Acoustics'08
Paris
June 29-July 4, 2008
www.acoustics08-paris.org

Effects of notches on span wise correlation of surface pressure fluctuations downstream of a wall-mounted spoiler

Paloma Mejia[a], Jong Beom Park[b] and Luc Mongeau[b]

[a]Purdue University, 140 S. Intramural Dr., West Lafayette, 47906, USA
[b]McGill University, 817 Sherbrooke St. West, Montreal, QC, Canada H3A 2K6
luc.mongeau@mcgill.ca

Leading edge spoilers are widely-used for suppressing flow-induced cavity resonance such as buffeting due to open sunroofs in moving cars. Spoilers deflect the grazing flow over the opening into a region of greater flow velocity, thereby increasing the critical velocity. Notched spoilers have been observed to enhance resonance suppression while moving the flow reattachment region upstream, resulting in a decreased drag. The mechanisms involved in the effectiveness of the notched spoiler were investigated experimentally. Static and dynamic pressures on the surface behind a wall mounted notched spoiler were measured, and the spatial correlations of the measured pressures were compared to those for a spoiler without notches. The span wise pressure correlation was decreased by the presence of the notches, suggesting a breakdown of the span wise leading vortices predominantly responsible for the cavity excitation.

1 Introduction

Flow grazing over open cavities causes vortices to be shed, which may induce large amplitude self-sustained, tonal pressure oscillations inside the cavity. This phenomenon is a species of flow-induced cavity resonance which typically occurs at acoustic resonance frequencies of the cavities, which depend on the geometry and dimensions of the cavity.

Geometric modifications to leading and trailing edges have been attempted to move the separation location or the flow reattachment region further downstream of the trailing edge of the cavity to suppress the pressure oscillations. Rockwell and Naudascher [1] reviewed various investigations using ramped edges, spoilers, cowls, and rounded edges. Uniform leading edge spoilers were investigated by Rossiter [2], who reported an increase of the upstream boundary layer thickness leading to reductions of the cavity sound pressure level by 25 dB. It has been, however, argued that the effectiveness of uniform spoilers to suppress buffeting is due to a shift of the reattachment zone downstream of the sunroof trailing edge [3]. Research has shown that uniform spoilers deflect the shed vortices over the spoiler into a region of greater flow velocity. The organized flow structures formed at the spoiler are prohibited from impinging on the trailing edge of the cavity, disrupting the feedback loop necessary to maintain large amplitude oscillations.

Many aspects of the excitation pressure in the orifice region of flow-excited cavities are postulated to be analogous (at least qualitatively) to the blocked pressure on the surface underneath similar outer flows. The wall pressure fluctuations produced by the impingement of turbulent flows on structures generate noise and cause structural vibrations. The characterization of fluctuating wall pressure fields on plates with surface irregularities was investigated by Farabee and Casarella [4], who measured the wall pressure field upstream and downstream of a backward-facing and forward-facing step. They found that the recirculation region is dominated by low frequency fluctuations close to the step, and higher frequency fluctuations further downstream. They also measured the wall pressure spectra and velocity profiles of various heights of backward-facing and forward-facing steps, observing that highly energized velocity fluctuations are convected downstream near the wall, decaying gradually and finally diffusing. Park [5] investigated the vibration response and sound radiation of a visco-elastically supported, aluminum plate excited by turbulent flow. Other investigators focused on the study of smooth-wall boundary layers such as Blake [6], Willmarth and Wooldridge [7] and Bull [8], among others. Experiments aimed at separating aerodynamic and acoustic excitation loads for structures excited by turbulent flows were performed by Arguillat and Ricot [9]. Their spectral analysis showed that the broadband acoustic pressure field component accounts for approximately 5% of the aerodynamic excitation pressure field.

