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Technical Notes

Alteration of Jet Noise by Jet Plume Deflection

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I. Introduction

THE effect of deflecting the jet plume on jet noise is examined. The idea of canting the nozzle and thereby vectoring the jet plume in order to obtain noise reduction has been proposed in the past. The changes to the noise field due to such a modification are assessed. Viswanathan [1–3], among others (see [4–6] for example), sought to alter the noise radiation through the use of a beveled nozzle. Figure 1 shows an illustration of a beveled round nozzle. The measurement conventions for the bevel as well as the polar and azimuthal angles are also indicated. The bottom portion depicts the computed Mach number contours and provides a visual feel for the flowfield. When a convergent single-stream nozzle is beveled, the plume deflects towards the short lip of the beveled nozzle. Thus, there is seemingly the same deflection introduced by both the canting and the beveling of a round nozzle. This resemblance has led some to believe that the noise reduction from the beveled nozzle is only due to plume deflection. The following two questions are addressed in this Note:

1) Are the noise characteristics the same for these two geometries?
2) How much of the observed change in noise between beveled and round nozzles is due to the kinematic effect of different plume orientations?

Experimental evidence from single-stream convergent beveled nozzles, dual-stream geometry with convergent beveled primary nozzles, and single-stream convergent-divergent beveled nozzles are reviewed and discussed. It is clearly established from the measured data that

1) The effects on the spectral characteristics are drastically different, even though there are outward similarities in the aerodynamic behavior of the jet plumes.
2) There is only a minor effect due to the canting of a round nozzle.
3) The observed noise reduction for the different beveled geometries is due to the modification of the noise radiation mechanisms and not due to the deflection of the jet plume that can be achieved with canting or swiveling of the round nozzle.

II. Measurement Details and Observed Trends

The experimental measurements were carried out in the Boeing Low Speed Aeroacoustics Facility, with simultaneous measurement of farfield noise and aerodynamic performance with a six-component force balance. Descriptions of the anechoic facility, the jet simulator, the capabilities of the jet simulator and the freejet wind tunnel, the facility-dedicated data acquisition systems, and other details are provided in Viswanathan [7,8]. Two different far-field microphone arrays were deployed; these were at azimuthal angles of 60 and 90°, respectively. The azimuthal angle is measured counter-clockwise from the bottom dead center (see Fig. 1). The microphones in each array were laid out at a constant sideline distance of 15 ft (4.572 m) from the jet axis. For the fixed sideline array, the distance to the microphone varies as $(15/\sin\chi)$, where χ is the polar angle measured from the nozzle inlet. The polar angular range covered 50 to 150°. Narrowband data with a bandwidth of 23.4 Hz were acquired and synthesized to produce 1/3-octave spectra, with a center band frequency range of 200 to 80,000 Hz. Noise measurements were made with three orientations of the beveled nozzle, with the long lip positioned at three azimuthal angles of 0, 90 and 270°, so as to map the noise fields at six azimuthal angles on one side of the symmetry plane of the beveled nozzle. Two beveled nozzles with bevel angles of 24 and 45° (referred to as bevel 24 and bevel 45 hereafter) and a round nozzle of diameter 2.45 in. were tested. The salient results from this test are described in [1,2]; see these two references for complete details.

The performances of the beveled nozzles are assessed against the reference round nozzle. The main findings from [1] are summarized first. From the measured axial and normal forces, the deflection angle of the plume can be calculated. The deflection angles for the single-stream 24° beveled nozzle and 45° beveled nozzle are ~7 and ~10°, respectively. In addition, there is a reduction in the effective flow area for the beveled nozzle due to the nonuniform pressure distribution at the nozzle exit plane. Consequently, the mass flow rates are reduced by ~8% for bevel 24 and ~13% for bevel 45. For direct spectral comparisons, the sound pressure levels would be lower by 0.33 and 0.53 dB for the bevel 24 and bevel 45, respectively, due to the lower flow areas. The beveled nozzles introduce significant azimuthal variations in the spectra, resulting in major differences in the polar directivities of the overall sound pressure levels at different azimuthal angles; these differences become pronounced when the jet velocity is increased. Significant noise reduction is achieved in the azimuthal directions below the longer lip of the beveled nozzle, principally in the polar angular range of ~110 to ~140°. Furthermore, this reduction is observed at all frequencies. The magnitude of the noise reduction is a strong function of the jet velocity, with progressively higher reductions as the jet velocity is increased. The characteristics of the canted and beveled nozzles are now examined, given this background information.

