mode, which agrees with the experimental observations at the same flow velocities. For single cavities, the different aspect ratios had no effect on the vorticity distribution over the cavity. Meanwhile, the acoustic particle velocity vectors were significantly different at the cavity leading and trailing edge. For a single cavity with $L/D_1 = 1.00$, the acoustic particle velocity is concentrated around the cavity mouth, where interactions with the vorticity field are bound to produce acoustic energy and lead to resonance excitation. As a result, the change in the aspect ratio significantly affects the aeroacoustic coupling.

The same finding regarding the effect of the cavity aspect ratio hold for the double cavity cases, where the deeper cavity has a concentration of the acoustic velocity vectors around the cavity mouth. An important feature of the double cavity configurations is the synchronization of vortex shedding at the separation points for the two cavities. The two cavities are separated by a distance of $2L$, which is much higher than the upper limit for any aerodynamic influence by the two shear layers on each other. The two shear layers are, however, connected by the pattern of the acoustic particle velocity, resulting in a specific shedding order as will be discussed next.

Although the two opposite shear layers are separated by a distance $2L$ for the configurations of two opposite cavities, the results discussed so far indicate that the acoustic and flow phenomena at the shear layers and inside the two cavities are correlated during the self-excitation of acoustic resonance. Moreover, the results also demonstrate a significant effect of the symmetry of the cavity aspect ratio, and in turn the topology of the first acoustic mode, on the shear layer dynamics.

To quantify this effect, the synchronization of the vortex separation and impingement pattern between the leading and trailing edges of the two opposite cavities is investigated. Table II compares the correlation between the flow and acoustic dynamics at the two cavities through three phase angles for the two configurations. The phase angle $\Theta_{p,b-i}$ represents the phase between the acoustic pressure signal at top and bottom walls during acoustic resonance excitation. $\Phi_{v,b-i}$ represents the phase difference of the transverse flow velocity $v$ at the middle of the shear layer planes. In the coupled model, the transverse velocity at the plane of impingement is closely related to the acoustic mode particle velocity and has an important role in acoustic power transfer. Representing the shear layer instability, the synchronization of the vorticity field is illustrated by the phase angle $\phi_{s,b-i}$ between the vorticity values at the middle of the shear layer. Table II shows that the symmetry of the double cavity configuration has a significant effect on the three phase angles. For the case of double symmetric cavities, it is found that the pressure is $180^\circ$ out of phase between the two cavities at the wall of the cavities, while it is $165^\circ$ out of phase when the cavity aspect ratios are different. At the shear layer plane, the difference is even higher. The transverse velocities at the mouth of the two cavities are exactly in phase when the two cavities are symmetrical, following the expected pattern of a pure standing wave for the first acoustic cross-mode. In such mode, the acoustic particle velocity is strictly in phase at the whole domain. On the other hand, the difference in the aspect ratios of the cavities in the asymmetric configuration had a significant deviation of $77^\circ$ from the pure standing wave phase. The same conclusion is detected for the phase of the vorticity signal, which deviates by nearly the same $80^\circ$ from the pure standing wave pattern for the asymmetric case. This shows that the separation and impingement of vortices are not well aligned with the standing wave distribution and therefore is not expected to contribute optimally to the excitation of acoustic resonance.

To further demonstrate the influence of the excited acoustic mode on the flow behavior over the cavity mouth, the instantaneous vorticity field is shown in Fig. 6 (Multimedia view) at the two
The distance between two successive vortices starts at 0.33 cavities are organized over the two shear layers in the same pattern. When the two opposite cavities have the same aspect ratio, the separation and impingement planes for the two double cavity configurations are observed after self-excitation of acoustic resonance showing that the pattern is not random, but periodic, demonstrating that the acoustic field still strongly influences the flow separation and impingement at the two cavities.

The influence of symmetry on the dynamics of the two opposite shear layers is evident in the vortex convection velocity, which has a significant effect on the shear layer dynamics. Rossiter used a value of $u_c = 0.57 U_\infty$ to identify the frequencies of the shear layer modes. Figure 13 shows the velocity of the vortex cores as they are conveyed along the shear layer over the two opposite cavities during acoustic resonance excitation. This velocity was determined by tracking the location of the vortex center using the scalar eigenvalue $\lambda_2$ and using a least-square difference scheme to calculate the vortex convection speed $u_c/U_\infty$. The values are found to be periodic so that the vortex lasts three acoustic cycles, confirming the excitation of the third shear layer mode. For the symmetric configuration, the vortices conveyed along the opposite shear layers have the same average convective velocity $u_c/U_\infty = 0.59$ and have the same velocity when they are at the same location along the shear layer. It is important to note that the vortices are not at the same location along the cavities at the same time because of the antisymmetric shedding pattern. In contrast, for the case of asymmetric cavities, although the vortices propagate the same distance along the shear layers, they have different convective speeds. The average convective speeds are $u_c/U_\infty = 0.58$ and 0.61 over the deeper and shallower cavities, respectively. The depth of the cavities and the separation of the two shear layers proof that this variation is caused by the difference in the strong acoustic pressure and acoustic particles velocities shown in Figs. 11 (Multimedia view) and 12 (Multimedia view).

