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DEVELOPMENT OF NARROW-BAND VELOCITY FLUCTUATIONS IN VORTEX FLOWS

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ABSTRACT[1]

The velocity field in the vicinity of the twin-tails of combat aircraft at high angle of attack exhibits small-amplitude fluctuations which are nearly periodic. Their frequency increases in direct proportion to freestream velocity, and inversely with model size, the relationship holding over a wide range of Reynolds number. The Strouhal number and spectral shape vary with angle of attack and wing leading edge sweep but appear to be relatively insensitive to leading-edge shape. The phenomenon is general to leading-edge vortex flows for angles of attack ranging from 15 to 40 degrees depending on the geometry. It is a probable driver of tail fatigue. The search for the origin and mechanism of this phenomenon is summarized. Empirical correlations are developed for various configuration shapes and isolated wing planforms. A 1/32-scale model of an F-15 and a 59.3-deg. cropped delta wing are used for detailed studies. Cross-spectral analysis of hot-film anemometer signals traces the fluctuations upstream along a helical path. Surface streaklines visualized in two orthogonal planes show nearly-spanwise vortical structures amplifying and propagating downstream, suggestive of cross-flow instability. Spectra obtained using laser velocimetry (LV) confirm the hot-film data. LV data phase-synchronized with a surface hot-film signal capture the size, partial shape, and convective speed of cross-flow vortical structures as they move downstream. Counter-rotation is observed. Remaining hypotheses for the origin of these fluctuations are based on centrifugal instability of the flow beneath the vortex center, cross-flow shear layer instability and unsteady phenomena associated with the interaction of the secondary vortex with the surface. Preliminary attempts to modify the spectra based on the surface-origin hypotheses are successful.

NOMENCLATURE

b	=	wing span
c	=	root chord
$\bar{\bar{c}}$	=	mean aerodynamic chord
DW	=	delta wing
f	=	frequency, cycles per second
G()	=	nondimensionalized autospectral intensity function
L	=	length
mac	=	mea aerodynamic chord
n	=	reduced frequency, $f\bar{\bar{c}}/U$ unless specified otherwise
Re	=	Reynolds number
U	=	freestream speed
u,v,w	=	streamwise, lateral, and vertical velocity, body coordinate system
$\bar{u},\bar{v},\bar{w}$	=	time-averaged velocity of u, v, w
$\hat{u},\hat{v},\hat{w}$	=	fundamental periodic velocity of u, v, w
u',v',w'	=	random fluctuating velocity of u, v, w
x',y',z'	=	body coordinate system, origin fixed to model apex
X,Y,Z	=	tunnel coordinate system, origin fixed to model apex
α	=	angle-of-attack
β	=	angle between the root chord and a surface ray originating from the apex
Λ	=	wing leading-edge sweep
ϕ	=	phase of cycle
θ	=	angle between the root chord and a ray originating from the apex in the vertical plane

INTRODUCTION

In the late 1980s, a project at our laboratory aimed to define the environment of twin vertical tails at high angles of attack in order to help improve design specifications for future aircraft. The flow around a 1/32-scale F-15 was visualized using tufts and laser sheets, and the velocity field at $\alpha = 20$ deg. was mapped using laser velocimetry[1]. The time-averaged results were verified by comparison with a Navier-Stokes solver[2]. Fig. 1, from

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Ref. 2, shows some of the features of the flow. Strong vortex cores are not seen in this flow, anywhere over the wings, very much unlike the situation encountered over an F/A-18 with its highly-swept leading-edge extensions. In fact the flow visualization was conducted precisely to detect such vortices, their bursting, and the trajectory of the highly-turbulent region expected: our complete failure to detect any such feature forced deeper studies of the problem.

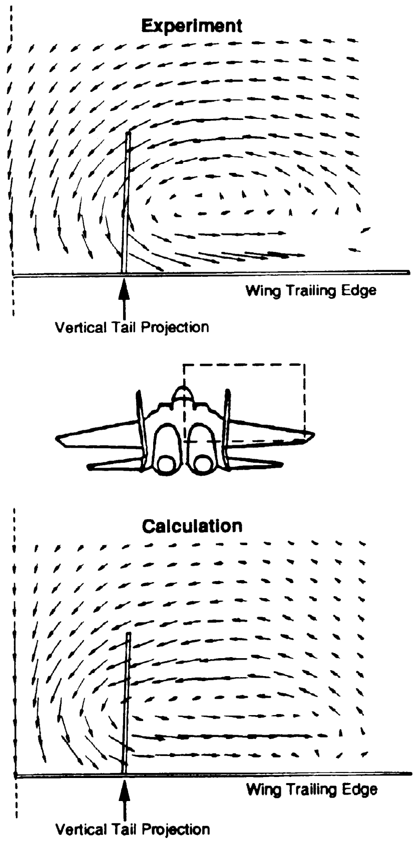

Figure 1. Measured and computed time-averaged cross-flow velocity at the wing trailing edge plane of a 1/32 scale F-15 at $\alpha = 20$ deg., Mach 0.1 (Ref. 2).

The autospectra of velocity fluctuations were measured over a rigid model using hot-film anemometer sensors to better understand the frequency distribution of the fluctuation energy in the flow near the tails. The prevailing model of tail vibrations was that of structural response to "broadband turbulence". The hot-film spectral results were a surprise. Fig. 2[3] shows a small spectral peak beginning over the wing surface, then amplifying, shifting lower in frequency, and finally focusing most of the energy of the fluctuations into a dominant, narrow band of frequencies enveloping the upper half of the vertical tails. Thus it appeared that tail vibrations might be "driven" at a very well-defined frequency, amenable to smart techniques for reducing these vibrations if the phenomenon is understood. The search for this understanding is the subject of this article.

