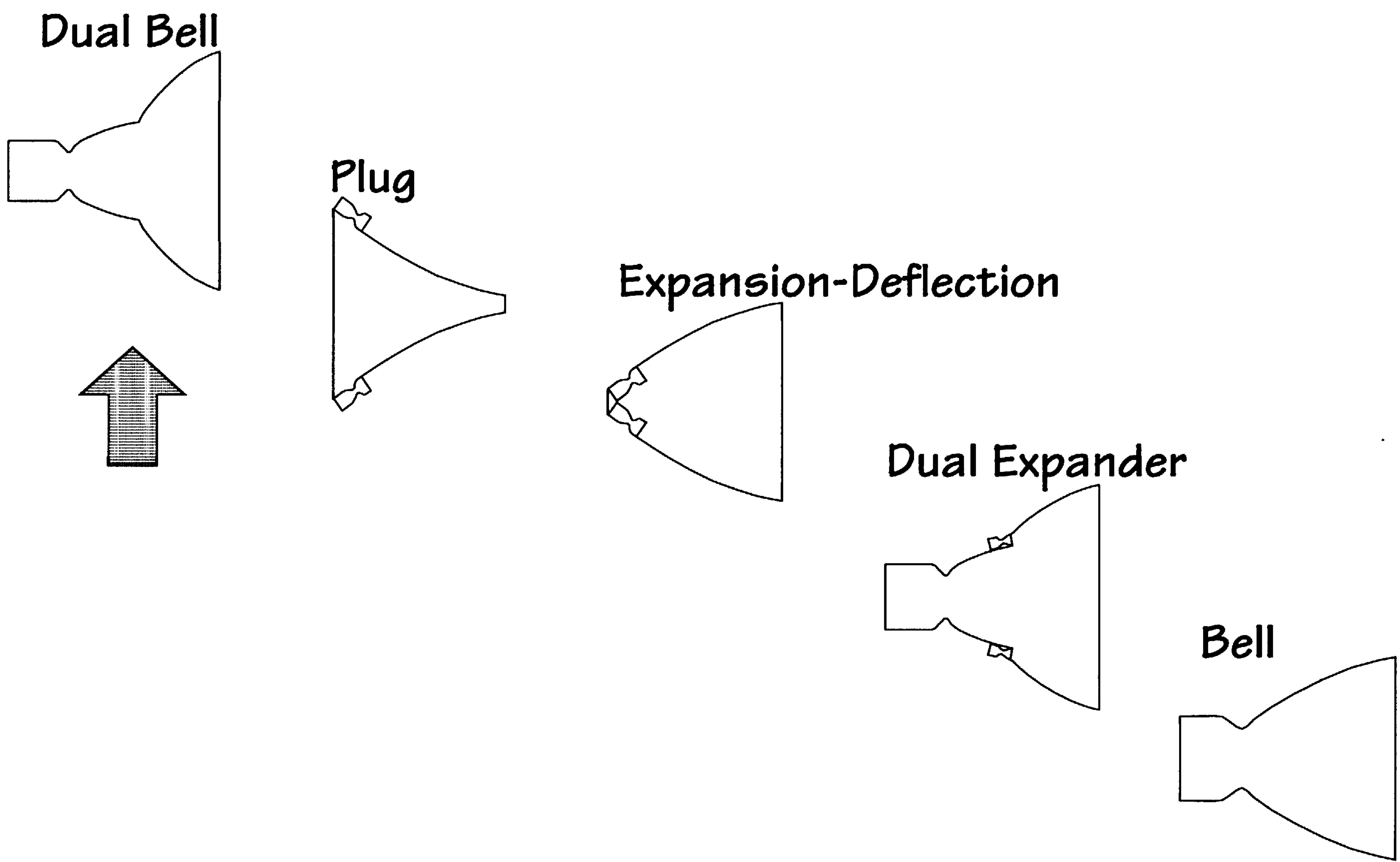
STD Fluids Workshop 2001

Fluctuating Pressure Data from 2-D Nozzle Cold Flow Tests (Dual Bell)

TD63/Tom Nesman

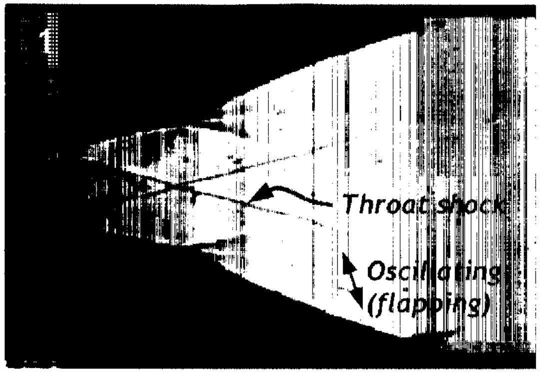
Introduction

- Rocket engines nozzle performance changes as a vehicle climbs through the atmosphere
- An altitude compensating nozzle, ACN, is intended to improve on a fixed geometry bell nozzle that performs at optimum at only one trajectory point
- In addition to nozzle performance, nozzle transient loads are an important consideration
- Any nozzle experiences large transient loads when shocks pass through the nozzle at start and shutdown
- Additional transient loads will occur at transitional flow conditions
- The objectives of cold flow nozzle testing at MSFC
  - CFD benchmark / calibration
  - Unsteady flow / sideloads
- Initial testing performed with 2-D inserts to 14" transonic wind tunnel
- Recent review of 2-D data in preparation for nozzle test facility 3-D testing
- This presentation shows fluctuating pressure data and some observations from 2-D dual-bell nozzle cold flow tests


