Acoustic Analogy

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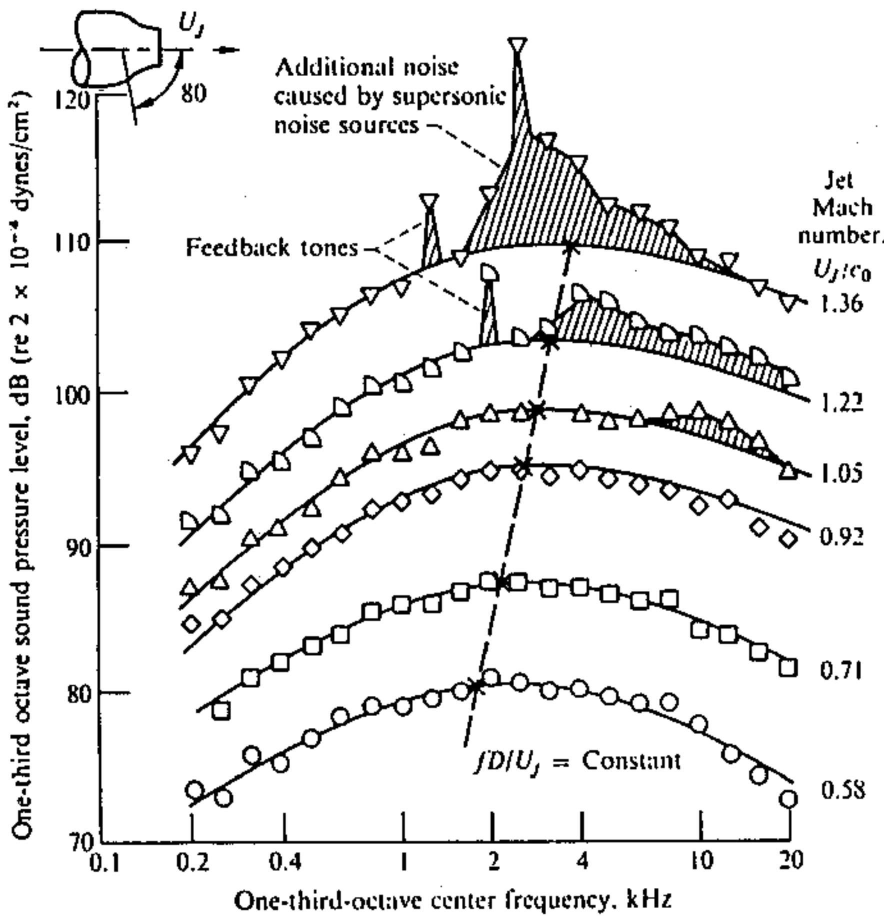
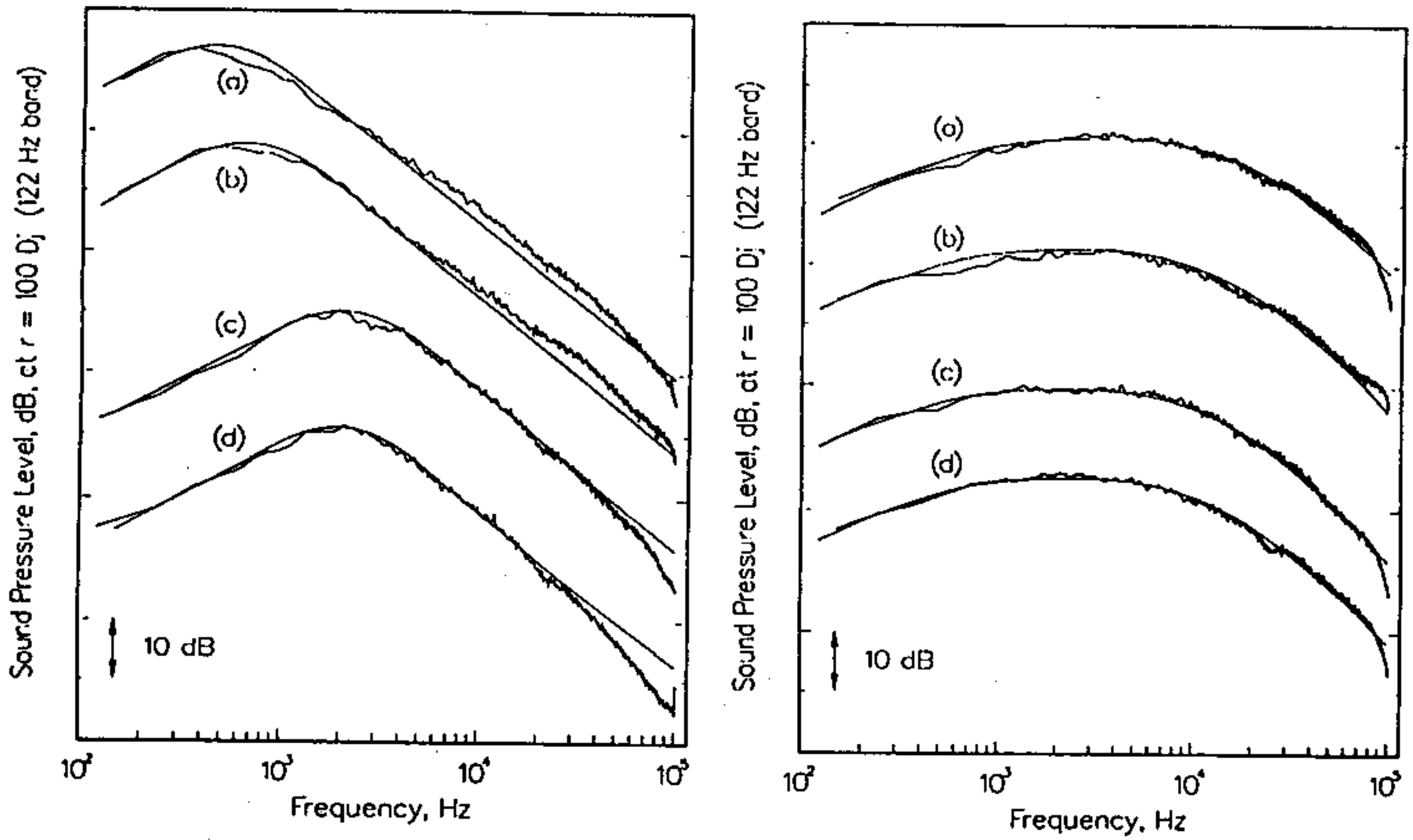
One-Third Octave Jet Noise Spectra For A Convergent Nozzle At Subsonic And Supersonic Velocities; Angle from Downstream Jet Axis, 80°. Based On Data From Olsen