These results reveal a significant effect of the asymmetry of the cavity configuration on the topology and dynamic characteristics of the flow and acoustic fields. These deviations from symmetry are bound to affect the mechanism of acoustic resonance excitation by impacting the optimal transfer of energy between the flow and the acoustic fields, resulting in the lower strength of acoustic resonance excitation in the case of asymmetric cavities at frequency coincidence, as indicated experimentally in Fig. 8(c). The mismatch in the flow and acoustic field quantities due to the asymmetry of the opposite cavities is an indicator that the flow and acoustic fields are not in complete sync. Such mismatch suggests that the generation of acoustic power can occur with phasing other than a complete 180 degrees as in the symmetric case. In this situation, the in-phase component of the acoustic source power will have an attenuating effect on the excited acoustic mode. After steady-state excitation is sustained, the out-of-phase component will have to overcome the system damping as well as the effect of the in-phase component. In the following discussion, the transfer of acoustic energy is evaluated through the aeroacoustic analogy to quantify the effect this

![Figure 10](image-url)  
**FIG. 10.** One cycle of the normalized acoustic pressure. (a) single $L/D_1 = 1$, (b) single $L/D_1 = 1.67$, (c) double symmetric, and (d) double asymmetric.
mismatch has on the acoustic power transfer sustained by the coupling mechanism.

V. ACOUSTIC ENERGY TRANSFER IN THE COUPLED FIELD

In this section, the effect of different cavities configurations on the transfer of acoustic energy from the flow field to the acoustic field during acoustic resonance excitation is presented. Figure 14 (Multimedia view) shows two instants in the pressure cycle where the generated instantaneous acoustic power is at its maximum source rate at $\phi = 0^\circ$ and at its maximum sink rate at $\phi = 180^\circ$. Figures 14(a) and 14(b) (Multimedia view) shows that the distribution of the instantaneous acoustic sources and sinks is slightly affected by the aspect ratio, despite the significant differences of the vorticity and acoustic particle velocity patterns in the case of the cavity with aspect ratio $L/D_1 = 1.67$, as shown in Fig. 12 (Multimedia view). As the pattern of vortex separation and impingement is essentially similar, the two single cavity configurations generated almost the same instantaneous acoustic power.

For the case of the double symmetric cavity represented in Fig. 15(c) (Multimedia view), the acoustic sources and sinks over the top and bottom cavity mouths are antisymmetric. Each source is opposite to a sink and vice versa, as the staggered alignment is enforced by the interaction between the acoustic particle velocity and the vorticity field, which was aligned in a staggered way as well. Moreover, the intensity of the sources and sinks is higher compared to the other configurations and more concentrated that is related to the strong vorticity field for this case as in Fig. 12(e) (Multimedia view) and 12(f) (Multimedia view). In addition, the identical distribution of the acoustic particle

| TABLE II. Phase angles in degrees between top and bottom cavities for the different double cavity configurations. Points a, b, c, and d locations are shown in Fig. 2. |
|-----------------|-----------------|-----------------|
| $\phi_{p,a-d}$ (deg) | $\phi_{a,b-c}$ (deg) | $\phi_{b,c}$ (deg) |
| Double symmetric | 180 | 0 | 180 |
| Double asymmetric | 165 | 77 | 100 |
FIG. 12. Instantaneous vorticity contours and acoustic particle velocity vectors at two instants of the acoustic cycle $\phi = 0^\circ$ and $180^\circ$ for (a) and (b) single $L/D_1 = 1$, (c) and (d) single $L/D_1 = 1.67$, (e) and (f) double symmetric, and (g) and (h) double asymmetric. Multimedia views: https://doi.org/10.1063/5.0051226.5; https://doi.org/10.1063/5.0051226.6; https://doi.org/10.1063/5.0051226.7; https://doi.org/10.1063/5.0051226.8
velocity resulted in equal values for the instantaneous sources and sinks. On the other hand, for the case of the double asymmetric cavities, Fig. 15(d) (Multimedia view) shows acute differences in the intensity and the distribution of the instantaneous acoustic sources and sinks between the top and bottom cavities in both instants. This major difference is due to the nonsimilarity in the magnitude and direction of the acoustic particle velocity distribution over the bottom cavity, \( L/D_1 = 1.67 \), compared to the top cavity, \( L/D_2 = 1 \), for both instants shown in Fig. 12(g) (Multimedia view) and 12(h) (Multimedia view).

To determine the locations of the averaged acoustic sources and sinks over the cavity mouth, the calculated instantaneous acoustic power is averaged over one cycle for all the studied cases. Figure 6(b) shows the distribution of the sources and sinks over the cavity mouth for a single cavity with aspect ratio \( L/D = 1 \). The acoustic sound is generated from multiple locations over the cavity mouth not only at the point of impingement. For the single cavity of aspect ratio \( L/D = 1.67 \), Fig. 16(a) indicates a similar distribution of acoustic sources and sinks.