While uniform sunroof spoilers have been shown to reduce interior sound pressure levels associated to buffeting in cars by as much as 25 dB [2], experimental investigations have shown that notched spoilers may further reduce the SPL by 20 dB over uniform spoilers. The fundamental physical mechanisms involved in the improved effectiveness of the notched spoiler are of interest for the development of better suppression devices. There are few detailed studies of flows over notched spoilers in the literature. The common explanation for the enhanced suppression mechanism is that the notches break the lateral coherence of the flow over the sunroof. But little objective measurements or detailed computations have been done to verify the validity of this hypothesis. The present investigation included dynamic surface pressure and velocity profile measurements to shed some light on the effects of the notches, on the size of the recirculation region, and on the spatial and temporal coherence of the dynamic wall pressure field downstream a spoiler mounted on a rigid wall. Changes in wall pressures on the rigid wall are presumed to be indicative in a qualitative sense of the excitation pressures that would act on the cavity orifice around the location downstream of the spoiler where the cavity would be located. It is hypothesized in this investigation that the notches may alter the hydrodynamic pressure fluctuations over the region downstream the spoiler in a way that reduces the net excitation.

2 Instrumentation

The experimental apparatus under investigation consisted of spoilers with and without notches, mounted into the test section of a low-speed, quiet wind tunnel. The notched spoiler was similar to that was used on a Fiat Lancia Y. A circular aluminum pressure tap plate was placed in the middle of the wind tunnel test section, as shown in Fig. 1. A spoiler of 2.5 cm height was installed 5 cm upstream of the pressure tap plate. Two spoilers, with and without 2.5 cm wide notches, were used. The pressure tap plate included a rectangular array of 15 x 22 pressure-measuring points with a spacing of 2.5 cm in both streamwise, *x*, and the lateral, *y*, directions. To minimize spatial average effects in pressure measurements, pinholes with a 0.05 cm diameter were drilled at each location on the measuring grid. The pinholes were then counter-sinked from below at a depth of 1.17 cm for insertion of the measuring devices. The static surface pressure field was measured using a MKS pressure gauge, Baratron 220D, connected by a plastic hose to each

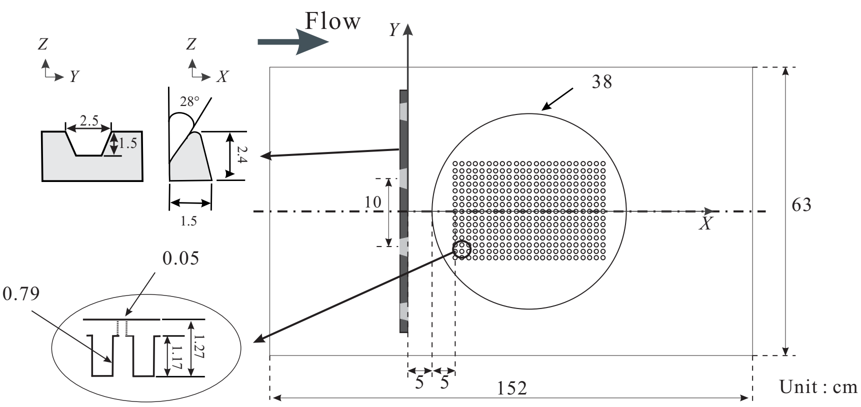

Fig. 1 Schematic of the experimental setup and its dimensions. Circular pressure tap plate with a rectangular array of pinholes is placed downstream of the spoiler to measure the surface static and dynamic pressures.

pressure tap. Three 6 mm diameter B&K microphones, type 4939, were installed in adjacent holes to measure the instantaneous dynamic pressure. Measurements were repeated with one fixed microphone and two roaming microphones over the measuring grid to map the dynamic pressure field. The free stream velocity was 50 km/h (~14 m/s). Unused transducer holes were blocked with putty while pressure measurements were conducted at each measuring points.

Hot-wire anemometry was used for measuring flow velocity profiles. A dual sensor hot-wire probe, TSI 1241, was employed to measure two components of flow velocity. The sensor was mounted on a 3D motorized linear traversing stage moved along x-z and y-z planes, referred to as streamwise and cross-streamwise measurement plane, respectively, hereinafter. The streamwise measurement plane spanned $\{(x, z) : 1.5 < x/h < 18, 0.3 < z/h < 2.5\}$ for $y/h = 0$ and -2, where streamwise and vertical velocity components, u_x and u_z, were measured. The goal was to compare the flow recirculation and reattachment zones behind the notched area ($y/h = -2$) with those of the non-notched, uniform area ($y/h = 0$). The cross-stream measurement plane encompassed $\{(y, z) : -3 < y/h < -1, 0.2 < z/h < 1.5\}$ for x/h = 1, 3, and 5, where streamwise and lateral velocity components, u_x and u_y, were measured. This was to investigate the spanwise change of flow mean structure due to the presence of the notch. The measurements were made with a uniform spacing of 1 cm and 0.5 cm in x- and z- directions for the streamwise measurement plane, and 0.2 mm in y- and z- directions for the cross-streamwise measurement plane. At each measuring point, 0.5 seconds long anemometer output records were recorded with a sampling rate of 16,384 samples per second