Narrow Band Jet Noise Spectra At 90° And Small Angles To Jet Axis From Tam, Golebiowski & Seiner (1996)



(a) $M_j = 2.0$, $T_r/T_\infty = 4.89$, $\chi = 160.1°$, $SPL_{max} = 124.7$ dB, (b) $M_j = 2.0$, $T_r/T_\infty = 1.12$, $\chi = 160.1°$, $SPL_{max} = 121.6$ dB, (c) $M_j = 1.96$, $T_r/T_\infty = 1.78$, $\chi = 138.6°$, $SPL_{max} = 121.0$ dB, (d) $M_j = 1.49$, $T_r/T_\infty = 1.11$, $\chi = 138.6°$, $SPL_{max} = 106.5$ dB.

$M_j = 1.49$, $T_r/T_\infty = 2.35$, $\chi = 92.9°$, $SPL_{max} = 96$ dB, (b) $M_j = 2.0$, $T_r/T_\infty = 4.89$, $\chi = 83.8°$, $SPL_{max} = 107$ dB, (c) $M_j = 1.96$, $T_r/T_\infty = 0.99$, $\chi = 83.3°$, $SPL_{max} = 95$ dB, (d) $M_j = 1.96$, $T_r/T_\infty = 0.98$, $\chi = 120.2°$, $SPL_{max} = 100$ dB.

$$\chi \equiv 180° - \theta$$

V-Large Eddy Simulation

Filtered N.S. Eqs. (Favre-averaged)

$$\frac{\partial}{\partial t}\begin{Bmatrix}\bar{\rho}\\ \bar{\rho}\tilde{v}_i\\ \bar{\rho}\tilde{s}\end{Bmatrix}+\frac{\partial}{\partial x_j}\begin{Bmatrix}\bar{\rho}\tilde{v}_j\\ \bar{\rho}\tilde{v}_i\tilde{v}_j+\delta_{ij}\bar{p}\\ \bar{\rho}\tilde{s}\tilde{v}_j\end{Bmatrix}-\text{viscous terms}=\frac{\partial}{\partial x_j}\begin{Bmatrix}0\\ \bar{\rho}\left(\widetilde{v_i v_j}-\tilde{v}_i\tilde{v}_j\right)\\ \bar{\rho}\left(\widetilde{s v_j}-\tilde{s}\tilde{v}_j\right)\end{Bmatrix}$$

unresolved Reynolds stress (to be modelled)

$$\tilde{f}\equiv\overline{\rho f}/\bar{\rho}$$

$$\bar{f}(\mathbf{x},t)=\int_{-\infty}^{\infty}\int_V F(\mathbf{x}-\xi,t-\tau)f(\xi,\tau)\,d\tau\,d\xi$$

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Equation for Small Scale (Unresolved) Components

$v_i = \tilde{v}_i + v_i',$ velocity $p = \bar{p} + p',$ pressure $s = \tilde{s} + s',$ entropy

Inhomogenous Linearized Euler Equation

$$\underbrace{L_{ij}u_j}_{\substack{\text{Linear operator} \\ \text{(depends on filtered vel.)}}} \underbrace{= S_i \equiv \frac{\partial}{\partial x_j}\left(T_{ij}' - \tilde{T}_{ij}\right) + \frac{\partial}{\partial t} T_i' + \text{visc. terms}}_{\text{source terms}}$$

$$ij = 1, 2, \ldots 5$$

$$u_i = v_i',\ i = 1, 2, 3;\ u_4 = p',\ u_5 = s'$$

T'_{ij} is quadratic in unresolved quantities (unresolved Reynolds stress)

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Formal Solution for Pressure

$$u_4 \equiv p' = L_{4j}^{-1} S_j \qquad \text{(sum on j)}$$

$$p' = \lim_{T \to \infty} \iint_{-T}^{T} G_{4k}\left(\mathbf{x}|\mathbf{x}';t-t';\bar{t},\sigma\right) S_k(\mathbf{x}',t')\,d\mathbf{x}'dt'$$

$$\left\langle p'(t+\tau,\mathbf{x})p'(\tau,\mathbf{x})\right\rangle = \text{pressure auto correlation function}$$

$$= \iiint \left[\Gamma_{k\ell}^{+}(\mathbf{x},t|\mathbf{x}',\mathbf{x}'',t')\left\langle S_k(\mathbf{x}',t'+\tau)S_\ell(\mathbf{x}'',\tau)\right\rangle + \Gamma_{\overline{k\ell}}^{-}(\mathbf{x},t|\mathbf{x}',\mathbf{x}'',t')\left\langle \left|S_k(\mathbf{x}',t'+\tau)S_\ell(\mathbf{x}'',\tau)\right|\right\rangle\right] dt'd\mathbf{x}'d\mathbf{x}''$$

$$\langle \bullet \rangle \equiv \lim_{T \to \infty} \int_{-T}^{T} \bullet \; d\tau = \text{time average}$$

$$\left\langle \bar{f}(t+\tau)g'(\tau)\right\rangle = 0 \qquad \text{For tophat filter (in Fourier space)}$$