III. Results and Analysis

We start with single-stream convergent beveled nozzles. As already noted, when a convergent nozzle is beveled, the plume deflects towards the short lip. In the experimental study of Viswanathan [1], the far-field microphones were positioned with respect to the coordinate system for a round nozzle, for which the jet plume is aligned with the x-axis. When the jet plume is deflected, the polar angles with respect to the plume axis are modified depending on the orientation of the beveled nozzle. Therefore, spectral comparisons at fixed microphone angles introduce some ambiguity as discussed at the end of Sec. IV.B in [1]. This problem is overcome when integral quantities such as the effective perceived noise level (EPNL) or the sector power levels are examined (see Figs. 17a and 17b and associated discussion in [1]). Here, we allay any doubts about the effectiveness of the beveled nozzle in reducing the important metric of the EPNL, by comparing the variation of the tone-corrected perceived noise level (PNLT) with time, for the round nozzle with those for the beveled nozzles. The measured model data are scaled to engine scale, with a linear scale factor of 8.0. As already noted, the range of frequency in the model data is from 200 Hz to

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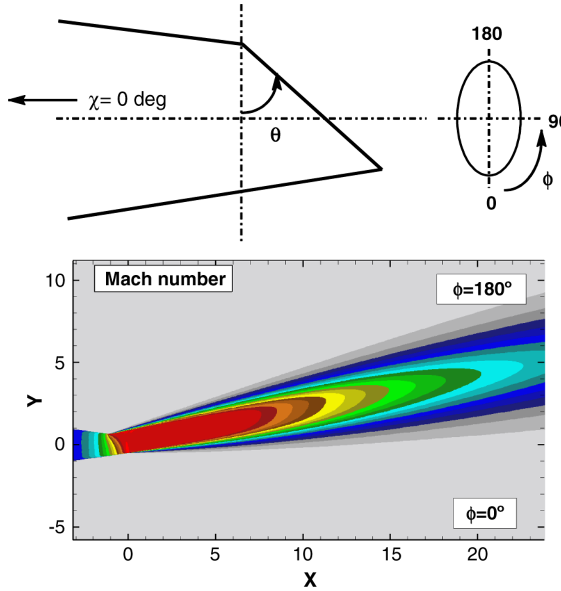

Fig. 1 Top: conceptual sketch of the beveled nozzle and the measurement convention for the bevel angle (θ), the polar angle (χ) and the azimuthal angle (ϕ). Bottom: typical computed flowfield for beveled nozzle.

80 kHz. With a scale factor of eight, the measured model frequency range is adequate to resolve the engine scale frequency range of 50 Hz to 10 kHz, which is used in the computation of the PNLT. The effect of the reduction in flow area is also taken into account, by increasing the scale factor such that the mass flow rates for the round and beveled nozzles are identical. The extrapolation is carried out with the assumption of straight level flight of the aircraft at a fixed altitude of 1000 ft. The EPNL is computed from the PNLT variation; it accounts for the maximum PNLT level as well as the duration effect, which is defined as the time period over which there is a 10 dB-reduction from the peak PNLT level.

Figure 2 shows a comparison of the PNLT variations for the round nozzle and the beveled nozzle in the azimuthal directions of the long and short lips of bevel 45. The jet Mach number (M) is 1.0 and the stagnation temperature ratio (T_t/T_a) is 3.2. As explained in [1], the time scale on the x-axis is somewhat arbitrary, because the shape of the PNLT variation alone determines the EPNL. An examination of Fig. 1 indicates that the peak PNLT in the direction of the short lip is observed at an earlier time, consistent with the movement of the directivity of overall levels to lower polar angles. However, this is only a side observation and has no real bearing on the EPNL. In the direction of the long lip, there is a reduction of ~5 PNdB in the peak PNLT value; a reduction in EPNL of 3.5 EPNdB results as a consequence. In the direction of the short lip, the reduction in the peak PNLT value is only ~1.5 PNdB. However, there is a much faster drop in the PNLT values in the aft directions, thereby yielding a benefit of 2.5 EPNdB. It should be clear that there is significant noise reduction in the important metric of EPNL from the beveled nozzle.