3 Experimental methods

General properties of the flow field were firstly obtained from the static surface pressure values. The pressure loss coefficient,

$$C_P = \frac{\Delta p}{1/2\rho u_\infty^2} \tag{1}$$

where u_∞ and Δp are free stream velocity and pressure difference with respect to ambient pressure, was calculated. The surface pressure distribution was used to determine the approximate location of the flow reattachment zone.

Auto-power spectra of the dynamic pressure at each measuring points were measured for both spoiler configurations to evaluate the influence of the notches on the streamwise variation of the fluctuating pressure. Frequency-spectral scaling was used in computing the auto-power spectrum to compare with experimental results from other studies [10]. Because velocity fluctuations of various scales in the boundary layer contribute to the wall pressure fluctuations, different scaling laws lead to a collapse of experimental data over different spectral ranges [8]. In the present study, the free stream dynamic pressure, $q=1/2\rho U_\infty^2$, and the spoiler height frequency scale, U_∞/h, were used, which yields spectral data in the form $\Phi_{xx}(\omega)U_\infty/q^2h$ as a function of $\omega\, h/U_\infty$.

Cross-power spectrum, coherence and phase distribution between lateral measurement locations were calculated from the dynamic surface pressure data and analyzed to investigate the influence of the notches on the lateral flow structure. The spectral analysis is based on Corcos' empirical model where cross-power spectrum is expressed by

$$S_{xy}(\xi_x, \xi_y, \omega) = \Phi_{xx}(\omega)\, e^{-\alpha_x\left|\frac{\omega\,\xi_x}{U_c}\right|} \cdot e^{-\alpha_y\left|\frac{\omega\,\xi_y}{U_c}\right|} \cdot e^{i\frac{\omega\,\xi_x}{U_c}} \tag{2}$$

where Φ is auto-power spectrum, ξ is a displacement between two locations, and α is a decay coefficient [9]**Error! Reference source not found.**. The coherence between two locations is therefore obtained as

$$\gamma = e^{-\alpha\left|\frac{\omega\xi}{U_c}\right|} \tag{3}$$

For the computation of the spectral densities of the fluctuating pressure, it was necessary to compensate the measured power spectrum to account for the effects of microphone installation on its frequency response. The acoustic transfer function of the mounted microphone to the external pressure was measured independently before the wind tunnel experiments. The transfer function was then used for compensation of the power spectra.

4 Results

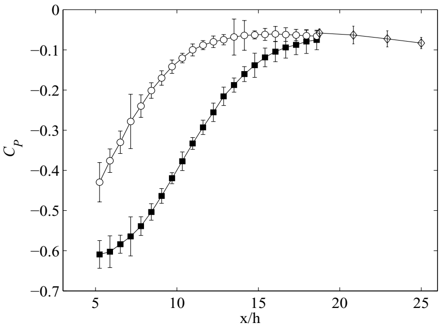

Fig. 3 Loss coefficients as a function of dimensionless streamwise distance for a spoiler with notches (○) and without notch (■).

The pressure loss coefficients are shown as a function of dimensionless streamwise distance in Fig. 3. The loss coefficients increase with distance and asymptotically converge towards a more or less uniform value. Downstream of the spoiler, the region of low pressure is indicative of a zone of the re-circulating flow. The flow is expected to reattach further downstream, where the slope of the loss coefficient first becomes zero [11]. The reattachment region was approximately located at x/h = 12 for a notched spoiler and at x/h = 18 for the uniform spoiler. The values are in general agreement with those reported for similar flows [12]. The notches caused the flow reattachment region to move upstream, resulting in a smaller flow recirculation zone. As expected, the flow resistance was observed to be smaller for the notched spoiler as shown from the pressure loss coefficient curve because ΔCp is smaller for the notched case. The Cp curve shows little variation in the lateral direction (y). Error bars in Fig. 3 indicate the variance between configurations.

