On wall-pressure-ring/wall interaction

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Molecular tagging velocimetry measurements from an earlier investigation are used to study the wall-pressure and the flow structures responsible for its generation in the flow field resulting from the impingement of an axisymmetric vortex ring on a wall. The velocity-field data are used to obtain the spatial distribution of the pressure sources, and the result is employed in conjunction with the solution to Poisson’s equation to yield the wall-pressure information. The outcome reveals a characteristic wall-pressure signature that is produced repeatedly whenever the primary vortex ring interacts with the wall to form vortex rings with opposite sense of vorticity. The details of the signature are analyzed and related to specific flow features and their mutual interaction at different phases of the generation/evolution cycle of the new rings. Finally, the flow mechanisms leading to the generation of substantial positive and negative wall pressure in the characteristic signature are clarified. © 2004 American Institute of Physics. [DOI: 10.1063/1.1756914]

I. INTRODUCTION

A. Background

Surface pressure fluctuations beneath unsteady and turbulent flows could cause significant vibration of the surface and subsequent generation of noise. To predict and/or control such vibration and noise effects one needs to understand the spatio-temporal character of the flow structures, or sources, responsible for the generation of the unsteady surface pressure. In many instances, flows are dominated by vortical structures that may interact with the wall. This includes impinging jets, separating/reattaching flows in the vicinity of the point of reattachment and delta wing flows. Another less evident example is that of the buffer region of a turbulent boundary layer, where the well-known streamwise vortex structures may interact with the underlying surface.

A more fundamental flow problem that may relate to all of the above flow situations is that resulting from the interaction of an isolated line vortex or vortex ring with a wall. In the current work, the wall-pressure sources associated with the impingement of an axisymmetric vortex on a planar wall are analyzed using time- and space-resolved velocity data from Gendrich et al.1 The goal of this analysis is to understand the physics of the wall-pressure (p_w) generation process as well as the nature of the wall-pressure flow sources associated with the vortex-ring/wall interaction.

In addition to Gendrich et al.,1 several investigators have studied the flow field associated with the impingement of a vortex ring on a flat wall. Some notable ones are Cerra et al.,2 Fabris et al.,3 Orlandi and Verzicco,4 and Chu et al.5 With the exception of the last study, none of these investigations examined the wall-pressure field. Chu et al.1 used numerical simulation of the Navier–Stokes equations to calculate the wall-pressure distribution and total surface force for a problem similar to the one investigated here. Their analysis provides an interesting insight into the contribution of the various flow zones to the total surface force. However, since the latter results from integrating p_w over the entire surface, it is not possible to employ this analysis to draw links between the various flow sources and the detailed features in the wall-pressure distribution or to identify the specific physical mechanisms resulting in the generation of the wall pressure at different points on the surface.

B. Poisson’s equation and wall-pressure sources

The dependence of the hydrodynamic pressure on the velocity field for incompressible flows is known through the solution of Poisson’s equation (Townsend,6 p. 43), which is given by

$$\nabla^2 p = -q(R,t).$$

(1)

p is the pressure, q(R,t) represents the spatial distribution of flow sources of pressure [the dependence of q on the velocity field is given by Eq. (4) below] at time t, and R is the position vector. Blake7 (p. 508) gives the solution to Eq. (1) in terms of a summation of a volume convolution integral over the semi-infinite flow domain z>0 plus an integral over a surface bounding this volume and consisting of the wall and an infinite hemispherical shell as follows (see Fig. 1 for an illustration of the control surface): 

$$p(R,t) = \frac{1}{2 \pi} \int \int \int \frac{q(R_i,t)}{|R-R_i|} dV_i - \frac{1}{2 \pi} \int \int \frac{\psi(R_i,t)}{|R-R_i|} d\omega_i,$$

(2)

where R_i is the position vector for the source location, and...
the denominator in the volume and surface integrands represents the distance between the source location and point of observation of the pressure. Thus, the farther the source is, the less influence it has on pressure generation. On the other hand, $\psi$ represents a spatial distribution of viscous-stress gradients on the control surface. Since no flow exists on the hemispherical portion of the control surface, the integral is only evaluated over the wall ($z=0$). For this evaluation, $\psi = -\mu \frac{\partial^2 v_z}{\partial z^2}$, where $\mu$ is the dynamic viscosity, $z$ is the wall-normal coordinate, and $v_z$ is the corresponding velocity component. It is worth noting that by evaluating the $z$ component of the Navier–Stokes equations at the wall, it can be shown that $\partial p/\partial z = \mu \frac{\partial^2 v_z}{\partial z^2} = -\psi$. Thus, the surface integral in Eq. (2) essentially accounts for the nonhomogeneous wall boundary condition associated with the mathematical solution of the pressure field.