In the rest of the article, we use f_{pk} to denote the frequency of the spectral peak. The spectrum of velocity fluctuations does rise to a sharp peak in most cases. Sometimes, two closely-spaced peaks are seen. Where there is uncertainty about the peak, we now use a "moving window average" of three successive frequency intervals to determine the correct frequency of the spectral peak from experimental data. The Strouhal number computed using this frequency, freestream velocity and some length scale of the model is of most interest:

$$\mathbf{n} = f_{pk} L / U \quad . \qquad (1)$$

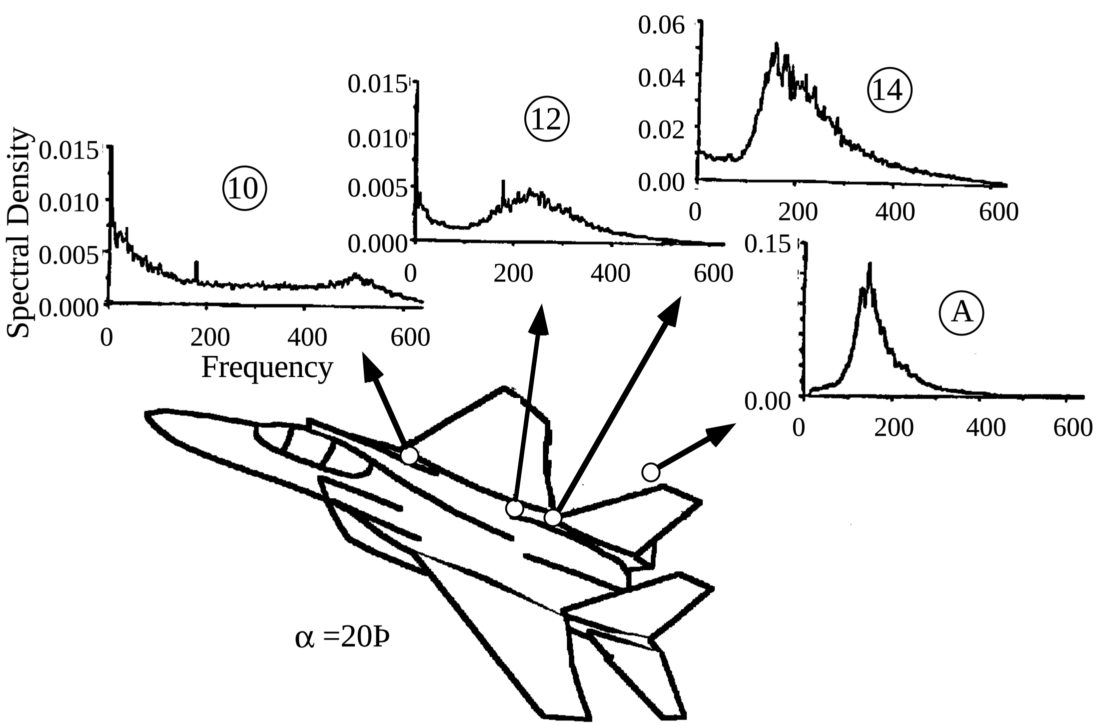

Figure 2. Hot-film velocity spectra measured above a 1/32- scale model of the F-15 at 33 m/s. (Ref. 3).

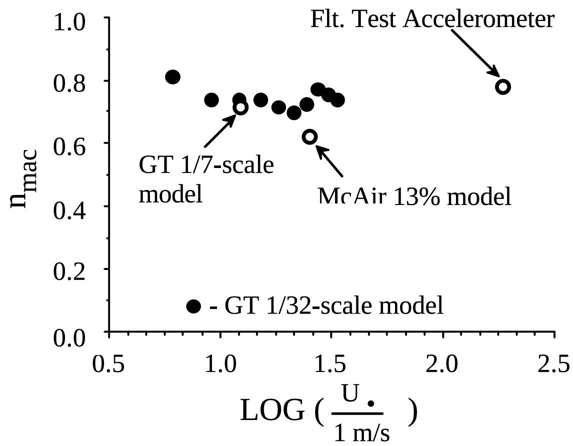

Figure 3. Strouhal number based on mac over F-15 models and flight test data at α =20 deg. (Ref. 3).

Figure 3 shows that $f_{pk}L$ for the F-15 scales with U , all the way from wind-tunnel tests at 7 to 33 m/s on a 1/32-scale model, past tests of a 1/7-scale model at 13 m/s and 13% scale model at about 28 m/s (Ref. 4), and matches the frequency of the tail *vibrations* measured at the top of a full-scale aircraft tail at Mach 0.6. This spans three orders of magnitude in Reynolds number and inevitable variations in leading-edge shapes, surface smoothness, and freestream turbulence levels. For the F-15, f_{pk} also decreased with increasing angle of attack (as did the tail vibration frequency in the flight test), but in a complex manner. While this matching is a very encouraging finding, this does not tell us what particular length dimension is of physical significance, and hence at the time we could not determine a numerical value of the Strouhal number **n** with any significance: we just knew that increasing the size of the model by a factor would reduce the frequency by the same factor. Until better scaling parameters were found, we used Strouhal number values based on mean aerodynamic chord.

OBSERVED FEATURES

Refs. 4-16 provide representative samples covering much of what is published on the dynamics of leading edge vortex flows and vortex breakdown. We will focus for now on the specific problem of tail vibration relevant to aircraft with moderately-swept wings. On such configurations, the narrow band phenomenon is observed even at angles of attack above the range where vortex core bursting is observed over the wings. An example is the F-15.