The effect of the plume deflection due to canting/swiveling the round nozzle on the PNLT variation is assessed in Fig. 3; the test conditions are again $M = 1.0$ and $T_t/T_a = 3.2$. The measured spectra at the various polar angles are reassigned to different angles so as to account for a plume deflection of 10° towards the jet inlet (corresponding to the deflection for the bevel 45), and the resulting PNLT variation is compared with the PNLT of the normal jet. As expected, the shapes of the PNLT curves are similar; the peak for the deflected jet occurs at an earlier time. There is a slight reduction in EPNL of 0.25 EPNdB due to the deflection, because of the faster drop in the aft direction associated with longer propagation distances. Thus, the effect of canting the nozzle and deflecting the plume yields a small reduction in EPNL. It is quite clear that the significant noise reduction of 3.5 EPNdB in the direction of the long lip is due to the alteration of the noise radiation characteristics and not because of the plume deflection. Similar trends are observed for other single-stream heated jets.

It was also shown in [1] that there are drastic differences in how the spectral shapes change with polar angle, at different azimuthal angles for bevel 45; see Fig. 18 in [1] for a progression in spectral shapes. Specifically,

1) The broad spectral shape with gentle roll-off away from the peak is observed at lower polar angles for the round nozzle up to a polar angle of ~120° and the peaky spectral shape (narrow peak with rapid roll-off away from the peak) is seen at angles ≥ ~140°.

2) For the bevel 45 towards the short lip, the peaky shape is observed for all angles ≥ 110°. That is, the peaky shape is moved upstream by ~30° when compared with the round nozzle; recall that the plume deflection is only ~10°. The large change in polar directivity and the modifications to the spectral shapes are not mere kinematic effects. Therefore, the noise reduction observed for the beveled nozzle is not due to plume deflection but due to altered noise radiation mechanism; see Viswanathan [1,9] for more details. Thus, there are fundamental differences between the noise characteristics of the beveled nozzle and the canted round nozzle in spite of seeming similarities vis-à-vis plume deflection.

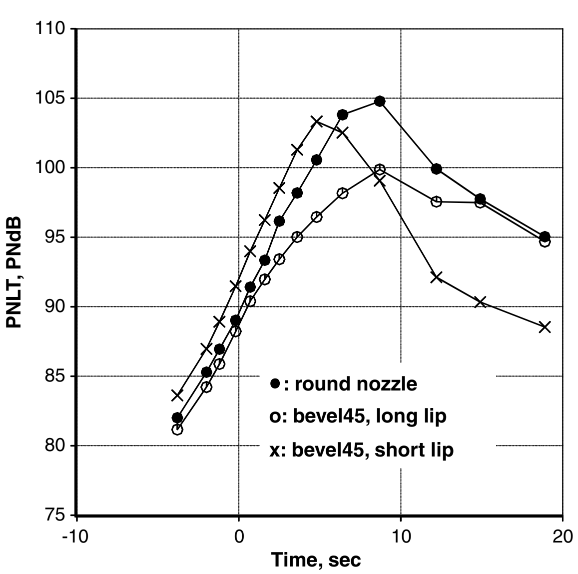

Fig. 2 Variation of PNLT with time. $M = 1.0$, $T_t/T_a = 3.2$. ●: round nozzle; o: bevel 45 long lip; x: bevel 45 short lip.

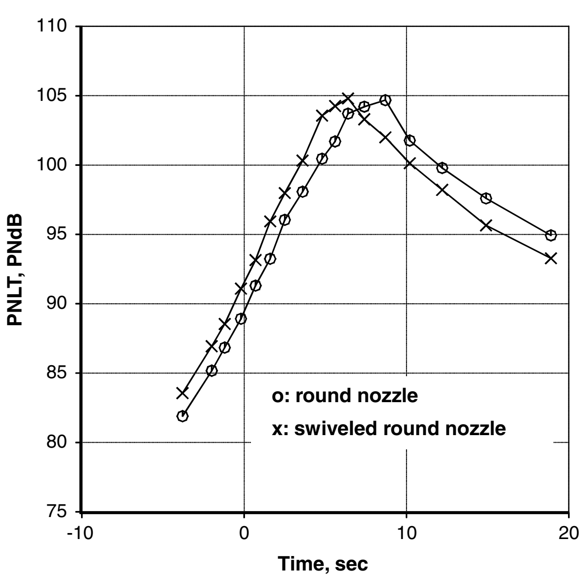

Fig. 3 Variation of PNLT with time. $M = 1.0$, $T_t/T_a = 3.2$. o: round nozzle; x: swiveled round nozzle.