For an axisymmetric flow and cylindrical coordinates, Eq. (2) may be rewritten for the pressure at a point on the wall ($r=r_o$, $\theta=\theta_o$, $z=0$) as follows:

$$p_w(r_o,t) = \frac{1}{2\pi} \left[ \frac{q(r_i, z_j, t)}{\sqrt{r_i^2 - 2 r_o r_s \cos(\theta_s - \theta_o) + r_o^2 + z_j^2}} \times r_o dr_o d(\theta_s - \theta_o) dz_j ight.$$

$$\left. + \int \int \int \frac{\mu \frac{\partial^2 v_z(r_s, z_s, t)}{\partial z_s^2}}{\sqrt{r_s^2 - 2 r_o r_s \cos(\theta_s - \theta_o) + r_o^2}} r_s dr_s d(\theta_s - \theta_o) dz_s \right]$$

with the volume source distribution given by

$$q = \rho \left[ \left( \frac{\partial v_r}{\partial r} \right)^2 + \frac{\partial v_r}{\partial r} \frac{\partial v_z}{\partial z} + \left( \frac{\partial v_z}{\partial r} \right)^2 \right].$$

$\rho$ is the fluid density, $r$ and $\theta$ are the radial and azimuthal-angle coordinates, $v_r$ is the radial velocity component, and $v_z$ is the wall-normal one. Term I in Eq. (4) is similar to that found in Cartesian coordinates, while Term II is a consequence of the use of cylindrical coordinates. Term II is found to be one to two orders of magnitude smaller than Term I, and hence when considering spatial distributions of $q$, the outcome should be qualitatively relevant to the problem of a pair of counter-rotating line vortices interacting with a wall as well.

II. EXPERIMENTAL SETUP

A schematic of the flow apparatus used by Gendrich et al. is shown in Fig. 2. The vortex ring generator is a gravity-driven system through which a small slug of water is ejected into a reservoir from a vertical tube during a short interval controlled by a solenoid valve. In the experiments, a 0.06 m long slug is ejected during the 0.5 s opening of the solenoid valve causing a head change of less than 3%. The ejected fluid originates only within the terminal straight portion of the generator, which is approximately 0.28 m long, and therefore is not affected by the pipe bends or the valve upstream. A flat solid wall is placed normal to the vortex generator axis at a distance of 0.07 m (2.75 tube diameters) from the lip of the generator. The resulting vortex ring Reynolds number is 1860 (based on the initial vortex diameter, $D_o=0.0364$ m, and convection speed, $U_o=0.051$ m/s) and 4500 (based on the initial circulation, $\Gamma_o=45 \times 10^{-4}$ m$^2$/s). Approximately 1700 velocity vectors are obtained using molecular tagging velocimetry (MTV) over a plane that is perpendicular to the wall and passes through the center of the vortex ring. In particular, both the radial and wall-normal velocity components ($v_r$ and $v_z$, respectively) are recorded over the $r-z$ plane at locations spaced 1-mm apart. The velocity vector fields are available at sampling rate of 30 fields per second for a duration of approximately 3.5 s, starting from the valve opening time. Detailed documentation of the experiment and characterization of the data quality are given in Gendrich et al.\(^1\)
The flow visualization in Fig. 3 provides a qualitative picture of the time evolution of the flow structure encountered in the vortex-ring/wall interaction. These images are obtained using two-color laser induced fluorescence (LIF), where the vortex ring and boundary layer fluids are labeled by green- and red-emitting laser dyes (seen in gray and white in the figure), respectively. The advantage of the two-color visualization is that the original fluid in the primary vortex ring (gray) and the separated boundary layer fluid (white) can be monitored independently.

The onset of boundary layer separation can be seen in Fig. 3(c). The evolution of a secondary vortex ring is clearly indicated in Figs. 3(d)–3(f), and a tertiary vortex ring has already formed and is seen orbiting the primary in Fig. 3(f). Ejection of the secondary ring can be seen in Fig. 3(g) in a late stage of development. The near axisymmetry of the entire flow field, well into the ejection phase, is noteworthy.