Dual Bell
Plug
Expansion-Deflection
Dual Expander
Bell

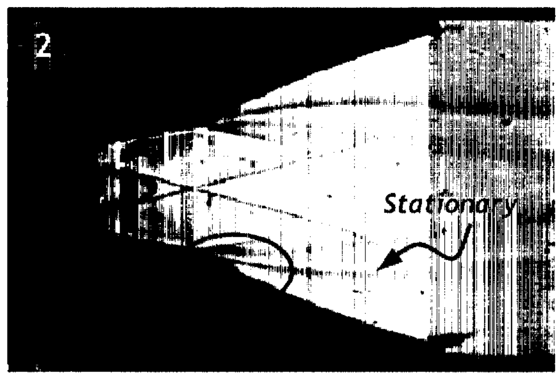
Nozzle Flow Patterns

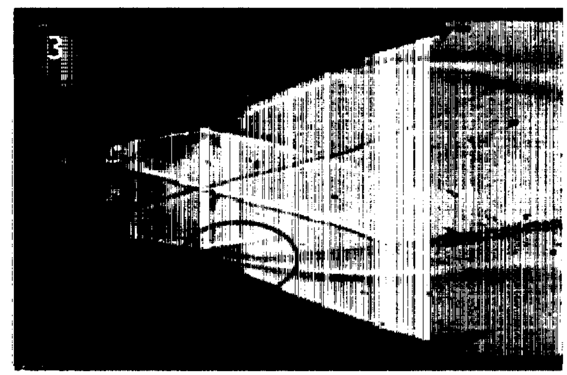
$29 < P_0/P_{exit} < 51$



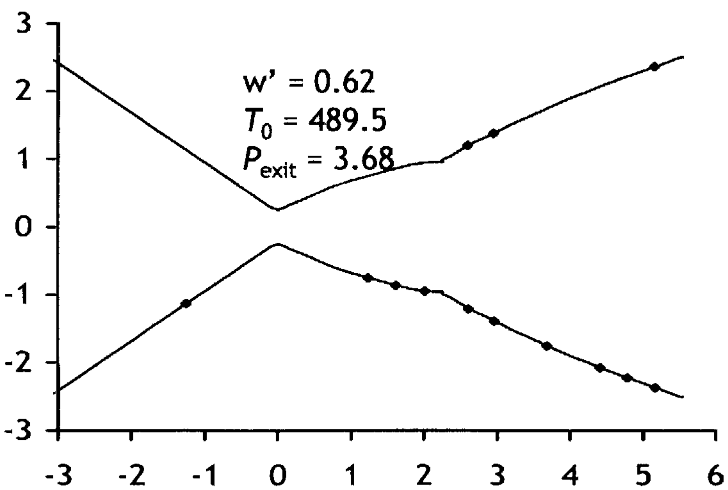
Dual Bell Nozzle

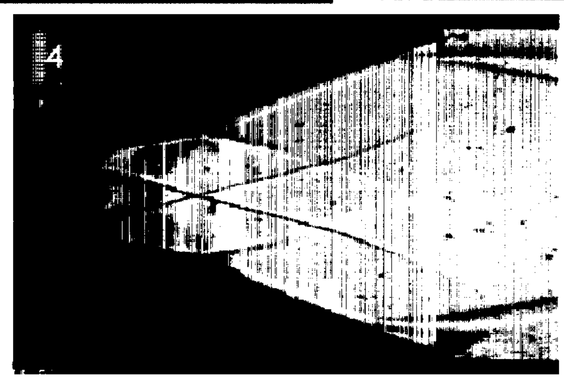
1	13:58:52:9	flapping at transition	29
2	13:58:55:1	steady shocks at nozzle transition	↓
3	13:59:00:6	top shock jumps (strong sideload)	P_0/P_{exit}
4	13:59:01:4	bottom shock jumps	↓
5	13:59:21:1	entire nozzle flows full	51

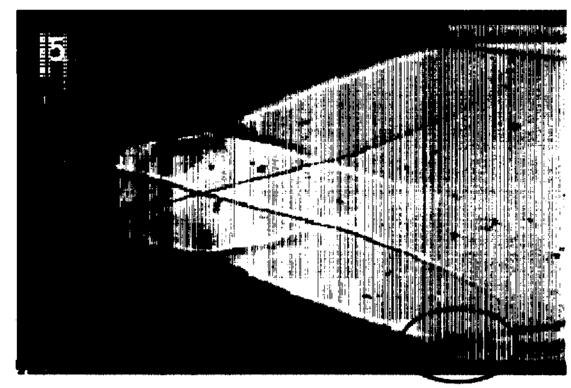




schlieren
(vertical filter array)







From TWT 746 run 21/0 11/03/1995

Dimensional Analysis

Strouhal scaling uses "reduced frequency"

- assumes the non-dimensional frequency is same ... model to full-scale

$$\left.\frac{f\ell}{U}\right]_{Model} = \left.\frac{f\ell}{U}\right]_{FullScale}$$

- furthermore, for the same Mach number then

$$\frac{f_M \ell_M}{M \cdot a_M} = \frac{f_{FS} \ell_{FS}}{M \cdot a_{FS}}$$

- so that

$$f_{FS} = f_M \cdot \left(\frac{\ell_M}{\ell_{FS}}\right) \cdot \left(\frac{a_{FS}}{a_M}\right)$$

f - frequency
ℓ - characteristic length
U - velocity
M - Mach number
a - sound speed

Dimensional Analysis

Amplitude scaling

- assumes the non-dimensional fluctuating pressure is same ... model to full-scale

$$\left.\frac{p'}{q}\right]_{Model} = \left.\frac{p'}{q}\right]_{FullScale}$$

- this leads to the concept of a pressure coefficient for fluctuating pressures

$$\Delta C_p = \frac{p'}{q}$$

- furthermore, if the model fluctuating pressure coefficient is determined for a given flow, then the full scale fluctuating pressure is simply

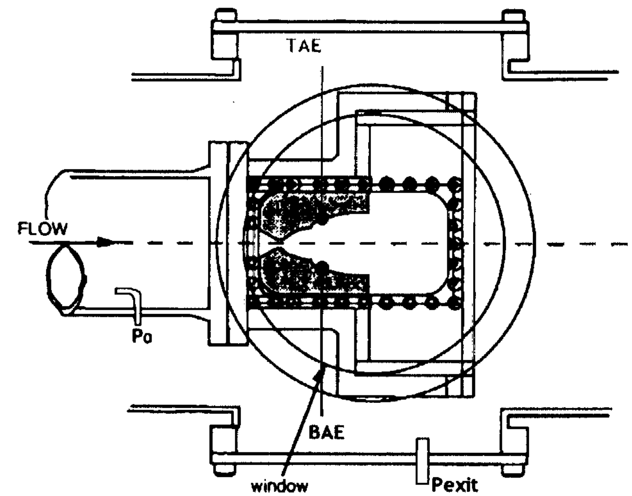
$$p'_{FS} = p'_M \cdot \frac{q_{FS}}{q_M}$$

q- dynamic pressure
p' - fluctuating pressure
αC_p - fluctuating pressure coefficient