Sharp-Peaked Velocity Spectra

Ref. 4 describes wind tunnel tests on a 13% F-15 model using rigid tails, with hot-wire measurements, tuft tests, and smoke trail photos. The smoke tests attempted to determine a trajectory for the flow impinging at the top of the vertical tails and found that this passed above the "gun bumps" on the engine inlets. The hot-wire results showed sharp-peaked spectra near the rigid tails, just as we measured in Ref. 3. The value of $f_{pk}L$ from these tests is seen on Fig. 3.

Broadband Pressure Spectra under Tail Boundary Layer

Triplett[5] reported surface pressure and accelerometer data on F-15 model tails in wind tunnel tests, using both rigid and elastically-scaled tails. The surface pressure fluctuations, measured with Kulite transducers on the tail surface, showed relatively broadband spectra for the rigid tails and of course sharp spectral peaks at the vibration frequency for the elastic tails. This appears to be one of the origins of the "broadband turbulence" hypothesis where the tail structure was thought to respond at its structural modes to a broadband forcing from the turbulent flow. Note that surface pressure transducers capture the pressure fluctuation beneath a turbulent boundary layer: the small-amplitude narrow-band velocity fluctuation may not show up in these data. We were unable to duplicate these results in a quick test: our amplifiers were too noisy to extract the Kulite signals from noise at tunnel speeds up to 33 m/s. Recently, Ashley et al.[14] have pursued active-control strategies to cancel vibrations of the F-15, regardless of precise details of the flow excitation.

No Strong Vortex Cores over F-15

Ref. 15 confirmed our observation of Ref. 1 that the flow over an F-15 at $\alpha \geq 20$ deg. does not contain strong vortex cores whose "bursting" would explain the observed fluctuations. We note that our observations of the overall time-averaged F-15 flowfield were directly confirmed by the Navier-Stokes calculations of Ref. 2, as shown on Fig. 1.

Quasiperiodic

The sharp-peaked spectra as shown in Fig. 2 indicate a periodic phenomenon with a very narrow band of frequency. Ref. 16 obtained similar results on a canard-wing fighter configuration with moderate sweep. The signal, however, exhibits considerable phase "jitter" and cycle-to-cycle variation in structure shape, as discussed later. While the phase is not as chaotic as in the case of natural instabilities of an unforced shear layer, it is far from being as regular as, for instance, a rotor flowfield.

Seen on Many Configurations

We have measured such spectra over many configurations at angle of attack. These include 1/32 scale F-15s (with and without tails, engine through-flow, and inlet droop), above the burst-vortex (and above the tops of the tails) of a 1/32-scale F/A-18, an F-117, a generic double-swept delta wing/body of revolution model (Ref. 17), a YF-22, isolated wing planforms equivalent to most of

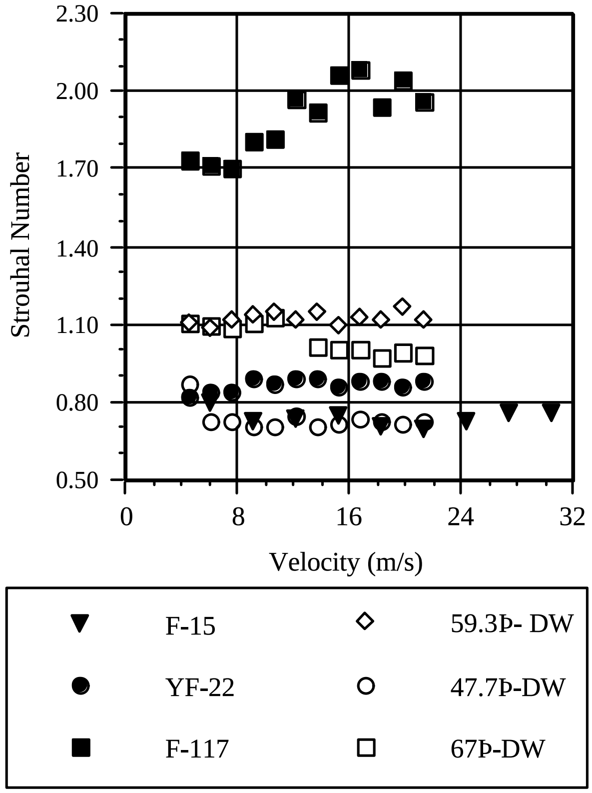

Figure 4. Comparison of scaled frequency with freestream speed for various models (Ref. 18): α = 20 .

those models, and a 59.3-deg. delta wing. In each case the measuring location was selected upstream of where the top of one of the tails would be located. In every case except the F-117 (whose geometry appears to generate several vortices), the f_{Pk} vs. U line remained straight. Fig. 4 from Ref. 18 shows some of these data.

Empirical Prediction: Full Configurations and.Flat-plate Wings

The above tests showed that the presence of tails had nothing to do with the generation of the fluctuations. The effect of the fuselage and the rest of the configuration on the Strouhal number was noticeable but secondary, except for the F-117. The scale-model results of Ref. 20 provide a starting point for empirical prediction of possible driver frequencies for tail vibration; whether the results are as encouraging as those on the F-15, can only be determined from flight tests. We thus see that the basic phenomena can be seen on simple wing shapes: precise understanding of the frequency selection and amplification requires studies of "representative" configurations including the fuselage shape.