Figure 15(c) (Multimedia view) shows the staggered alignment of the instantaneous acoustic sources and sinks for the case of the double symmetric cavities. This pattern allowed for a perfect alignment of the averaged acoustic sources and sinks between the top and bottom cavities as shown in Fig. 16(b). This perfect alignment allowed for higher values of the generated acoustic pressure. In contrast, for the case of the double asymmetric cavities, it is clear from Fig. 16(c) that when the two cavities have different aspect ratio, the topology of the averaged acoustic power is heavily impacted. The acoustic sources and sinks are neither aligned nor have the same intensity, which affected the generated acoustic pressure for that case making it almost equal to the cases of single cavities.

Finally, to quantify the net acoustic energy transfer from the flow field to the acoustic field, the averaged acoustic power is integrated over vertical lines from the top wall to the bottom wall over the entire length of the cavity. Figure 17 shows the spatial distribution of the net acoustic power over the cavity mouth for all studied configurations.

![Fig. 13.](https://doi.org/10.1063/5.0051226.9; https://doi.org/10.1063/5.0051226.10)

![Fig. 14.](https://doi.org/10.1063/5.0051226.11; https://doi.org/10.1063/5.0051226.12)
The figure shows a behavior that is similar to the measured acoustic pressure shown in Fig. 8(a). It is clear that the trapped acoustic mode that enforced staggered distribution of the vorticity field and the instantaneous acoustic sources and sinks lead to higher values of net generated acoustic power compared to the other cases. Moreover, for the case of double asymmetric cavities, although that configurations encounter two cavities but the different aspect ratios affected the

**FIG. 15.** Instantaneous acoustic power for (a) single \( L/D_1 = 1 \), (b) single \( L/D_1 = 1.67 \), (c) double symmetric cavity, and (d) double asymmetric cavity. Multimedia views: [https://doi.org/10.1063/5.0051226.11](https://doi.org/10.1063/5.0051226.11); [https://doi.org/10.1063/5.0051226.12](https://doi.org/10.1063/5.0051226.12); [https://doi.org/10.1063/5.0051226.13](https://doi.org/10.1063/5.0051226.13); [https://doi.org/10.1063/5.0051226.14](https://doi.org/10.1063/5.0051226.14)

The averaged acoustic power over a cycle for (a) single \( L/D_1 = 1.67 \), (b) double symmetric, and (c) double asymmetric.

**FIG. 16.** Averaged acoustic power over a cycle for (a) single \( L/D_1 = 1.67 \), (b) double symmetric, and (c) double asymmetric.
acoustic particle velocity magnitude and directions as well as the vorticity field and ended up with a net generated acoustic energy in the same range of the single cavity configurations.

VI. CONCLUSION

In this work, the mechanism of acoustic resonance excitation by the flow over rectangular cavity configurations was experimentally and numerically investigated. Rectangular cavities of aspect ratios \(L/D = 1.00\) and \(L/D = 1.67\) were installed either on one side or two opposite sides of a rectangular wind tunnel. Four configurations were considered, with single cavities, double symmetric cavities, and double asymmetric cavities. In all cases, the cavity length \(L\) and the distance between the two cavities were kept constant at 127 mm and 254 mm, respectively. In all cases, the separating flow over the shear layers resulted in self-excitation of acoustic resonance at the first acoustic cross-mode frequency at frequency coincidence with the first three shear layer modes. The aspect ratio had an effect on the frequency of the acoustic resonance as well as the reduced flow velocity required for maximum resonance amplitude. Symmetry on the other hand greatly enhanced the mechanism of energy transfer leading to optimal conditions for acoustic resonance excitation. Notably, the configuration of two opposite cavities with the same aspect ratio resulted in a significantly higher acoustic resonance amplitude at all resonant conditions. In order to investigate the dynamic acoustic and flow characteristics that lead to this behavior, two-dimensional unsteady Reynolds-averaged Navier–Stokes (URANS) simulation was carried out for the four cases. The Reynolds stress model was used to accurately simulate turbulent flow, and a fluid compressibility was resolved to model the coupled acoustic and flow phenomena and capture the self-excitation of the acoustic resonance. Results showed that the symmetry of the double cavity configuration plays an important role in determining the synchronization of the process of vortex separation and impingement at the two opposite shear layers. Moreover, the symmetry ensures that the vortices are shed and impinge exactly at the trailing edge, and are conveyed at the same velocity to ensure optimal transfer of energy to sustain the acoustic mode. To identify the spatial characteristics of energy transfer, the strength of the acoustic sources and sinks was calculated using the Howe’s aeroacoustic analogy, using the numerical and experimental results. The results showed that the acoustic energy is transferred from the shear layer region through a distinct pattern of sources and sinks over the cavity mouth, with the strongest energy exchange occurring close to the impingement point. As a result of the complete synchronization of the flow and acoustic dynamics over the acoustic cycle, the symmetry of the double cavity configuration drives a higher rate of acoustic energy transfer over a larger region over the cavities. On the other hand, opposite cavities of different aspect ratios contribute unevenly to the acoustic energy transfer. The net energy transfer in the double asymmetric cavity case was of a similar rate to the single cavity cases, explaining the lower acoustic amplitude at the peak of acoustic resonance excitation.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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