Figure 4 provides a sample velocity vector field of the right half of the flow field captured during the development of the secondary vortex ring. In the figure, the coordinate variables have been normalized by the initial vortex diameter and the velocity vectors by the initial convection velocity of the primary vortex ring. For the volume integral, all data grid points were used in the integration, while for the surface integral, the location corresponding to the point of observation of the wall pressure is omitted in the integration in order to avoid the singularity of resolve the details of the flow in the near wall region may be verified from the “zoomed-in” velocity-vector-field sequence in Fig. 5. This sequence is captured during the process of boundary layer separation and the subsequent formation of the secondary vortex. For a detailed discussion of the flow field, the reader is referred to Gendrich et al.1

III. RESULTS AND DISCUSSION

A. Space–time behavior of the wall-pressure field

The wall-pressure $p_w(r,t)$ is calculated from the measured velocity field using the convolution integral given by Eq. (3). The integration is conducted using the “method of rectangles” (i.e., by assuming the measured velocity at each grid point to be uniform over the 1 mm×1 mm grid area). For the volume integral, all data grid points were used in the integration, while for the surface integral, the location corresponding to the point of observation of the wall pressure is omitted in the integration in order to avoid the singularity of

![FIG. 5. Demonstration of the spatial resolution of the near-wall flow (time units in seconds), from Gendrich et al. (Ref. 1).](attachment:fig5.png)
the integrand at that location. Lastly, the velocity-field derivatives required for evaluation of the source term \( q \) [see Eq. (4)] and the wall-normal pressure gradient are calculated using a first-order finite-difference scheme. The velocity data are not smoothed before or after determination of the derivatives.

Gendrich et al.\(^8\) estimated the root mean square (rms) of the random velocity error of the MTV data employed here to be 0.5 mm/s. This results in 0.7 s\(^{-1}\) rms error in calculating the spatial gradients of the velocity field (as estimated from the finite difference equations coupled with error-propagation analysis). The corresponding rms uncertainty in \( q \) was found to be 3%, or less, of the maximum \( q \) value within the measurement domain. Because of the random nature of the uncertainty, subsequent volume integration of \( q \) to calculate the wall pressure, using Eq. (3), should “average out” some of these random variation and result in a smaller propagated error associated with \( p_w \) estimation. However, one must be careful that the nonlinearity of \( q \) in the velocity derivatives gives rise to a quadratic (positive definite) component of the random error. This component could produce a “bias” error in \( p_w \) because of the additive accumulation of these small positive numbers in the integration over the entire volume. To estimate the amount of this bias, the rms uncertainty in \( q \) was assumed to be uniformly distributed over the entire volume and to be the only flow source of pressure present. The resulting radial distribution of the wall pressure was then calculated using Eq. (3), and the results are shown in Fig. 6.

Note that in Fig. 6, the pressure has been plotted in the form of a pressure coefficient: \( C_p(r^*) = \frac{p_w(r^*)}{\frac{1}{2} \rho U_o^2} \) (where \( p_w \) is a reference pressure taken as that far away from the wall). The \( C_p \) value is approximately equal to unity, which is pronounced relative to the calculated values under flow conditions (see Fig. 9). Nevertheless, the error effectively produces a constant offset in the pressure distribution without influencing its shape. Moreover, this bias is a consequence of utilizing the Poisson equation solution to calculate the pressure, rather than direct integration of the momentum equation. The need to employ Poisson’s equation here is motivated by the desire to understand the physical nature of the structures within the flow volume that are responsible for the generation of \( p_w \), which cannot be achieved with the use of the momentum equation solution. The corresponding wall-pressure data should be viewed as providing the shape of the signature associated with the various flow features, rather than the absolute magnitude of \( p_w \).