Spectral Characteristics and Scaling on a Delta Wing

Having determined that the basic phenomenon existed in the flow over an isolated, sharp-edged delta wing, we selected a ~60-deg. delta wing to enable comparison with published data and with the extensive work elsewhere on vortex core bursting. This wing has beveled lower leading edges and trailing edges, and has been used in extensive measurements in two wind tunnels and is part of the generic wing-body model used in Ref. 17. Hubner and Komerath[19] plotted contours of f_{Pk} measured in a vertical cross-flow plane at the trailing edge at α = 25 deg. The peak frequency is nearly constant over most of the plane, away from the vortex core. In the core region (post-burst), the frequency is lower, the spectrum is broader, and the amplitudes are high. Figs. 5 & 6 confirm the features seen on the F-15: the frequency decreases downstream along rays (inversely proportional to local span), the amplitude increases sharply, and the spectrum focuses into a narrow peak. Further downstream in the wake of the model, the peak frequency leveled off and the intensity decreased. Fig. 6 shows that the fully developed peak frequency scales with projected-chord for the isolated wing, as opposed to the full F-15 configuration, where Ref. 3 found a much sharper variation of the peak frequency with angle of attack.

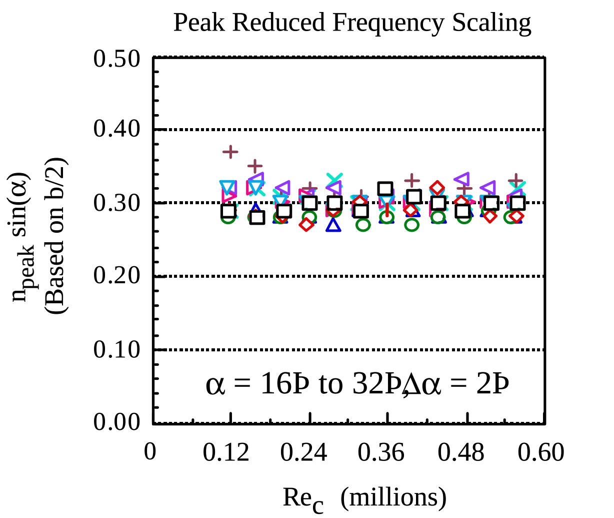

Figure 6. Peak frequency vs. Reynolds number with respect to a nominal wake scaling for a 59.3 delta wing (Ref. 19).

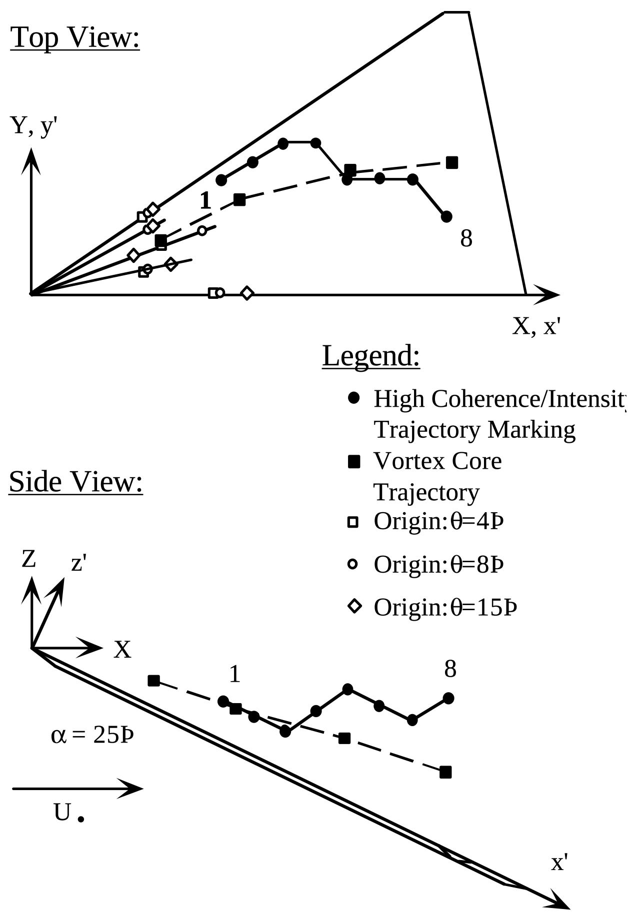

Figure 7. Trajectory of high coherence and energy for a 59.3 delta wing (Ref. 19).

Coherence Tracking

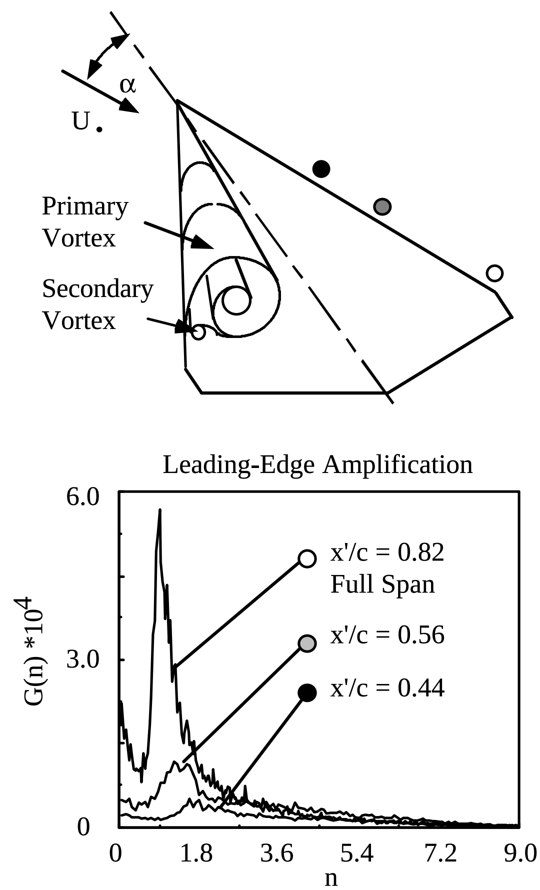

Figure 5. Spectra amplification and focusing along the leading-edge of a 59.3 deg. delta wing (Ref. 19).