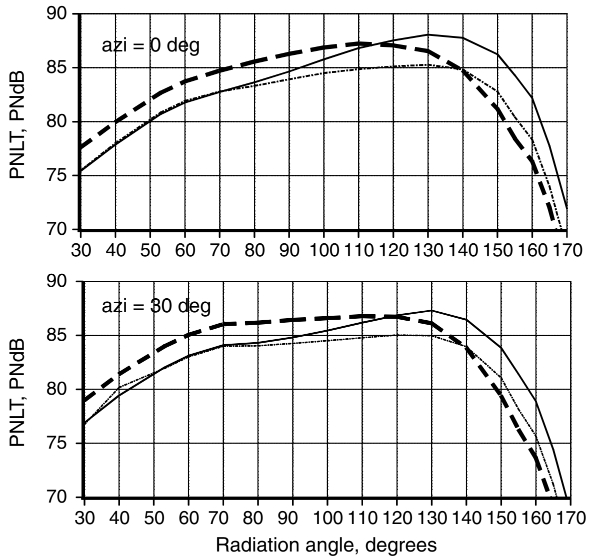

Fig. 4 PNLT directivity. $M_t = 0.32$, NPR$p = 1.96$, $T_p/T_a = 2.46$, NPR$s = 1.8$, $T_s/T_a = 1.0$. Solid: round; thick dashed: bevel 45; dot-dashed: bevel 24.

Let us examine the noise of dual-stream jets from Viswanathan [2]. The primary nozzle is beveled and the secondary nozzle remains unmodified. Comparisons with the baseline nozzle system of round primary and round secondary indicate that the modified geometry again provides significant noise reduction in the aft angles $\geq \sim 110°$. The magnitude of noise reduction is proportional to the velocity of the inner stream. The plume deflection for bevel 24 varies from ~ 1.2 to $\sim 3°$, and ~ 3 to $\sim 5°$ for bevel 45, depending on the cycle conditions in the primary and secondary streams. In a high bypass ratio (BPR) turbofan engine with BPR $\geq \sim 5$, the plume deflection due to beveling the primary nozzle is reduced substantially by the large mass flow of the secondary jet. Therefore, the plume deflections tend to be much lower compared with a single-stream jet with the same bevel angle. A sample comparison of noise results from the baseline, primary bevel 24 and primary bevel 45 with a common secondary nozzle is shown in Fig. 4. The jet conditions are NPR$p = 1.96$, $T_p/T_a = 2.46$, NPR$s = 1.8$, and $T_s/T_a = 1.0$. The flight Mach number (M_t) for these measurements is 0.32. The PNLT directivities at two azimuthal angles of 0° (towards the long lip) and 30° from the long lip direction are depicted in Fig. 4. Note that the radiation angle is used on the x-axis instead of time. There is one-to-one correspondence between angle and time, because the flight path and the flight speed are known. The following trends may be identified in Fig. 4:

1) There is a noise increase at the lower angles for the bevel 45 (dashed line) for angles $\leq 120°$ at both azimuthal angles.

2) Bevel 45 produces larger noise reductions in the aft angles.

3) Bevel 24 does not increase noise at the lower angles, but provides noise reduction for all angles $\geq \sim 90°$. Because bevel 24 yields noise reduction over a wider angular range without any increase at the lower angles, there are reductions of 2.50 and 1.72 EPNdB at the two azimuthal angles of 0 and 30°, respectively. The corresponding EPNL reductions for bevel 45 are 1.79 and 0.72 EPNdB at the azimuthal angles of 0 and 30°, respectively. At lower freestream Mach numbers and at static conditions, bevel 45 outperforms bevel 24. However, for realistic takeoff Mach numbers in the range of ~ 0.25 to ~ 0.28 (160–180 knots), bevel 24 is seen to provide a larger noise reduction.