Flow velocity measurement results confirmed these observations. Fig. 4-(a) shows streamwise velocity magnitude profile for the notched spoiler as a function of dimensionless streamwise distance, x/h, along a uniform portion of the spoiler at y/h~0. Fig. 4-(b) shows the same velocity profile but along a notched region of the spoiler at y/h~ -2. The presence of the notch causes the region of the low velocity components at z/h<1.4 to reduce in size compared to the region downstream of a uniform region of the spoiler at z/h<2.1. The recirculation zone approximately corresponds to {(x, z): x/h < 14, z/h < 1} while the reattachment zone corresponds to {(x, z): x > 14, z/h ~ 0}. The smallest absolute magnitude of u_x was found at (x/h, z/h) ~ (8, 0.5), which suggests the center of the recirculation region because flow motion in the recirculation region is analogous to a rotation initiated by the shear action of the free stream at the boundary. The flow direction within the circulation zone may be opposite from the principal flow direction, along the positive-x direction. Flow direction cannot be conclusively established from the hot-wire data alone because of the reversed-flow ambiguity in hot-wire measurements. However, with the use of directional information from flow visualization allowed the possible ambiguity in flow direction to be resolved. On both measurement planes, u_x, shown in Fig. 4-(a) and (b), indicates that the shear layer (8 < u_x < 12 m/s) clearly divides free stream (u_x > 14 m/s) and circulation (u_x < 7 m/s) zones. The velocity field is consistent with the observed flow motion from visualization, where the streamlines were seen to rise over the spoiler before incurving towards the floor.

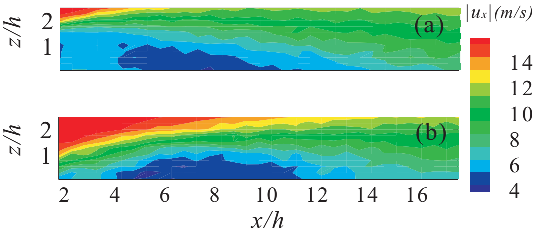

Fig. 4 Streamwise and vertical velocity distribution, $|u_x|$, from hot-wire measurements; (a) u_x at y/h = 0; (b) u_x at y/h = -2. The uniform portion of the notched spoiler is located at y/h=0 and the notched portion is at y/h=-2. Velocity magnitudes (moduli) are shown here for u_x since reversed flow cannot be detected in hot-wire measurements.

Power spectra of the surface dynamic pressures measured inside and outside re-circulation zone are compared in Fig. 2 for uniform and notched spoilers. In case of the notched spoiler, surface pressure was smaller approximately by 8 dB outside the recirculation zone at a low frequency range whereas the spectra changed little for the case of uniform spoiler. The power spectra of the surface pressure were also observed to remain unchanged along the spanwise direction, y. It therefore indicates that the notched spoiler would result in a smaller surface force than the uniform spoiler when the surface pressure is integrated over the whole surface area.

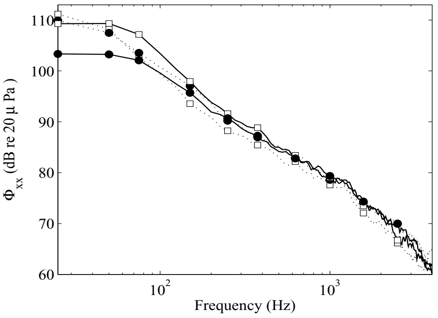

Fig. 2 Power spectra of the surface dynamic pressures inside and outside recirculation zone (□: x/h ~ 8; ●: x/h~19) for uniform (- - -) and notched (—) spoilers.

Wall pressure spectra in the reattachment region (x/h~16), scaled by outer boundary layer variables, are shown in . Spectral shape is generally in good agreement with the turbulent wall pressure spectra of the reattachment region from a previous study by Farabee and Casarella [4][11] except an offset in magnitude. It is postulated that the offset in spectrum magnitude results from difference in the downstream flow patterns for the given length scale of h. In other words, the spoiler height may not be directly equivalent to that of the backward facing step for scaling the spectrum because the flow is elevated by the spoiler whereas it is not in the case of backward facing step. The measured wall pressure spectra for notched and uniform spoilers are similar, which suggests that the notch has little influence on the spectral content of the wall pressure field at the reattachment zone. The surface pressure spectra did not vary very significantly over the area of interest, with at most a 5 dB difference between the lowest and largest pressure spectral density levels. Variations were monotonic, with little apparent “footprint” in the region wet by the vortices shed from the notches.