Starting with two hot-film sensors at the trailing edge plane, we "walked" upstream along the path of highest coherence and intensity at the frequency f_{Pk}. As we moved upstream, f_{Pk} changed, increasing upstream as noted on Fig. 5. The trajectory is shown in Fig. 7, from Ref. 19. The structures responsible for these fluctuations appear to originate near the surface, around 1/3 chord from the apex for this case, and to take a helical trajectory around the periphery of the vortex. Thus it is not surprising that the smoke trajectory test of Ref. 4 showed the tail being hit by flow coming past the F-15 gun bump.

Surface Streakline Fluctuations

Having established the results of Figs. 4-7, we concentrated attention at the surface. Smoke was entrained into the surface layer through small surface ports. A laser sheet parallel to the wing surface illuminated a 2 mm thick region above the surface. Fig. 8 shows the surface streaklines. They are oriented approximately spanwise (as is well known), but also show a periodic "waving". We counted the frequency of this waving, by manually checking the change in frame code of the video tape over

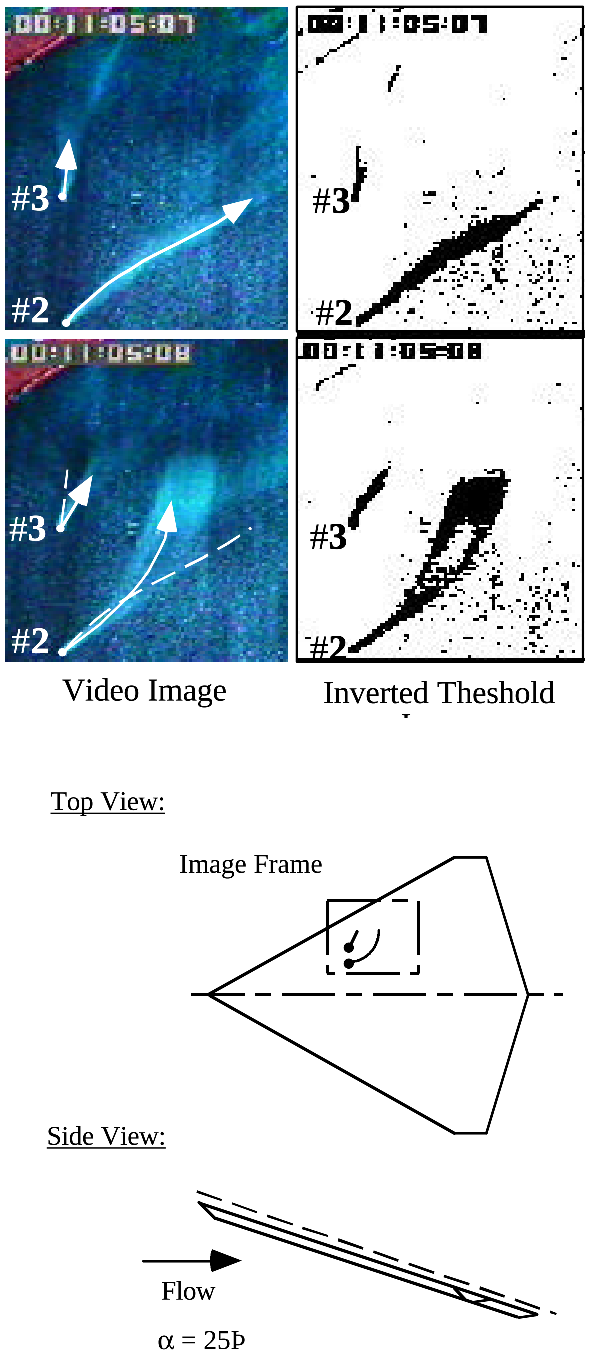

Figure 8. Visualization of surface streakline fluctuation (Ref. 20). Inverted images highlight streaklines.

several cycles of the waving. The tunnel speed and model size were chosen low enough to keep the frequency in the 10 Hz range, well below the 60 Hz framing rate of the camera . *The frequency fell on the f_{Pk} vs. U straight line for this wing,* as first reported in Ref. 20. This was repeated, with more ports, and two different tunnel speeds. A hot-film spectrum acquired near one of the ports, at the higher speed, verified the video-counted frequency directly.

We were seeing evidence of structures of the correct frequency, very near the surface. The amplitude of the waving increased downstream. Also, viewing the waving of streaklines from all ports together, it was evident that this was not a "stationary" phenomenon: the waving was sequential, clearly indicating that the structures were moving downstream.

Streakline Waving and Vortical Structures

Next, a chordwise vertical visualization plane cut across these streaklines. Fig. 9[20] shows vortical patterns of smoke, lifting off the surface layer and into the main vortex flow above. Again, these moved downstream. At the time, the sudden lifting was not understood: we were looking for a cross-flow shear layer roll-up. Oneinterpretation is sketched in Fig. 9.

<u>TESTED HYPOTHESES</u>

Over the years, we have tested many hypotheses about these fluctuations.

1. "Gun-bump" and "engine-inlet vortices" were ruled out: drooping the inlet, altering inlet flow (external acceleration, deceleration, and blocked) had no effect[3] on the spectra near the tails.
2. Removing the tails caused no change in the spectra measured upstream of the tail location.
3. In Ref. 5 we showed that a large vertical "splitter plate" along the spine of the F-15 model did not affect the spectra. This ruled out hypotheses about unsteady lateral coupling between the wing/forebody vortex systems.
4. Entrained vortices rotating around the primary vortex rotate at the wrong frequency. Forebody vortices entrained and rotating around the wing vortices might cause fluctuations at a fixed sensor. Some such cores are seen in videotapes from the generic wing-body model[17]. Tangential velocity data showed that these structures would pass the hot-film location at a completely wrong frequency.
5. Wing vortex shedding occurs only at a much higher angle of attack. What we see has nothing to do with large-scale shedding as seen by Redionitis et al.[21] at very high (>45 deg.) angles of attack: note that we see and measure a vortex velocity field which is quite steady in the mean.
6. The frequency of discrete vortical structures in the leading edge shear layer, attributed to Kelvin-Helmholtz instability, scales as the square root of the freestream velocity[22,23]. At freestream speeds higher than those used in water tunnels and flow visualization, the discrepancy between this frequency and the f_{Pk} measured by hot-film sensors begins to glare. The experiments in Ref. 23 did not connect the low-speed "control" results and the higher-speed frequency measurements. This hypothesis appears to

have been discarded (Ref. 21). Finally, using photography and direct frequency measurement, we have confirmed that the shear layer frequency is not in the range of interest.