Test - TWT 746

- 2D Cold flow test (ED34 95-37)
  - Sept. 1995
  - MSFC 14X14 Transonic Wind Tunnel
- Dual Bell Nozzle

Param	throat	transition	exit
x (in)	0	2.264	5.547
Area (in^2)	2.8	10	24.966
Width (in)	5	5	5
Height (in)	.56	2	4.993

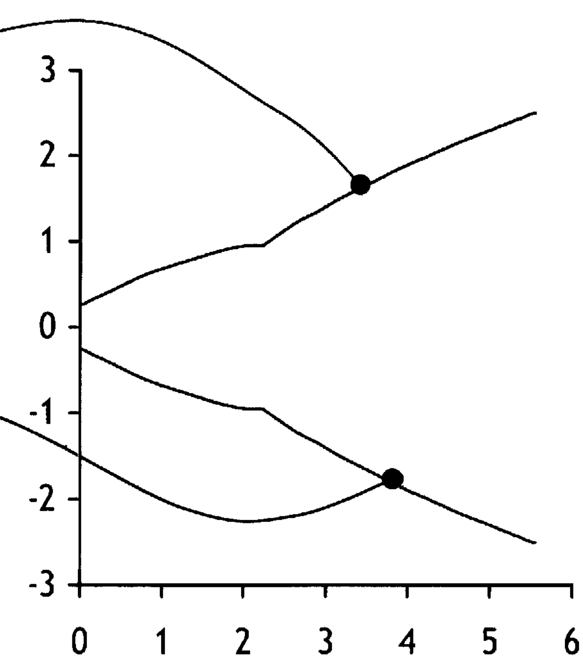


- Fluctuating Pressure Downstream of Transition (Top)

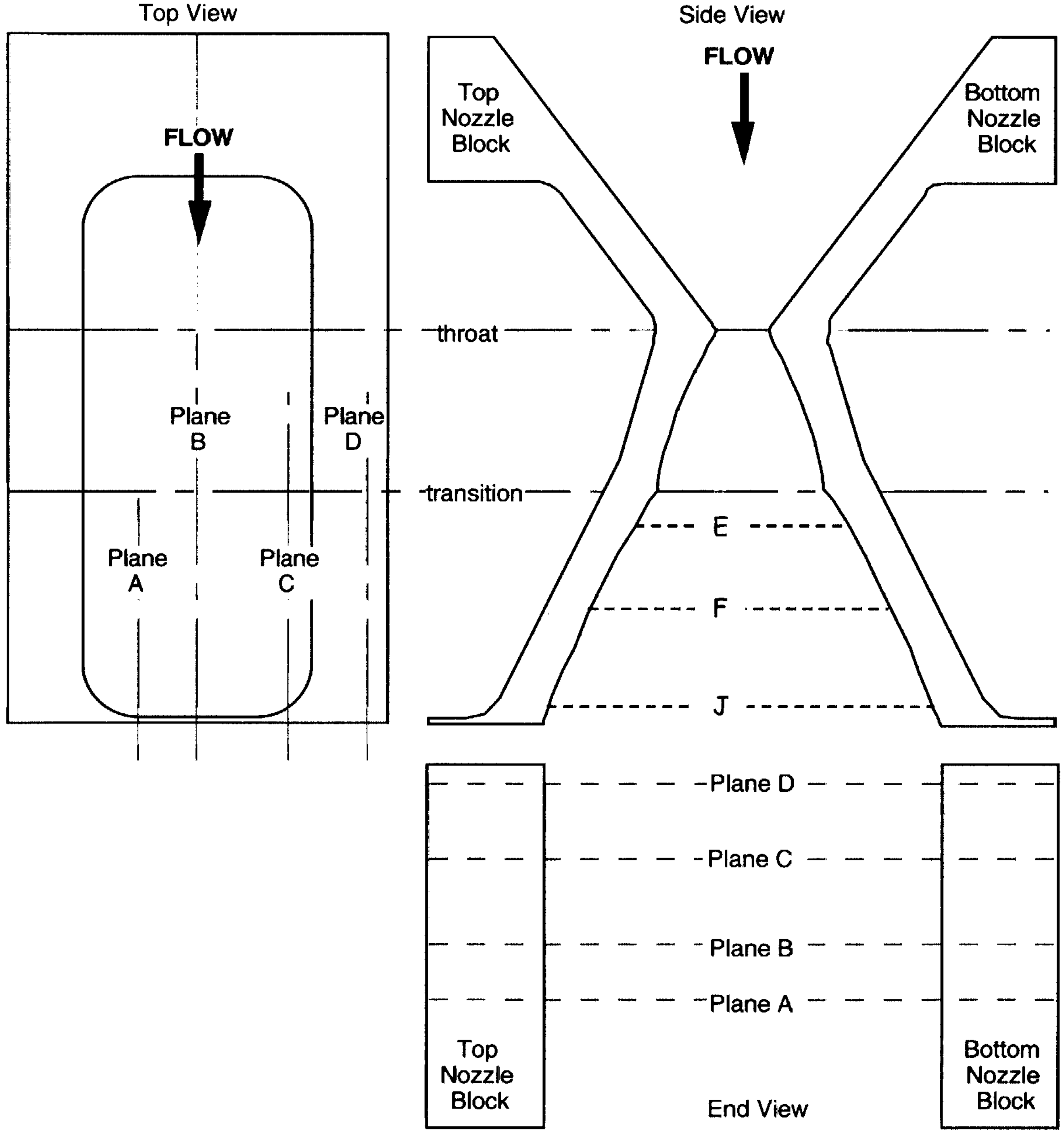
P_0/P_{exit}	p'/q_{exit} (pk)
30-33	.16
33-37	.01
38-40	.21
45-50	.01

- Fluctuating Pressure Downstream of Transition (Bottom)