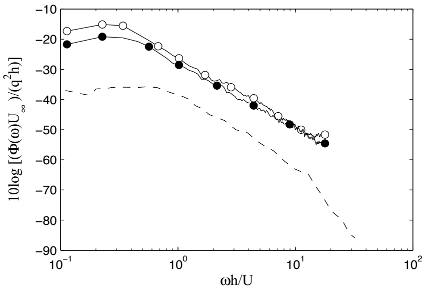

Fig. 5 Auto-power spectrum of wall pressure measured at (*x/h*, *y/h*) = (16, 2) for notched (●) and straight (○) spoilers. Spectral data are normalized by pressure and frequency scales, q(=1/2ρU$^2_\infty$) and U$_\infty$/h. Surface pressure spectra downstream of a backward facing step is shown for reference (- - -; Farabee and Casarella, x/h~6).

The phase distribution of fluctuating pressures along the cross-steam lateral direction was expected to be almost zero in the case of the uniform spoiler without notches. The flow fluctuations were found to be more or less in-phase, which was also supported by flow visualization. When notches were present, an organized phase difference in the lateral direction was expected as a result of lateral variations in convection velocity due to the changes in non-uniform spoiler height.

Fig. 6 shows the streamwise change of lateral phase distributions with and without notches at a frequency of 25 Hz, at which the coherence of the pressures at any two points was maximum. In the case of the uniform spoiler, the pressures near the spoiler were in-phase throughout the span as expected. For the notched spoiler, an initial lateral phase shift, i.e., a positive phase lead in the notched region, was observed. The phase on each side tends to lead the phase at the center location (*y*/*h* = 0) of the reference microphone. This non-uniformity in phase may result in destructive interferences and thus a lower overall fluctuating excitation force over the upstream portion of the measurement surface. At locations further downstream, however, a lateral phase lag gradually appeared for both spoiler cases. This phase lag was supposedly due to corner effects, i.e., gaps between the spoiler and the wind tunnel walls. These gaps may have shed corner vortices that might change the local flow velocity and convection speed.

The ordinary coherence of the wall pressure field was calculated from auto- and cross- spectral densities at various locations. The coherence provides insight into the temporal and spatial characteristics of flow structures. Fig. 7 shows the coherence at low frequencies at two lateral locations. It was observed that the overall coherence was significant only at low frequencies. The coherence was high near the center of the spoiler, and decreased with lateral distance. In general, the coherence for the uniform spoiler was greater than that for the notched one at any lateral locations. The notches were found to significantly decrease coherence at low frequencies.

Using the Corcos' model described in the preceding section, the lateral decay rate was found as |*α*| ~ 0.6 for the uniform spoiler and |*α*| ~ 0.9 for the notched from the lateral spatial distribution of coherence, respectively. The notches induced a decay rate in the lateral direction that is greater for the notched spoiler than for the uniform spoiler, indicating spatial de-correlation between adjacent spanwise flow structures.

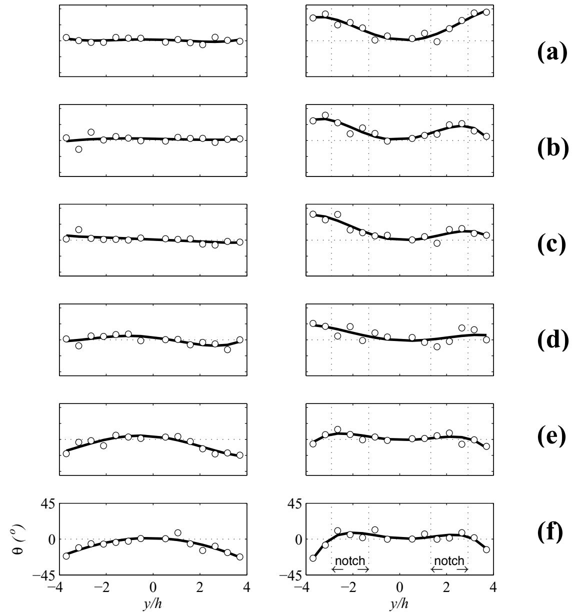

Fig. 6 Comparison of lateral phase differences of straight (left column) and notched spoilers (right column) for several downstream locations: (a) x/h~5.4;(b) x/h~6.5; (c) x/h~7.6; (d) x/h~9.1; (e) x/h~11.8; (f) x/h~13.4. Notch areas are denoted by dashed lines.