7. The frequency of rotation of spiral breakdown matches the measured f_{Pk}. However, spiral breakdown immediately leads to chaotic flow downstream. Thus, on wings where a strong core does exist in the region where these sharp-peaked spectra are measured, a "chicken-or-egg" question arises: Does spiral breakdown cause the surface fluctuations or vice versa? To answer this, consider a moderately-swept wing (the 45 deg. F-15 wing) at $\alpha > 20$ deg. Here an un-burst core cannot be detected; yet the fluctuations appear to originate near the surface, *and grow and focus downstream*, in an otherwise highly turbulent flowfield. Thus *the surface layer fluctuations are the more basic phenomenon*. Spiral core breakdown does not explain results on moderately swept wings.

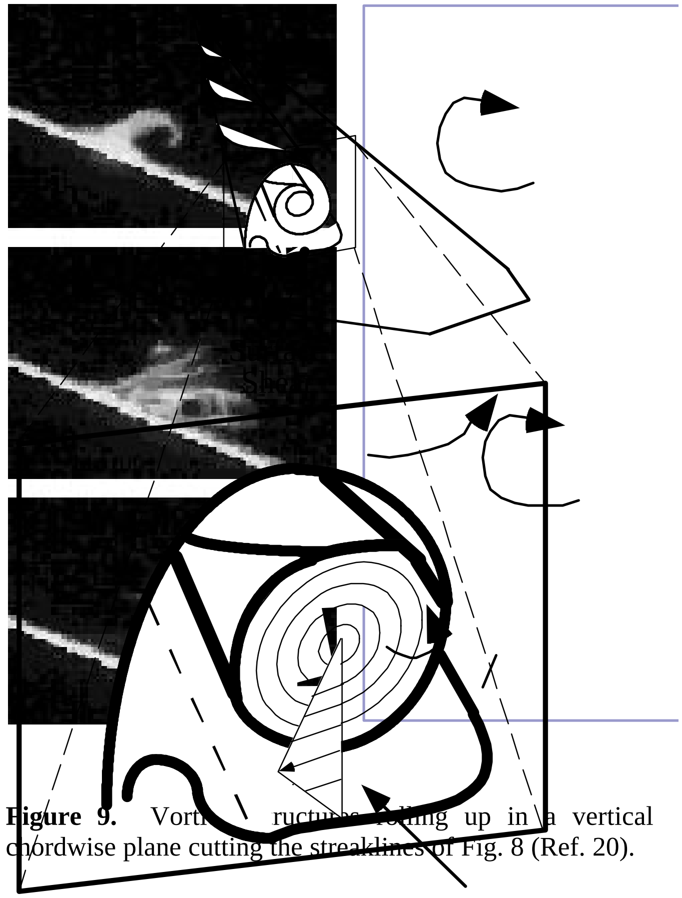

Figure 9. Vortical structures rolling up in a vertical chordwise plane cutting the streaklines of Fig. 8 (Ref. 20).

Figure 10. Decelerated flow region between the surface and the vortex core.

SURFACE SHEAR HYPOTHESES

Unsteady Secondary Separation due to Vortex/Surface Interaction

Visbal[13] has observed fluctuation of the secondary separation line in computations. We see this too, in visualization above the 59.3-deg. delta wing, though intermittently. Is this a cause, effect or something in between? The evidence to-date does not permit a clear answer.

Centrifugal Instability

Rayleigh's second theorem on the instability of velocity profiles[24, 25] states that the profile is unstable if, anywhere in the flow,

$$\frac{d(rV)^2}{dr} < 0 \qquad (2)$$

where V is the tangential velocity and r is the radial distance from the center. The presence of axial velocity generally narrows down the range of this instability, as seen by many researchers. The occurrence of this condition at the surface under the primary vortex is sketched in Fig. 10. Deceleration at the surface must cause the tangential velocity profile of the vortex flow to drop sharply near the surface, leading to possible centrifugal instability of the flow. A counter-rotating pair of vortices must then be generated at the "preferred" frequency and spatial scale, lift off, and go around the periphery of the vortex. In the front parts of the wing, these structures may go around the vortex and interact again with the surface layer, focusing the roll-up into themselves and amplifying greatly. This phenomenon, given a velocity profile with the right unstable characteristics, is essentially independent of Reynolds number. In a helical flow, the measured velocity disturbance at a fixed point due to the passage of these counter-rotating structures will be merely a periodic velocity fluctuation. We proceed to detail recent evidence of such structures, after considering the obvious question: Why wasn't this seen before?