Two important points are reiterated. The plume deflection for bevel 24 is between ~ 1.2 to $\sim 3°$, but spectral reductions of ~ 5 to ~ 10 dB are observed in the aft quadrant (not shown here). Further, there is noise reduction at all frequencies. Substantial reduction in EPNL is realized as a consequence. Clearly, this is not a kinematic effect. See [2] for complete details.

Finally, we consider single-stream convergent-divergent beveled nozzles. Viswanathan and Czech [10] adapted the beveled nozzle for application to typical nozzle geometry of engines that power fighter aircraft and assessed the aeroacoustic performance of four different beveled nozzles with bevel angles of 20, 24, 28 and 35°. The aerodynamic characteristics of a choked convergent-divergent (CD) beveled nozzle are different from those of the convergent beveled nozzle. The most striking difference is that the plume deflection is very small. Whereas the plume deflects towards the short lip for a convergent beveled nozzle at all nozzle pressure ratios, the plume deflection for a CD nozzle is dependent on whether the nozzle is operated overexpanded or underexpanded. For overexpanded nozzle pressure ratio (NPR), the plume deflects towards the long lip; as the NPR is progressively increased the deflection angle decreases and at some NPR, the plume is aligned with the jet axis. In the under-expanded regime, the plume deflects towards the short lip of the bevel. This phenomenon was verified both experimentally and through computational simulations; see [10] for more details. One of the main observations is the following: the plume deflection is within in $\pm 1.5°$ for a wide range of NPR. Given this extremely small deflection angle, it should be possible to examine spectra from the round and beveled nozzles from a fixed set of polar microphones,

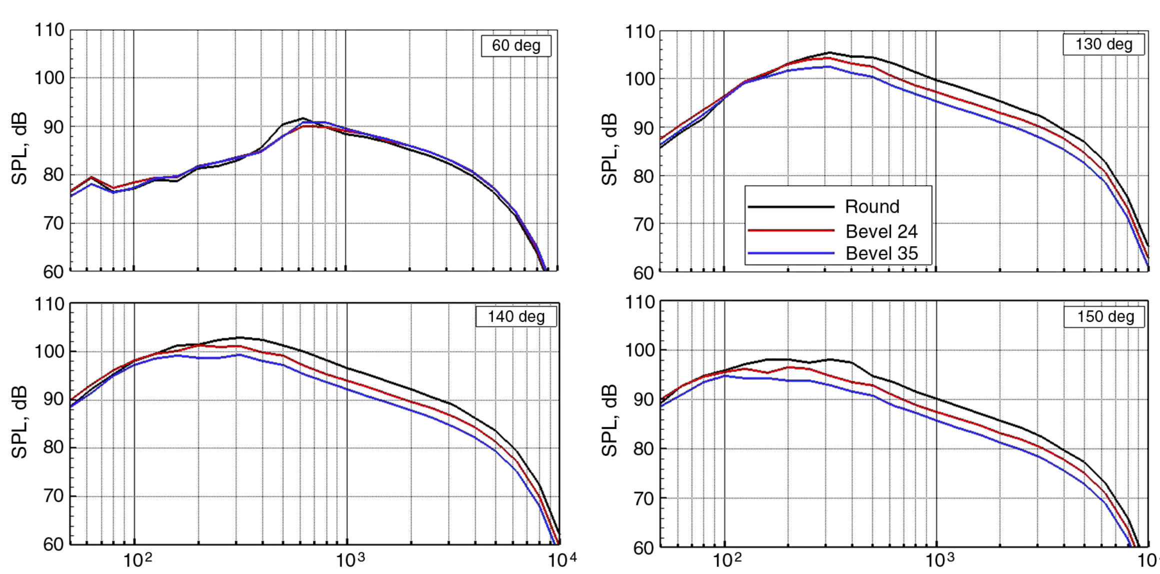

Fig. 5 Comparison of spectra for the round, bevel 24 and bevel 35 nozzles. MIL power, $M_t = 0.0$.