P_0/P_{exit}	p'/q_{exit}(pk)
30-33	.22
33-37	.03
38-42	.29
42-50	.01

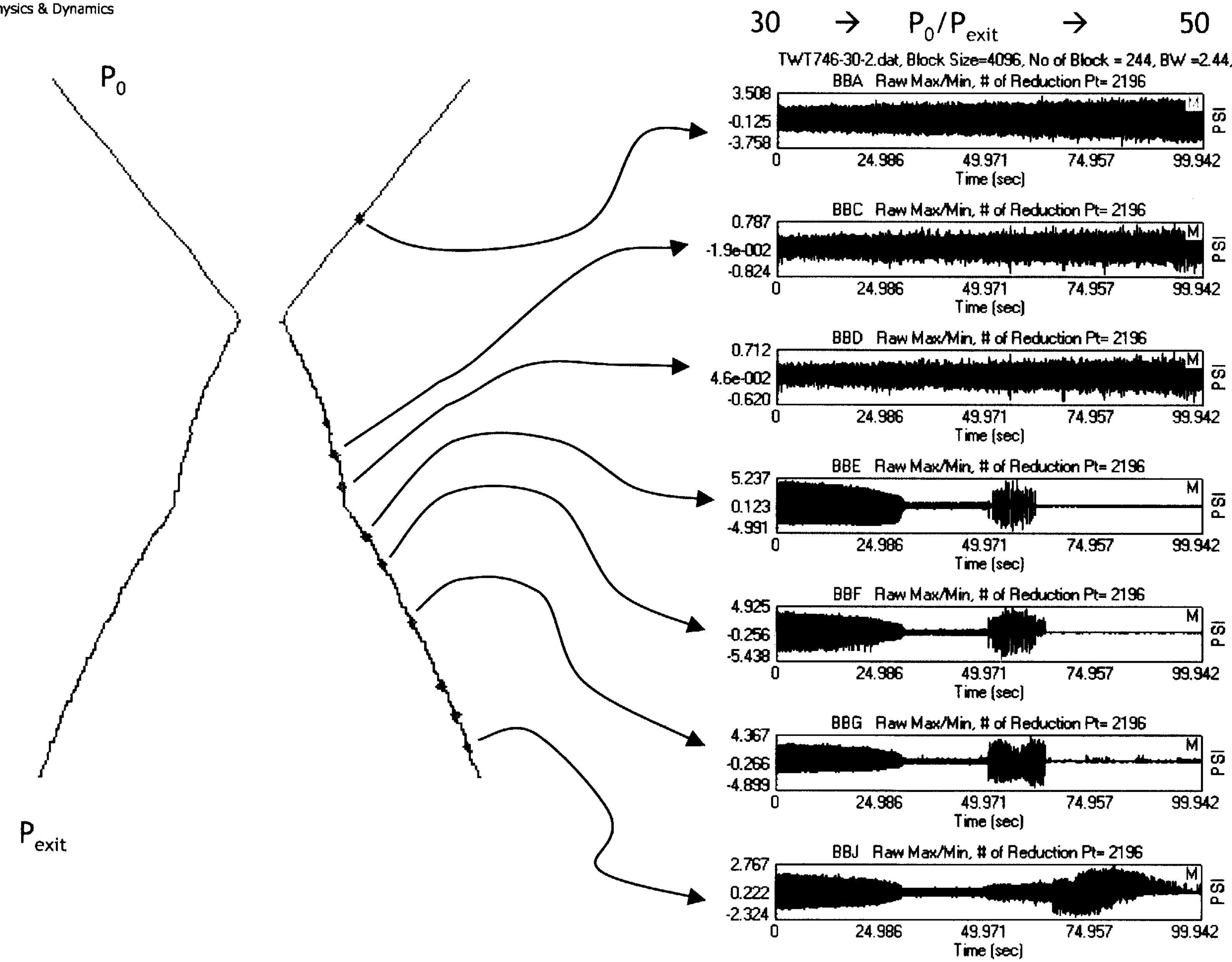


Dual Bell 2D Model



(from ED34 95-37)

Nozzle Wall Fluctuating Pressures

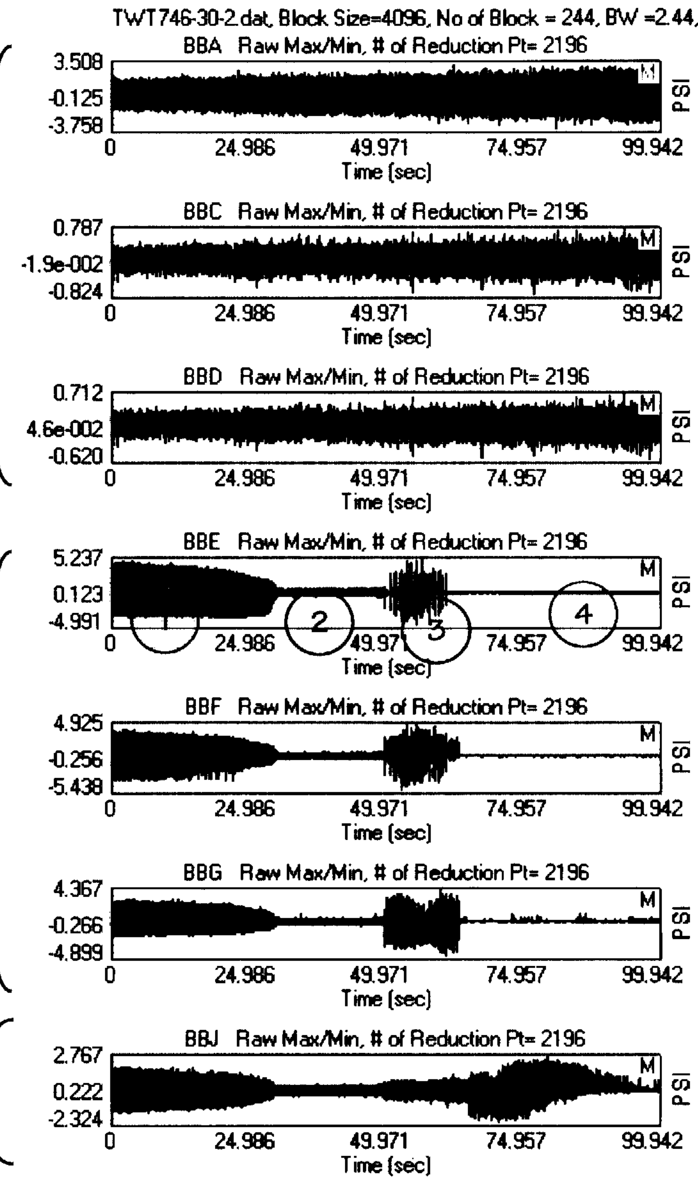


Nozzle Wall Fluctuating Pressures

- The dual bell nozzle has a throat, a first nozzle, a transition, and a second nozzle
- The first three measurements to the right show the steady increase in oscillations as the pressure ratio increases
- The first measurement is in the chamber and is higher amplitude than in the first nozzle