Figure 7 displays two flooded contour plots of the wall-pressure coefficient, \( C_p(r^*, t^*) \) over the radial range \( r^* = 0 - 1.37 \) and time period extending from \( t^* = 1.68 \) to 4.48 after the actuation of the solenoid valve. The color scale is chosen such that yellow/red shades indicate positive pressure values, blue shades represent negative values, and green is in the vicinity of the zero crossing. Also note that the starting time of \( t^* = 1.68 \) was chosen after ensuring that the vortex ring has moved fully within the measurement zone to guarantee that no significant velocity-field gradients were left out of the integration volume of Eq. (3). One of the contour plots in Fig. 7 corresponds to the pressure resulting from the volume integral component of Eq. (3) while the other represents...
the remainder, or surface integral portion. It is evident that the surface integral is practically zero for all time, and therefore it will be ignored for the rest of this work. For completeness, it is noted here that the rms random uncertainty in the second-order derivative of the wall-normal velocity, which is used in evaluating the surface integral, is about 6% of its maximum value observed. The corresponding uncertainty in the result of the integration is less than 1% because of the averaging effect of the integration process.

The contour plot in Fig. 7(a) demonstrates the highly dynamic nature of the wall-pressure signature associated with the vortex-ring/wall interaction. Initially, at $t^* = 1.68$, the pressure coefficient is negative and changes slowly in the radial direction. No particularly interesting wall-pressure features are observed during the time period from 1.68 to 2.1.

For the remaining time duration of the observation ($2.1 < t^* < 4.48$), a certain characteristic wall-pressure signature seems to be repeated in three consecutive time windows: 2.1–2.8, 2.8–3.78, and 3.78–4.48 (identified as I, II, and III in Fig. 7). The signature is strongest and most well defined in the first window. A magnified view of the flooded contour plot during this window is provided in Fig. 8. As seen from the figure, the characteristic pressure signature is initiated with a strong negative pressure peak that forms at $t^* = 2.38$. The peak is localized in the $r-t$ plane as indicated by the closed circular-like contours. The dominant signature changes quickly to that of a localized positive peak as depicted from the closed contours at $t^* = 2.66$ and $r^*$ location that is offset outwards with respect to the negative peak. In the short time interval between the observation of the positive and negative peaks, the wall-pressure contours in the vicinity of the location of the peaks become wavy and open rather than closed.

As mentioned above, the same pressure pattern presented in Fig. 8 is also observed during two later time windows. The three occurrences of the pattern could be related to specific observations by Gendrich et al. of the evolution process of the flow field. In the first time window, spanning the time period from 2.1 to 2.8, Gendrich et al. find the boundary-layer separation to begin at or slightly before $t^* = 2.38$. This process leads to the formation of the secondary vortex ring, which is clearly identifiable close to the wall at approximately $t^* = 2.52$. The secondary ring then orbits the primary one, moving away from the wall to reach a height above that of the primary at about $t^* = 2.8$. Thus, it appears that the localized negative peak in $p_w$ is associated with the beginning of the boundary layer separation process. This seems reasonable since the negative peak imposes a strong adverse wall-pressure gradient in the radial direction on the boundary layer for $r$ locations larger than that of the peak. This causes the boundary layer to separate. The subsequent formation of the secondary vortex from the separated layer in the near-wall region appears to coincide with the observation of the wavy $p_w$ contours. As the secondary vortex moves away from the wall, the wavy contour pattern disappears and the localized positive pressure peak is observed.

A similar sequence of events is also found by Gendrich et al. to lead to the formation and subsequent evolution of a tertiary vortex ring. This is seen to commence at $t^* = 3.08$. Furthermore, evidence for early development of a quaternary vortex ring is also found at $t^* = 3.74$. Both of these times coincide approximately with the start of the second and third time windows where the characteristic wall-pressure pattern discussed above is observed. Therefore, the signature of the wall pressure in Fig. 8 is apparently characteristic of the process of formation and early evolution of a vortex ring due to the interaction of another vortex ring with the wall. This is clarified further in the next section where links are drawn between specific flow features and the observed wall-pressure signature.

B. Flow sources of the wall-pressure field

To attain a deeper understanding of the physics of generation of the wall pressure, the instantaneous distribution of the wall-pressure flow sources ($q$) are examined at $t^* = 2.24, 2.38, 2.52,$ and 2.66. Of these times, $t^* = 2.38$ and 2.66 coincide with the occurrence of the negative and positive peaks, respectively, in the $C_p$ signature shown in Fig. 8. The results are given in Fig. 9, where $q^*$ is represented using a flooded contour plot that is superimposed on top of the corresponding velocity vector field. Below each contour plot, the associated wall pressure variation, $C_p(r^*)$, is provided for reference.