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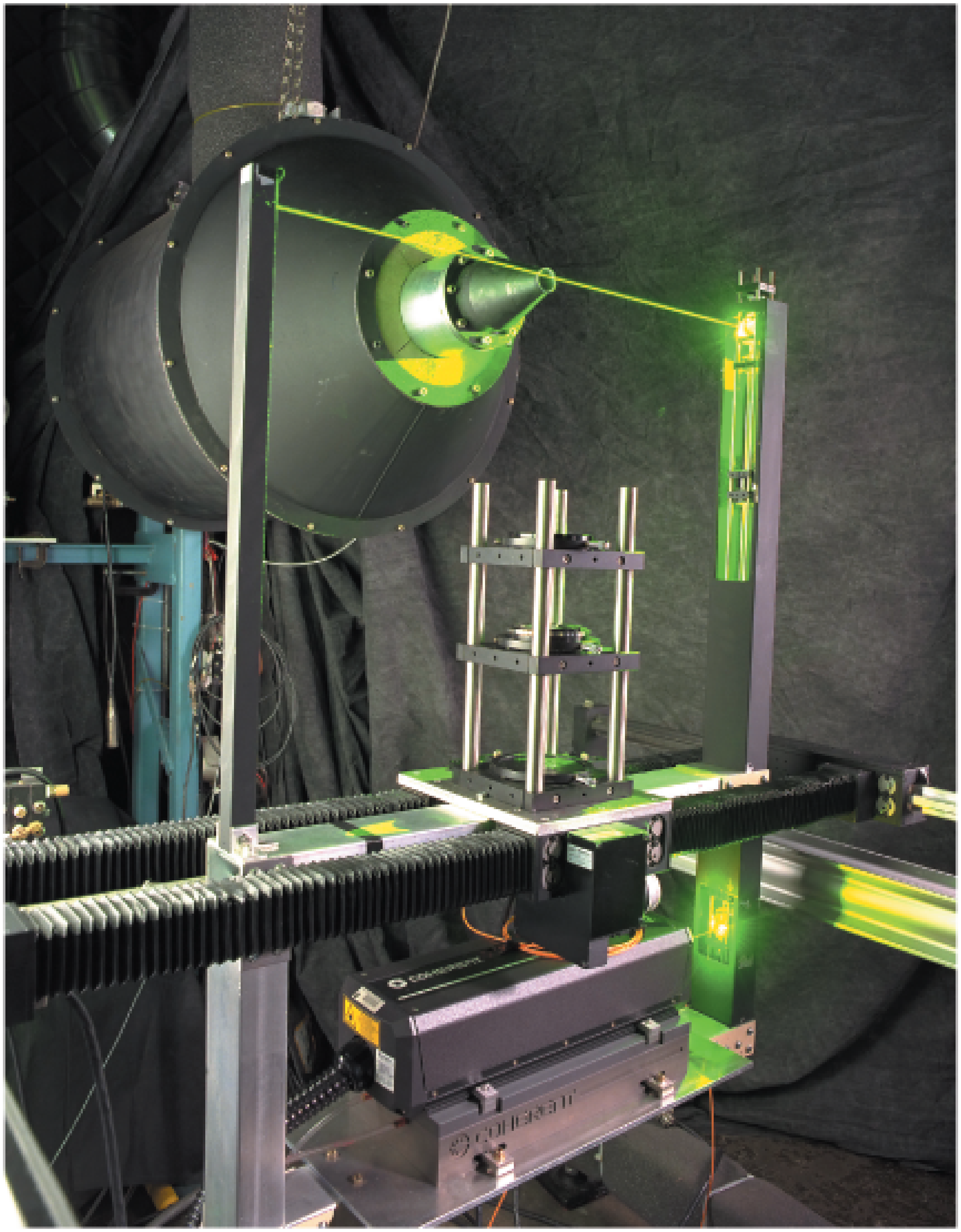