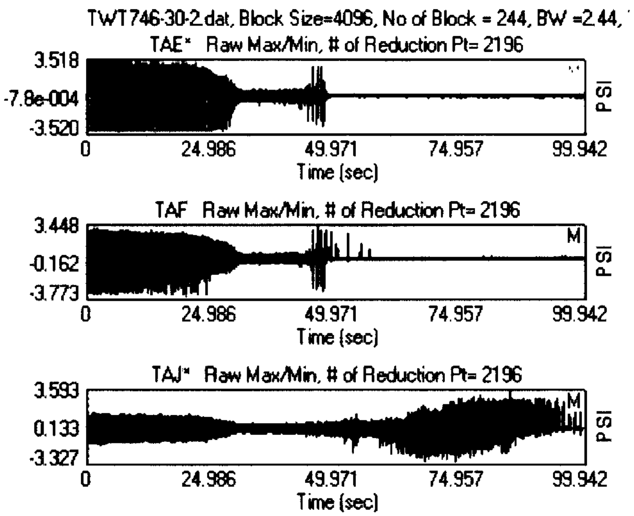
- The second three measurements show the fluctuating pressure downstream of the transition
  1. Flapping / screech (only 1st nozzle full)
  2. Expansion at transition
  3. Shock jumps from transition and oscillates up and down 2nd nozzle wall (not symmetric)
  4. Separation at or near second nozzle lip

- The last measurement shows the oscillations measured near the second nozzle lip