Re-examination of the literature on leading edge vortices encourages this model. Ludwieg[6] showed instability of vortex flows in annular regions bounded by solid walls, and predicted instability when streamline inclinations reached about 42 degrees (see Fig. 9 for our streakline orientations). He proposed that this type of three dimensional disturbance causes the breakdown of free vortices over delta wings. Unfortunately, research since then appears to have focused on the core of the vortex. Ludwieg's approach was rejected by many subsequent reseachers because the solid wall boundary condition was considered inapplicable to the core flow instability problem[9]. In addition, stability of the core flow was shown when there was a substantial axial velocity in the core. Again, note that our interest is not in the development of instability of a vortex core flow: it is in the development of organized structures around the periphery of a turbulent vortex flow where the core may have already become chaotic, and the axial velocity in the core may be insignificant. In fact, in the post-burst flowfield, the cross-sectional velocity profile of the vortex is known to be essentially a solid body rotation. Here, Ludwieg's analysis should be re-examined. Leibovich[9,10] emphasizes that the role of asymmetric and 3-D disturbances is simply not known, and in later publications considers both symmetric and asymmetric disturbances to a cylindrical vortex core flow. Stability criteria developed for inviscid columnar vortices, based on the axial and azimuthal gradients, are sufficient to explain the formation of spiral disturbances similar to Ludwieg's. Disturbances of this nature could explain the observed focusing of flow energy away from the core. Escudier[8] shows why much of the research on vortex stability would not have found a centrifugal instability mechanism: it generally assumed an inviscid, steady laminar flow around the core, and thereby would not have the shear at the wall which produces the unstable velocity profile in this case. The assumption of inviscid flow has been justified on the grounds that vortex breakdown phenomena appear not to depend on Reynolds number except for the core velocity profile. Our quasiperiodic disturbances also are independent of Reynolds number, but shear at the wall is necessary to set up the unstable region. The precise size of this region appears not to play a role.

Quantitative Evidence of Counter-Rotating Structures

In Ref. 26 we verified that spectra obtained with a fiber-optic laser velocimeter (LV) are the same as those obtained with a surface hot-film sensor immediately upstream of the LV measurement location. We obtained ensemble-averaged traces of velocity fluctuations, measured from the LV data phase-synchronized with a trigger generated from the hot-film signal. The amplitude of the phase-locked variation was only about 20% of that measured from the spectral energy at this frequency, primarily because the later portions of the cycle were smeared considerably: this is because the phenomenon is "quasiperiodic", not quite the same in phase or frequency from cycle to cycle. However, we used the data to generate a map of the periodic fluctuations in a vertical plane as shown in Figs. 11 a and b. *They show quantitative evidence of counter-rotating, periodic structure in this section.* It is emphasized that these data underestimate the strength of these structures because of the deviations from periodicity. The size of these structures is bigger than the measuring grid.

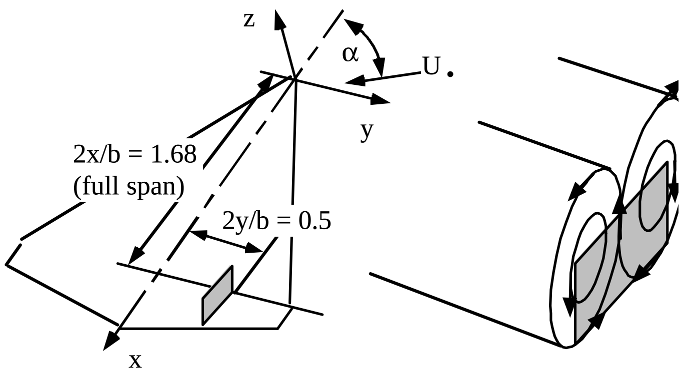

Figure 11a. LV measurement plane schematic, showing orientation of counter-rotating structures observed.

Spectra Are Sensitive to Surface Disturbances

The last piece of evidence for the surface-layer hypothesis is that we are able to modify the spectra without significantly modifying the overall flowfield or the lift and drag, by placing small (height on the order of the boundary layer thickness) fences on the surface at different orientations. This is shown in Fig. 12 along with various fence orientations. Ref. 4 also reports surface modifications using inboard fences, aligned with the freestream direction and much larger than the boundary layer: these produced roughly a 50% attenuation of tail tip pod accelerations on the F-15.

Görtler vortices or Cross-Flow Shear Layer Instability?

The formation of asymmetric structures in an environment with mean streamline curvature indicates an interaction between the centrifugal forces and the radial pressure gradient of the primary vortex. Schlichting[24] and the review by Saric[25] indicate that counter-rotating vortex pairs of this type can properly be called Görtler vortices. The upflow between these structures, cited as evidence of Görtler vortices in previous experiments cited in Ref. 25 is

Figure 11b. Phased-syncronized, fluctuating velocity vector plots, $(\hat{u} + u')/U \; \mathbf{i} + (\hat{w} + w')/U \; \mathbf{k}$. Successive images with respect to the phase of the trigger cycle show structure counter-rotation and convection near the surface.