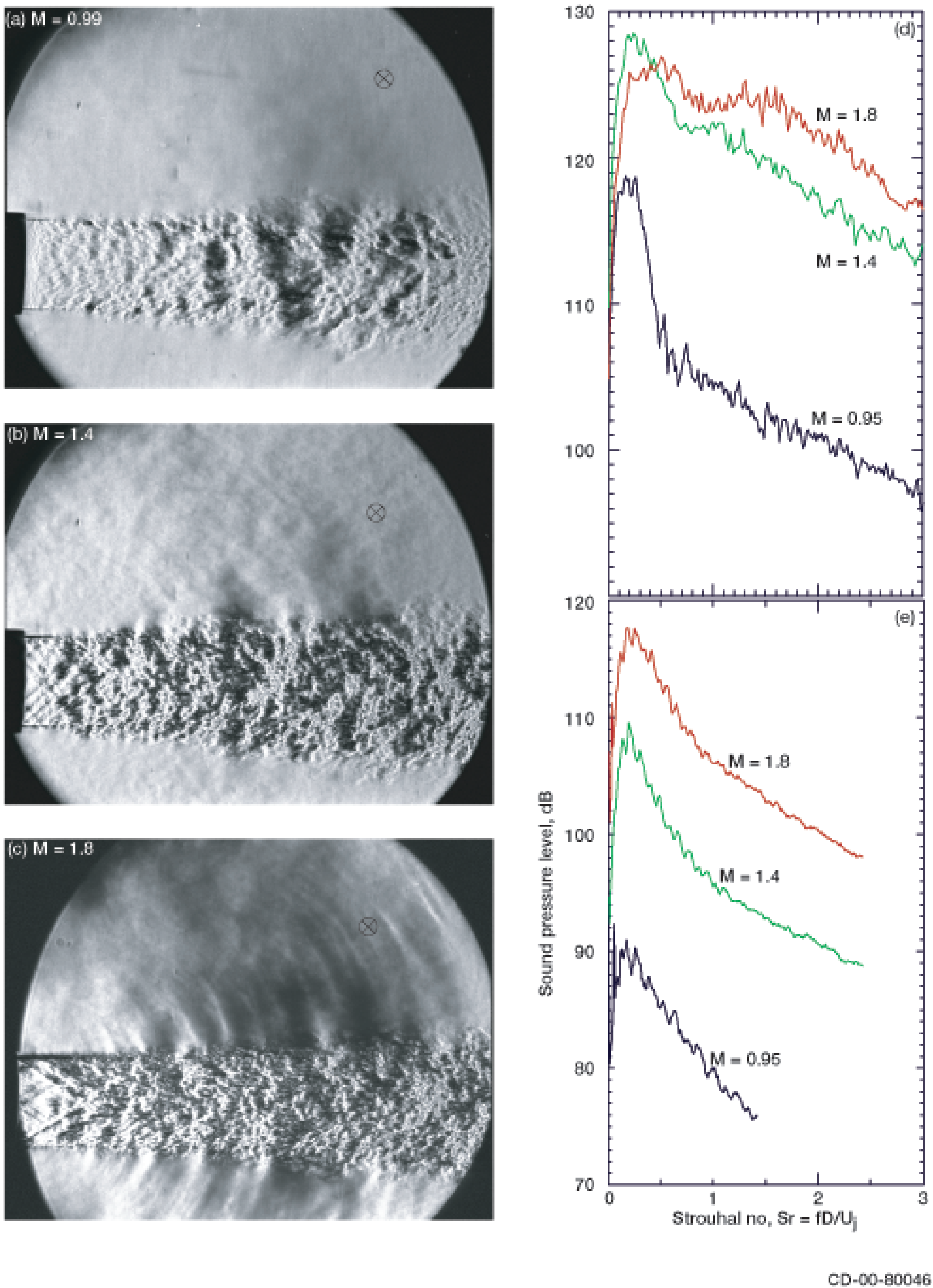
(a) M = 0.99
(b) M = 1.4
(c) M = 1.8
(d)
(e)
M = 1.8
M = 1.4
M = 0.95
130
120
110
100
90
80
70
Sound pressure level, dB
0
1
2
3
Strouhal no, Sr = fD/U_j
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