For all four time instants, the wall-pressure sources are concentrated within the vorical structure(s) and its (their) immediate surroundings. At $t^* = 2.24$ (top left plot in Fig. 9), the only significant wall-pressure generation comes from a strong negative source that appears to be located at the core of the primary vortex. The identification of the vortex and its core here is based on visual inspection of the velocity vector field relative to a stationary observer. (A more precise evidence of the concentration of the negative sources at the core of vortical structures is given in the following section.) The corresponding $C_p(r^*)$ has a positive pressure peak at $r^* = 0$ and a broad negative minimum directly below the vortex location. The positive peak is presumably associated with the stagnation point of the induced flow near the center of the vortex ring. On the other hand, the negative peak is consistent with the inviscid solution of Walker et al. of the velocity field of a vortex ring above a wall, which shows the maximum induced velocity, and hence the lowest pressure, near the wall to be directly below the vortex core. Thus, it appears that at this stage of evolution of the vortex, the wall pressure may be viewed as a manifestation of the pressure field of the potential flow induced by the vortex ring.

As time elapses, the primary vortex moves closer to the wall and radially outwards as seen at $t^* = 2.38$, resulting in a corresponding outward motion in the location of the minimum of $C_p(r^*)$, which remains directly below the vortex (bottom left plot in Fig. 9). The negative wall-pressure peak is now narrower, stronger and somewhat asymmetric. A flat plateau in the pressure distribution is seen to extend over the range $r^* = 0.6–0.8$ and is located directly below a new small-size negative-pressure source. To the left, as well as above, of this negative source region, strong positive pressure sources are formed. Comparison with the study of Gendrich et al. indicates that the negative source region is
associated with the recirculating flow that is formed subsequent to the separation of the boundary layer, but before detachment of the secondary vortex ring. On the other hand, the creation of the near-wall positive source is apparently related to the intensification of the velocity gradients stemming from the progressive "squeezing" of the streamlines in this flow region as they are forced around the recirculation zone. This phenomenon is discussed in detail in Walker et al.\textsuperscript{9} who employ numerical computation of the boundary layer to capture the temporal evolution of the near-wall streamlines from the point of separation of the boundary layer to "just before detachment" of the secondary vortex. It is worth noting that the near-wall sources found at $t^* = 2.38$ are the first manifestation of pressure-generating mechanisms that grow out of the inviscid/viscous, or vortex/wall, interaction process.

Referring to the upper-right plot of Fig. 9, it is evident that at $t^* = 2.52$, the secondary vortex has already formed.
and it resides closer to the wall than the primary ring. Both rings have a strong negative pressure source at the core, albeit their opposite sense of vorticity, with the primary's source being stronger than that associated with the secondary. These two negative sources produce two local valleys in the wall-pressure signature. In-between the valleys, a local peak is formed due to strong positive sources that are now seen in the induced flow between the primary and secondary rings. This sinusoidal-like signature of the wall pressure was also found in the wall-pressure calculations of Chu et al.\textsuperscript{5} at a similar point in the evolution cycle of the flow associated with vortex ring impingement on a wall. Similar wall-pressure patterns were also found in the computational work of Dhanak et al.\textsuperscript{10} These authors examined the impingement of single and counter-rotating two-dimensional vortices on a flat surface in the presence of straining mean flow. In both cases, the sinusoidal-like signature was found directly below the interacting vortical structures. The signature was more evident, though, in the case involving the counter-rotating vortices.

The above observations suggest that with the birth of the secondary vortex, the flow resulting from the interaction of the two vortical structures creates appreciable positive pressure sources. These are to be distinguished from the substantially weaker positive sources found earlier at $t^* = 2.38$ due to the interaction of the primary vortex with the wall. In both cases, the primary vortex interacts with vorticity of the opposite sign. However, in the first case, the vorticity is concentrated in the secondary vortex while in the other case it is distributed within the boundary layer. It is also interesting to note that some of the strong positive sources at $t^* = 2.52$ are located directly below the right half of the primary vortex core. This results in the local valley in $C_p$ associated with the primary vortex source not being directly below the vortex core as seen at earlier times.