5 Discussion

Possible physical phenomena that could lead to sunroof buffeting suppression from notched spoilers were investigated in this study. Based on the results, the dominant factor appeared to be the reduction in lateral coherence of the surface pressure field. This was shown to lead to a significant reduction in the integrated wall pressure over the entire measurement region. Assuming a similar effect for the equivalent excitation force over an open sunroof, this is a plausible explanation of why notched spoilers are effective at reducing flow-induced cavity pressure oscillations. As observed in Fig. 8, the excitation force, an integration of the cross-power spectrum of surface pressure over the surface using Corcos' model,

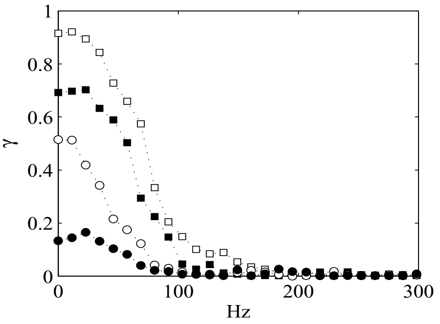

Fig. 7 Coherence (at 25 Hz) of surface pressures between the center reference point (y/h=0) and two other transverse locations: Δy/h~-0.5 (□:straight; ■: notched), Δy/h~-2 (○:straight; ●:notched).

$$F_{\mathrm{ex}}(\omega) = \int S_{xy}(\xi_x,\xi_y,\omega)\cdot d\xi_x d\xi_y \tag{4}$$

was found to be significantly reduced at all frequencies when the notches are present. The decrease in the equivalent force spectrum varied with frequency. The reduction was around 5 dB at low frequency, and up to nearly 20 dB at higher frequency.

The frequency of the maximum in the fluctuating excitation force spectra was observed to decrease in presence of the notches from a value of around 150 Hz to around 50 Hz. The uniform spoiler case exhibited higher levels of coherence throughout the streamwise direction at all frequencies, specifically at the center of the spoiler at y/h=0. The notched spoiler case exhibits significantly reduced coherence both at the center, y/h=0, and at the notch location, y/h = -2, compared to the uniform spoiler case at the same locations. The increased coherence behind the uniform region of the spoiler indicates that the transverse flow distribution is not as uniform as in the uniform spoiler.

The notched spoiler tends to de-correlate fluctuations leading to destructive interferences, especially within the recirculation region. The notches act as streamwise vortex generators that change the velocity distribution fluctuations behind the spoiler and lower the transverse coherence breaking down the main cross-stream shear layer responsible for the pressure excitation of the cavity.

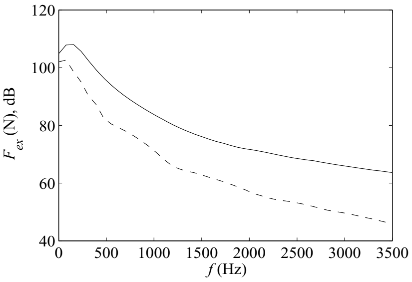

Fig. 8 Estimated excitation force spectra from surface pressures: uniform (—) and notched (– – –) spoilers.

6 Conclusions

The influence of notches in spoilers mounted on a rigid plane on the flow and the wall pressure field downstream was investigated. Experimental results were obtained for uniform and notched spoilers. Data included mean pressure, fluctuating pressure, and velocity distributions. It was found that the net force excitation was significantly reduced, when the notches are present, compared to the uniform spoiler. Static pressure measurements showed that the presence of the notches moved the flow reattachment closer to the spoiler. An initial lateral phase offset was observed upstream behind the spoiler in the presence of the notch whereas no phase difference was found for the uniform spoiler. The transverse coherence of the pressure fluctuations was reduced by the notches. The transverse exponential decay factor at the frequency of maximum coherence, 25 Hz, was found to be greater for the notched spoiler. The decrease of coherence along the transverse direction confirmed that the notch can be effective in disturbing the cross-stream vortices and therefore in weakening the excitation mechanism.

Acknowledgments

The work reported here was supported by Exa Corporation.

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