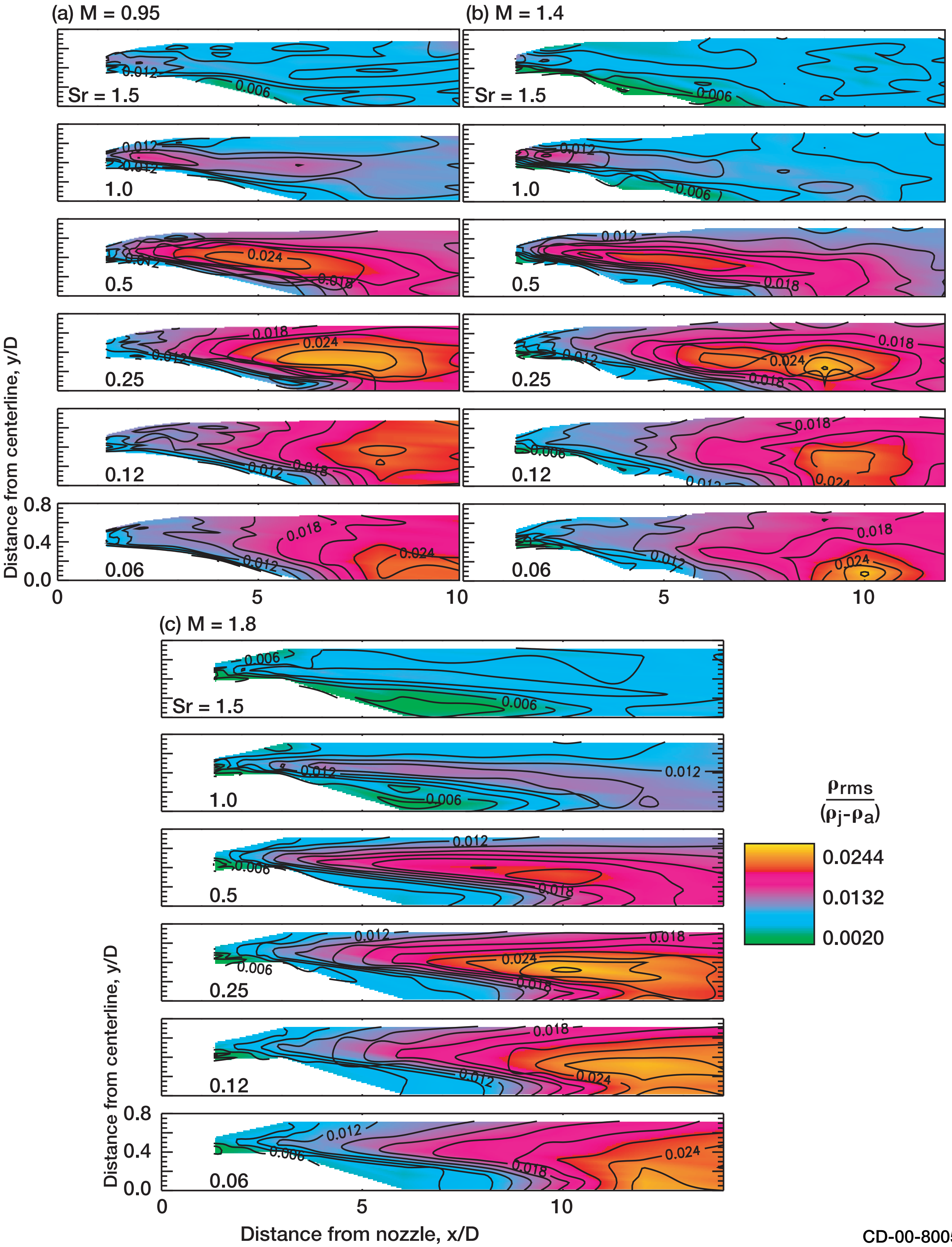
(a) M = 0.95
(b) M = 1.4
(c) M = 1.8
Sr = 1.5
1.0
0.5
0.25
0.12
0.06
Distance from centerline, y/D
Distance from nozzle, x/D
0.012
0.006
0.018
0.024
0.8
0.4
0.0
0
5
10
ρrms
(ρj-ρa)
0.0244
0.0132
0.0020