Finally, at $t^* = 2.66$, the secondary vortex orbits the primary, moving away from the wall. With the increased distance from the wall, the influence of the negative pressure source at the core of the secondary ring on $p_w$ is reduced substantially, and the local valley in $C_p$ directly below the secondary vortex has disappeared. Similarly, the primary vortex ring is now also located farther away from the wall than at $t^* = 2.52$. In fact, the cores of both vortex rings are now located at the same height. However, the pressure sources at the core of the primary structure are more intense and cover a larger area, making a small local valley in $C_p$ still visible at $r^* = 0.77$. As a result of the decreased influence of the vortical structures on the wall pressure, the positive sources associated with their mutual interaction become more dominant. This is partly caused by the localization of a good portion of these positive sources closer to the wall than the vortices themselves. Moreover, the positive sources associated with the fluid that is “pulled” from the near-wall region by the vortical structures (see bottom-right plot in Fig. 9) now extends over a larger area.

\section*{C. Vorticity vs strain-rate pressure sources}

In the previous section, it was found that the most intense negative pressure sources were concentrated around the core of the vortical structures, while the strongest positive sources are associated with the flow between the primary and secondary vortices. To explain the rationale for the specific association of positive/negative pressure sources with particular flow features, it is useful to consider an alternate form of Eq. (4). Although this equation represents the most common form of the pressure sources, Bradshaw and Koh\textsuperscript{11} showed that $q$ may be expressed in terms of the symmetric (strain rate, $e_{ij}$) and antisymmetric (rotation, $\gamma_{ij}$) components of the velocity-gradient tensor. In this formulation, $q$ is given by

$$q = e_{ij}e_{ji} - \gamma_{ij}\gamma_{ji}.$$  

(5)

The second term on the right-hand side of Eq. (5) may be rewritten in terms of the vorticity vector ($\omega_i$), leading to

$$q = e_{ij}e_{ji} - \frac{1}{2}\omega_i\omega_j = q_e + q_\omega$$  

(6)

with the strain-rate and vorticity source terms ($q_e$ and $q_\omega$, respectively) given by

$$q_e = \left(\frac{\partial v_r}{\partial r}\right)^2 + \frac{1}{2}\left(\frac{\partial v_r}{\partial \zeta} + \frac{\partial v_\zeta}{\partial r}\right)^2 + \left(\frac{\partial v_\zeta}{\partial \zeta}\right)^2,$$  

(7)

$$q_\omega = -\frac{1}{2}\left(\frac{\partial v_\zeta}{\partial r} - \frac{\partial v_r}{\partial \zeta}\right)^2,$$  

(8)

for the axisymmetric flow considered here.

Because $q_e$ and $q_\omega$ are positive and negative definite, respectively, it is immediately evident that positive pressure sources will be concentrated where the strain rate is highest, and negative ones will be associated with regions of high vorticity. Hence, a better understanding of the physical nature of the pressure sources may be gained by inspection of the strain-rate and vorticity source fields. To this end, the distributions of $q_e$ and $q_\omega$ over the flow field are displayed in nondimensional form using contour plots superimposed on top of the velocity vector fields in Fig. 10 for $t^* = 2.38$ and 2.52. These time instances correspond to the pressure-source distributions shown earlier in the bottom-left and top-right portions, respectively, of Fig. 9.

At $t^* = 2.38$, two different types of strain-rate sources caused by the interaction of the primary vortex with the wall could be identified. The first one results from intensification of the strain-rate field of the vortex itself by proximity of the wall. To clarify, consider the strain-rate sources at an earlier time ($t^* = 1.96$) when the vortex is farther away from the wall. The strength of the strain-rate sources at this time is shown in Fig. 11. Note that in the figure the source strength has been decomposed into elongation [first, third, and fourth terms in Eq. (7)] and shear-strain [second term in Eq. (7)] components. Also, the color scale covers ten-times smaller source-strength range to detect the substantially weaker sources at this phase of evolution of the vortex.

Inspection of Fig. 11 shows that, away from the wall, the maximum elongation and shear strain-rate sources are generally of equal strength, but are substantially weaker than the
strain-rate sources found closer to the wall at $t^* = 2.38$ (Fig. 10). Moreover, these sources are also substantially weaker than the negative sources at the core of the vortex, which are depicted in Fig. 12 for the same time instant ($t^* = 1.96$). Thus, a vortex in isolation is predominantly a generator of negative pressure. However, as the vortex gets closer to the wall, the vortex-wall interaction intensifies the strain-rate field of the vortex on the side closer to the wall. This may be depicted from Fig. 10 where the strain-rate sources within the regions delineated by white circles are significantly larger than those found at the same locations relative to the vortex in the bottom plot in Fig. 11. The same figure also makes clear that these sources are associated with elongation, rather than shear, strain; i.e., it is the elongation-strain field of the vortex that is affected the most by the proximity of the wall as the vortex moves downwards. Finally, it is noteworthy that the elongation sources have similar strength below and above the core of the vortex at $t^* = 1.96$ (this does not include the sources associated with the stagnation flow in the vicinity of $r^* = 0$). This symmetry is lost at $t^* = 2.38$, where the elongation sources below the core become stronger.