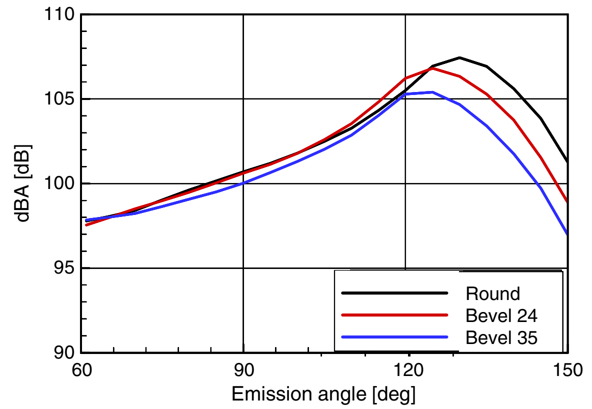

Fig. 6 Variation of dBA with emission angle for the round, bevel 24 and bevel 35 nozzles. MIL power, $M_t = 0.233$.

without incurring error. A 20% scale model is tested; as before, the spectra are extrapolated to full-scale conditions assuming a level flight at an altitude of 1000 ft.

Sample spectral comparisons are presented at static conditions; four polar angles of 60, 130, 140 and 150° cover a wide range. Figure 5 shows full-scale extrapolated spectra at military (MIL) takeoff power: $\mathrm{NPR} = 3.89$ and $T_t/T_a = 3.51$ for the round, bevel 24 and bevel 35 nozzles. The azimuthal angle is in the direction of the long lip of the beveled nozzle. There are minor modifications to the spectra at 60° due to beveling; similar trends are observed at all the angles in the forward quadrant. As we move aft, there is a reduction in levels at all the frequencies. The magnitude of the noise reduction is more pronounced in the peak radiation sector. Similar spectral trends are observed at other power settings. Once again, substantial reduction of noise is observed in the peak radiation sector in the aft quadrant. The variation of the dBA metric, which is used in noise exposure studies, is now presented. Figure 6 shows a comparison of the directivity of the dBA metric for the round, bevel 24 and bevel 35 configurations; the flight Mach number is 0.233. Consistent with the spectral trends, there is only a minor change at the lower angles; however a reduction of ∼4 dBA is observed in the peak radiation sector for bevel 35. The EPNL reductions for these two beveled nozzles are 0.7 and 2.1 EPNdB, respectively.

IV. Conclusions

The aeroacoustic characteristics of beveled nozzles and canted/swiveled round nozzles have been investigated in this Note, with the goal of clarifying the noise modifications due to jet plume deflection. Both the beveled nozzle and the canted round nozzle deflect the jet plume, thereby producing apparent similarities in plume aerodynamics. This superficial resemblance has led some to believe that the noise reduction observed with the beveled nozzle is solely due to the vectoring of the jet plume. Experimental evidence from single-stream convergent beveled nozzles, dual-stream geometry with convergent beveled primary nozzles, and single-stream convergent-divergent beveled nozzles are reviewed and discussed. An integral quantity, such as the PNLT, eliminates the ambiguities introduced in the true radiation angle with a fixed set of microphones when the jet plume is deflected.

The single-stream convergent jet has the largest plume deflection for a fixed bevel angle. When the same bevel angle is used for the primary nozzle of dual-stream exhaust geometry, but with an unmodified secondary nozzle, the larger mass flow of the secondary stream constrains the plume deflection. The deflection angle is consequently reduced; further, the deflection angle is dependent on the operating conditions in the two streams. The plume deflection for a convergent-divergent bevel nozzle is extremely small, and is within ±1.5° for a wide range of NPR and a range of bevel angles from 20 to 35°. Significant noise reductions have been measured in the polar angular range $\geq \sim 110°$ for all nozzle configurations. Note that this angular range corresponds to the peak noise radiation sector. The reductions in EPNL range from 2.1 EPNdB for the supersonic CD beveled nozzle to 3.5 EPNdB for a heated single-stream jet. It should be recognized that these values represent a large magnitude of noise reduction. In contrast, the effect of canting a round nozzle by the same deflection angle as for a single-stream bevel 45 nozzle yields a noise reduction of only 0.25 EPNdB. Therefore, it is clearly established from the measured data that the observed noise reduction for the different beveled geometries is due to the modification of the noise radiation mechanisms and not due to the deflection of the jet plume that can be achieved with canting. There should not be any confusion or misconception that the noise benefit obtained from the beveled nozzle is merely due to a kinematic change in plume orientation.

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