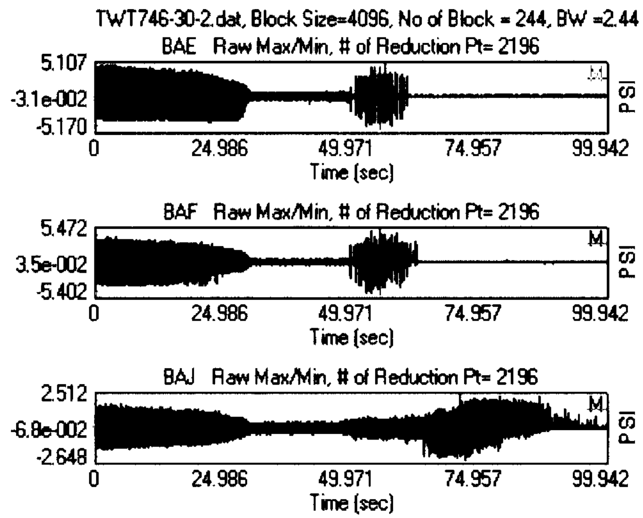


Wall Fluctuations Downstream of Transition

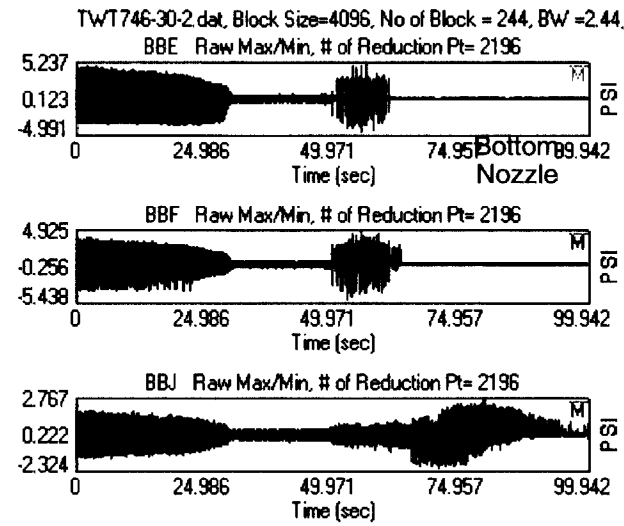
Top of model
"A" plane E, F, J

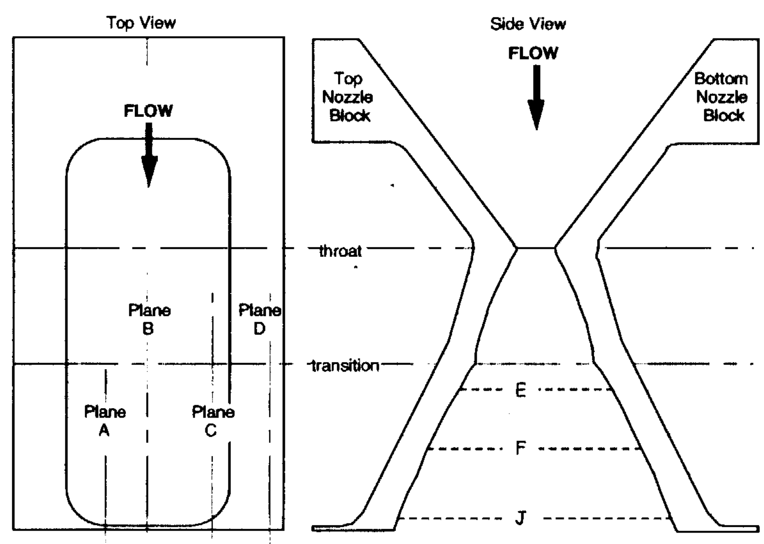


Bottom of model
"A" plane E, F, J

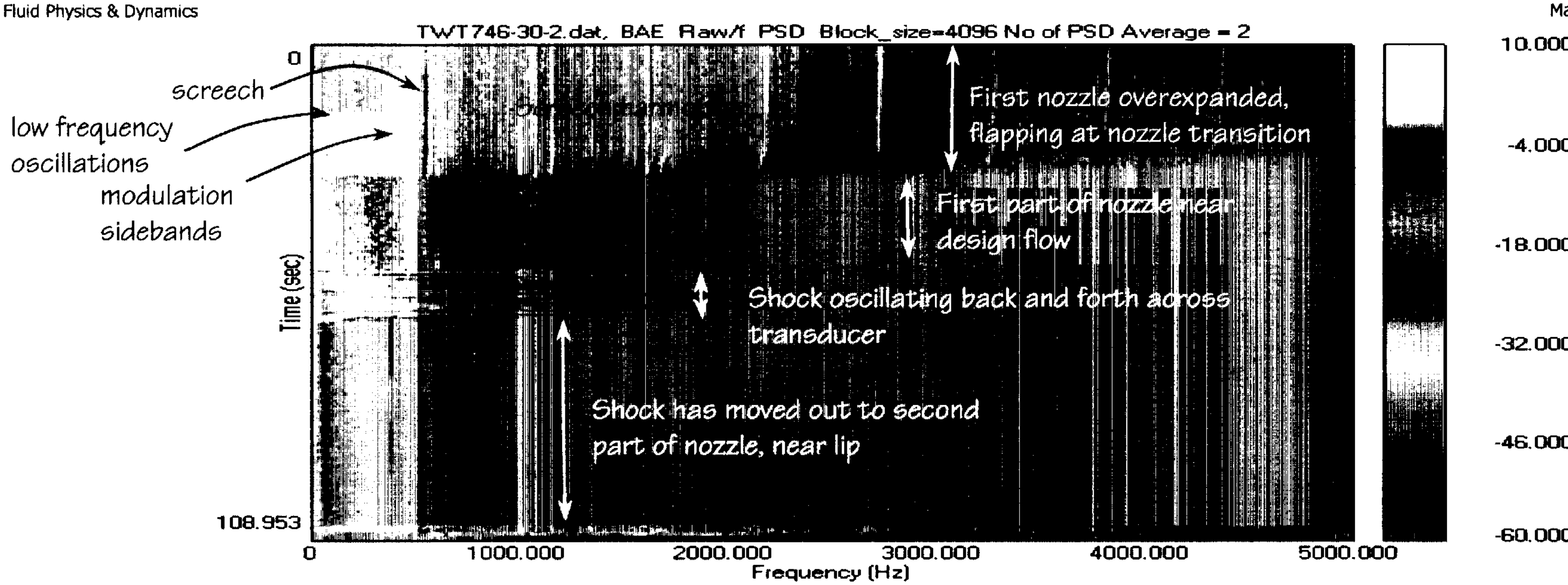


Bottom of model
"B" plane E, F, J

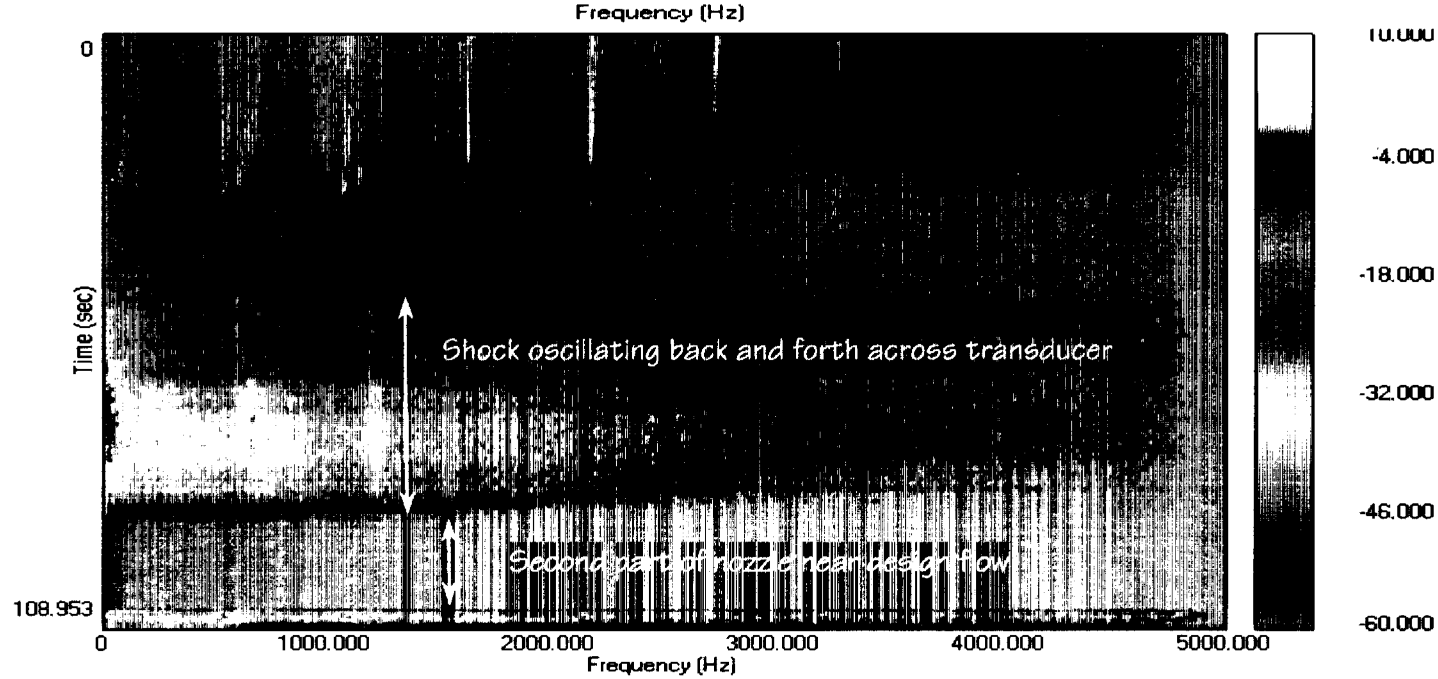




Spectragram of Nozzle Wall Fluctuating Pressure



BAE is located just downstream of nozzle transition



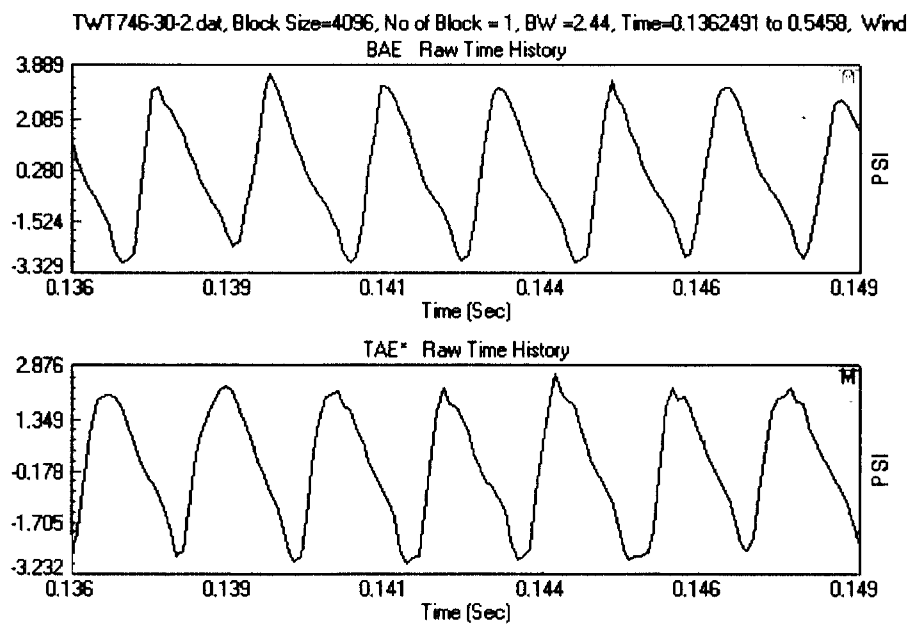
BAJ is located downstream of nozzle transition near nozzle lip / exit

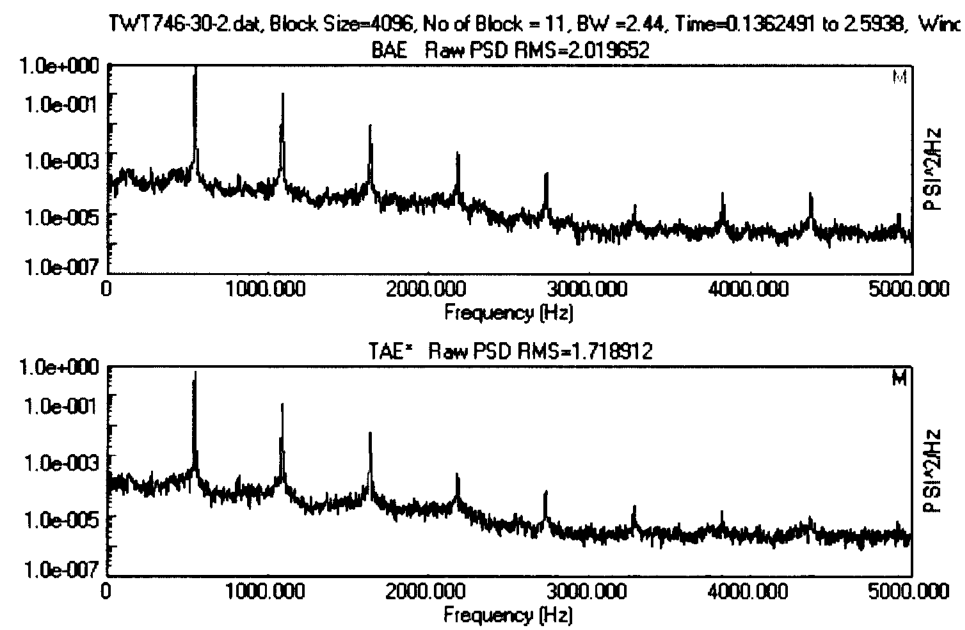
Increasing inlet pressure

Screech

Screech tones are a form of instability waves. The wave shape result from downstream propagation of large scale disturbances inside the jet plume plus a nonlinear propagation effect. The screech spectrum therefore shows not only the screech tone but also harmonics. The screeching supersonic jet may be the result of toroidal or helical modes and is manifested as a flapping motion. The thickness of the nozzle lip influences the magnitude of screech. Screech from nozzle flow in a tunnel or facility will be strengthened if impingement feedback occurs.

The figures below shows the time signal and power spectral density of fluctuating pressure, just downstream of the dual-bell transition where overexpansion coincides with a strong screech and flapping motion. Note that the top and bottom oscillations are out of phase.





Non-Dimensional Screech Frequency

Screech tone dimensionless frequency is shown here vs fully expanded jet Mach number, M_j. The 2-D dual bell nozzle data is plotted along with data from rectangular, oval, and circular nozzles.