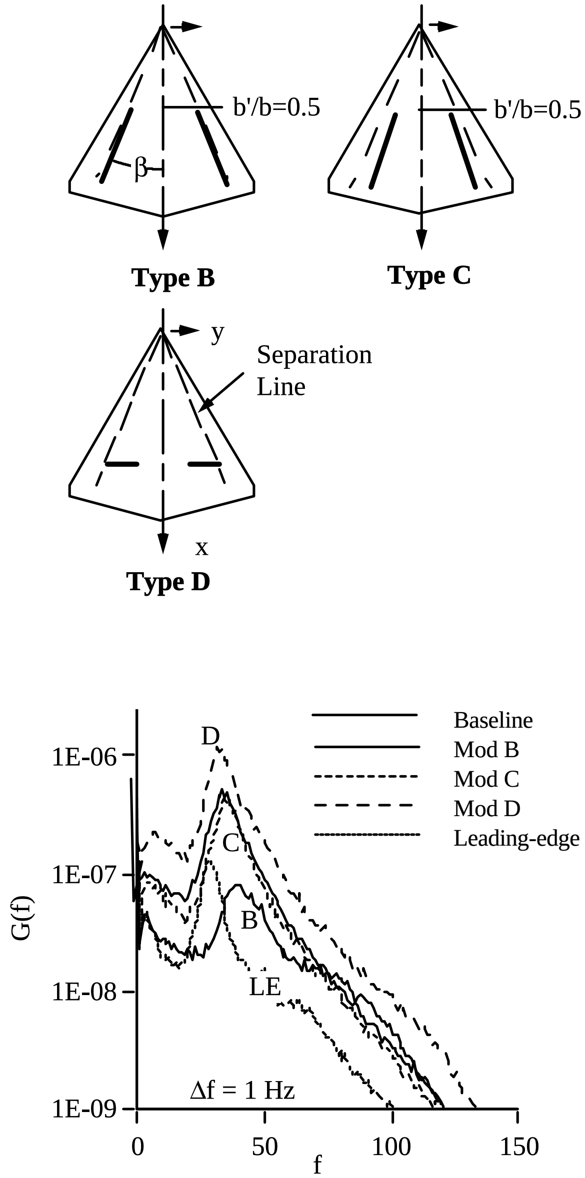

Figure 12: Various orientations of fences on the surface, and their effects on the velocity spectra (Ref. 26).

also seen in the LV data and the behavior of the surface smoke streaklines. On the other hand, the near-wall region has a severe cross-flow shear layer, and instability of this shear layer may also play a role. It is easy to conceptualize such a flow tending to produce roll-up, but not counter-rotating structures. Research on cross-flow instabilities on swept wings has focused in the area of boundary layer transition and appears not to have reached the high-angle-of-attack case of interest here.

In concluding this section, we note strongly that the phenomena originate in the region between the primary vortex core and the wall. The right answer is probably a combination of centrifugal instability, cross-flow shear instability, unsteady boundary layer separation due to the secondary vortex, and perhaps other as-yet-unseen mechanisms.

SUMMARY OF PRESENT KNOWLEDGE

It is clear that nearly-periodic drivers exist in nominally steady vortex flows for a wide range of conditions. Empirical prediction of the possible driver frequencies for a given configuration can be obtained by measuring velocity spectra over scale models in low-speed wind tunnels at varying speeds and angles of attack. Where structural modes coincide with the driver frequency, vibrations may be expected. Critical vibration conditions will depend on the structural dynamics. The Strouhal number of velocity fluctuations on scale models matches that of tail vibration in flight test on the F-15; however, this is just one datum, and more data are needed from flight tests on other configurations to verify that such an approach will work for other configurations. Success with passive control techniques is encouraging, and indicates that first-principles based prediction and suppression are possible. Success would lead to a broad-ranging prediction capability on a very important problem, and guide flow modification techniques to prevent the amplification of these fluctuations. Combined with the empirical findings, this can also lead rapidly to a design-stage capability to avert tail buffeting problems.

There are some clear differences between the violent fin buffeting encounted in burst-vortex flows, and the lower-amplitude periodic driving in the F-15 flows, as seen here. The latter phenomenon can drive insidious fatigue cracking over hours of operation at high angles of attack. This can be a serious problem as aircraft age, and newer engines and tactics require pilots to spend a longer portion of their flight hours practicing maneuvers involving high-α operation.

To achieve first-principles-based prediction, highly-resolved computations are required. Identification of the crucial phenomena is essential to this effort. After trying out many hypotheses, we see that the basic phenomenon is one which can be simulated using simple configurations, though precise prediction of frequencies does require inclusion of the full configuration. The phenomenon exists in every swept-wing vortex flow studied to-date, for angles of attack ranging from 15 to 40 degrees depending on the geometry. Our present understanding leads us to focus on flow structures originating in the surface shear layer. This is strenghtened by the observations of Ref. 13 where vortex-surface interactions are seen to cause fluctuations of the leading edge shear layer. The flow visualization and the velocity data synchronized with surface hot-films provides strong support for the argument that counter-rotating vortical structures exist under the primary vortex core, and that these amplify and convect downstream, causing nearly-periodic velocity fluctuations everywhere in the vortex flow.

It is argued that these structures correspond to expectations based on the centrifugal instability of the primary vortex flow as it is decelerated by wing surface shear. This also explains insensitivity of the Strouhal number to Reynolds number. The success in modifying the spectra without modifying the lift characteristics further supports the surface-origin hypothesis. The basic issue of secondary separation vs. centrifugal instability or other mechanisms remains to be resolved.

Measurement Uncertainty

As with all experimental results, measurement uncertainty must be quantified. The freestream velocity of the tunnel is accurate to within 1%: this is a major uncertainty for such a quantity, but its frequency content is extremely low; far below 0.1 Hz, which is the high-pass filter cut-off for fluctuating data. The spectra presented here were each obtained by ensemble-averaging 100 sample blocks of data. The analog-digital converters used in every case, whether with hot-film or LV data had a 12-bit mantissa and 4-bit exponent, with the signal level optimized to use the full scale in each case using amplifiers and on-line monitoring. The frequency response of the instrumentation exceeded the highest frequency of interest by at least a factor of 3 (the worst case was where streakline fluctuation frequencies of up to 10 Hz were counted using a 60-frame-per-second video system. Spatial dimensions are measured with accuracies of 0.25 mm for spans and chords and 0.25 deg. for angles; probe positioning accuracies are nominally 25 μm, but the measurement uncertainty of 0.25 mm controls this. The worst-case uncertainty is in the acquisition of phase-resolved LV data; deviations from periodicity of the trigger signal cause underestimation of the ensemble-averaged data by up to a factor of 5. In this case, improved measurements would sharpen the phenomena which we have identified. In conclusion, the uncertainties of the results presented are essentially less than the symbol sizes and line thicknesses dictated by the paper format.

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