The above observations suggest that as the vortex gets closer and closer to the wall, the streamlines on the lower side of the vortex become increasingly squeezed together, due to the presence of the wall, and the corresponding elongation-strain rates are magnified leading to increased generation of positive pressure. This mechanism is to be contrasted with that which produces the largest positive pressure source at $t^* = 2.38$, seen in Fig. 10 very close to the wall and in the range $r^* = 0.69–0.82$. This source is associated with the thin shear layer resulting from the separation of the boundary layer. The large velocity gradients associated with the shear layer result in substantial elongation and shearing strains and subsequent generation of positive pressure.

The separated shear layer is also an important source of negative pressure, as seen from inspection of $q_v$ sources in Fig. 10 at $t^* = 2.38$. These negative sources are not detectable in the total source distribution in Fig. 9 as they are masked by the stronger positive ones at the same location. However, the decomposition of the sources into positive and negative ones helps reveal the existence of the substantial negative pressure generation from the separated shear layer. Of course, the primary vortex remains the most significant negative-pressure generator with its much stronger negative-source strength. This source peaks at the location of maximum vorticity, and hence it is located at the core of the vortex, as suggested earlier from comparison of the source location to the velocity vector field.

Finally, at $t^* = 2.52$, the strain rate resulting from the interaction between the primary and secondary vortices pro-

FIG. 10. (Color) Strain-rate (top) and vorticity (bottom) sources at $t^* = 2.38$ and 2.52.
duces the largest positive-pressure sources (Fig. 10). These sources are located where the induced flow "enters" and "exits" the region between the vortices. In particular, as fluid is being pumped away from the wall, it is getting "squeezed" and accelerated into the smaller space between the two vortical structures. This results in large elongation-strain rates. Subsequent deceleration of the fluid as it is ejected out of the space between the two rings also produces large elongation-strain rate and significant generation of positive pressure. Also note that the strong positive-pressure source closer to the wall remains connected to the separated shear layer.

Lastly, inspection of the $q_v$ field at $t^* = 2.52$ shows that the strongest negative wall-pressure sources are now contained within the cores of the primary and secondary vortices. This agrees with the earlier inspection of the total pressure sources (Fig. 9). The secondary vortex source is seen to remain connected to the separated shear layer source that is closer to the wall.

IV. CONCLUSIONS

The wall-pressure field and associated flow sources resulting from the impingement of an axisymmetric vortex ring on a flat wall have been investigated. The wall-pressure information is obtained from integration of the flow-field pressure sources using the solution of Poisson’s equation. Finely resolved molecular tagging velocimetry measurements of the velocity field are used to yield the pressure source distribution over the flow domain. Overall, the results are consistent with observations reported in the literature concerning the flowfield of a vortex interacting with a wall, while providing information pertaining to the associated wall-pressure field and its generating mechanisms for the first time. In particular, links have been drawn between known flow features and their inviscid/viscous interactions, on one hand, and the process of generating significant positive and negative pressures, on the other. Moreover, a characteristic wall-pressure signature is discovered to be associated with the initiation, formation and early evolution of secondary, and higher-generation, vortex rings due to the interaction of the primary ring with the wall. Various features of this characteristic signature are analyzed and related to specific flow structures/events at different phases of the evolution of the vortex rings.

It is also found that negative pressure generation is dominated by the large vorticity at the cores of the vortical structures. In contrast, positive-pressure generation takes place in flow regions with high strain rates caused by the interaction of the primary vortex with the wall on one hand, or with the secondary vortex on the other. In the vortex–wall interaction, positive pressure is produced by: (1) intensification of the strain-rate field of the vortex by proximity of the wall, and (2) generation of a high strain-rate region due to the separation of the boundary layer under the influence of the primary vortex. The latter is a more dominant positive wall-pressure source since it generates stronger positive pressures and is located closer to the wall.
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