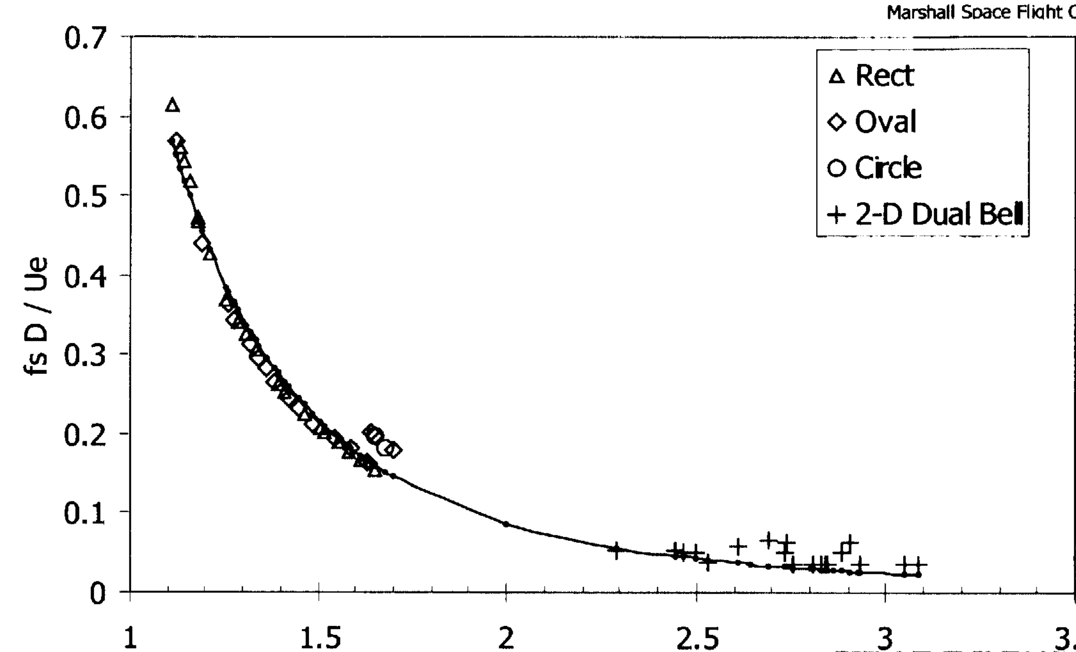
$$M_j = \frac{U_j}{a_{exit}}$$

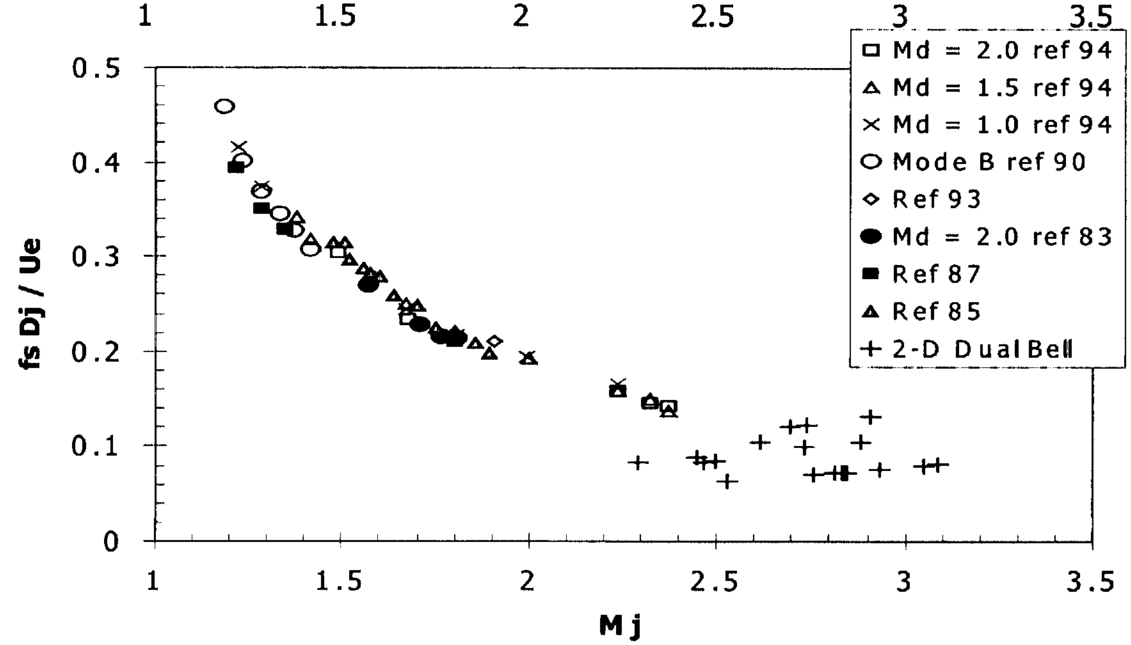
Here U_j is the velocity at nozzle exit and a_{exit} is the ambient sound speed. M_j is related to the pressure ratio as follows.

$$M_j = \sqrt{\left(\left(\frac{p_0}{p_{exit}}\right)^{\gamma-\frac{1}{\gamma}} - 1\right)\frac{2}{\gamma-1}}$$

Collection of dominant screech tone frequencies, f_s, from supersonic jets. The data is collapsed using fully expanded jet diameter, D_j ... conservative mass flux. (see Tam in References)

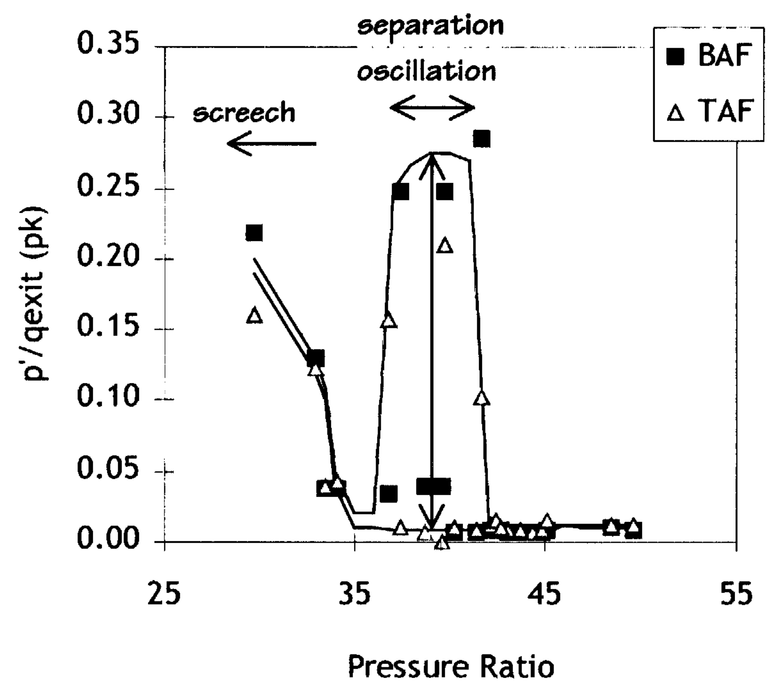
$$\frac{D_j}{D} = \left\{\frac{1+\left[(\gamma-1)\frac{M_j^{\,2}}{2}\right]}{1+\left[(\gamma-1)\frac{M_d^{\,2}}{2}\right]}\right\}^{\frac{\gamma+1}{4(\gamma-1)}} \left(\frac{M_d}{M_j}\right)^{1/2}$$





Summary

- Fluctuating pressure associated with observed 2-D dual-bell nozzle flow patterns
- Flow patterns during ramp-up and ramp down in pressure ratio show hysteresis
- High amplitude fluctuations during overexpansion of first nozzle (screech) and when shock passes over transducer (separation oscillation)
- Screech oscillations
  - discrete and periodic
  - top & bottom out of phase
- Separation oscillation
  - refers to when separation shock location on the nozzle wall is oscillating
  - shows up as low level random oscillations interrupted by sharp spikes on fluctuating pressure measurements between nozzle transition and nozzle lip
  - not symmetrical
- Characteristics above will be compared to 3-D dual-bell nozzle cold flow data



Acknowledgements

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