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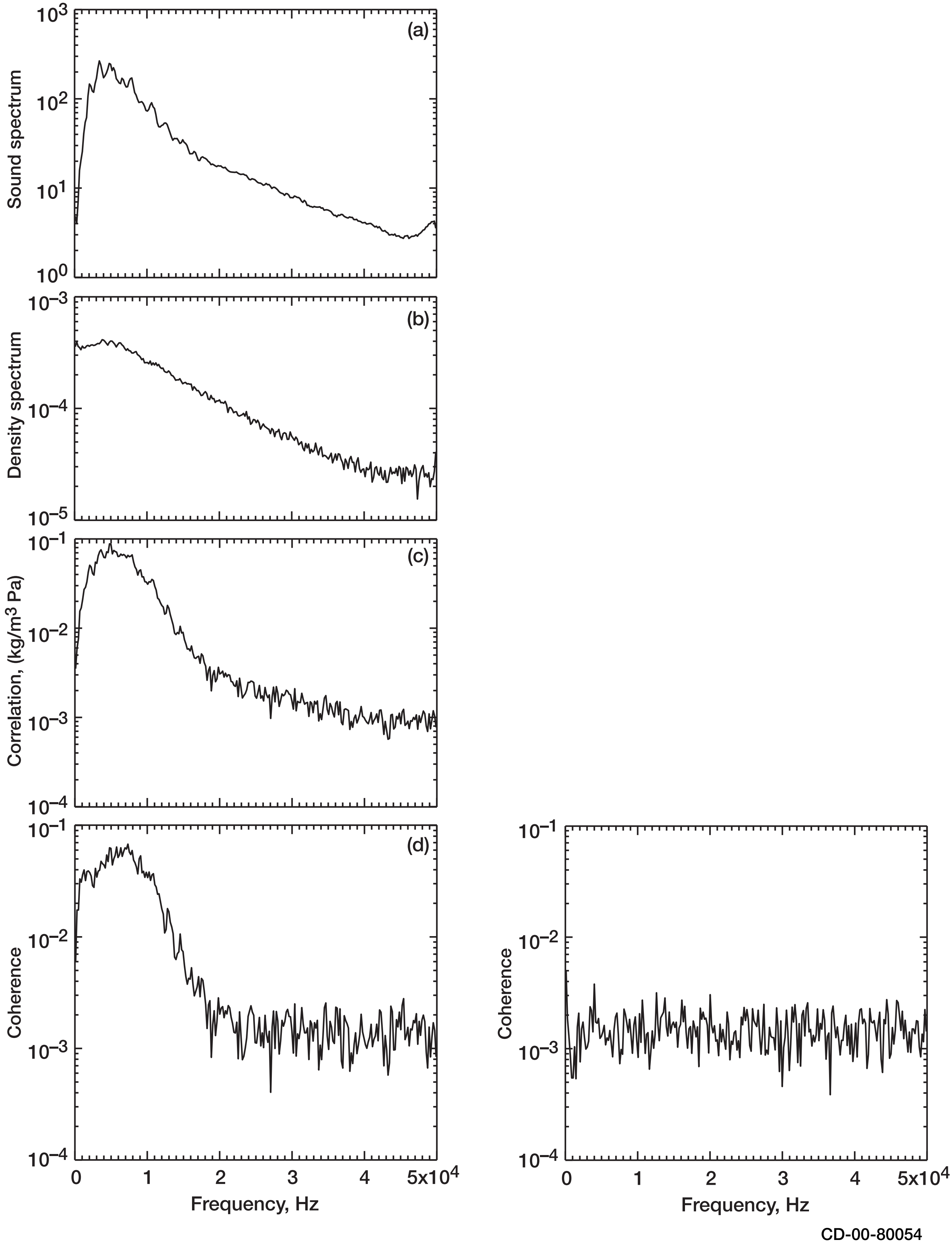
(a)
Sound spectrum
(b)
Density spectrum
(c)
Correlation, (kg/m3 Pa)
(d)
Coherence
Coherence
0
1
2
3
4
5x10^4
Frequency, Hz
Frequency, Hz
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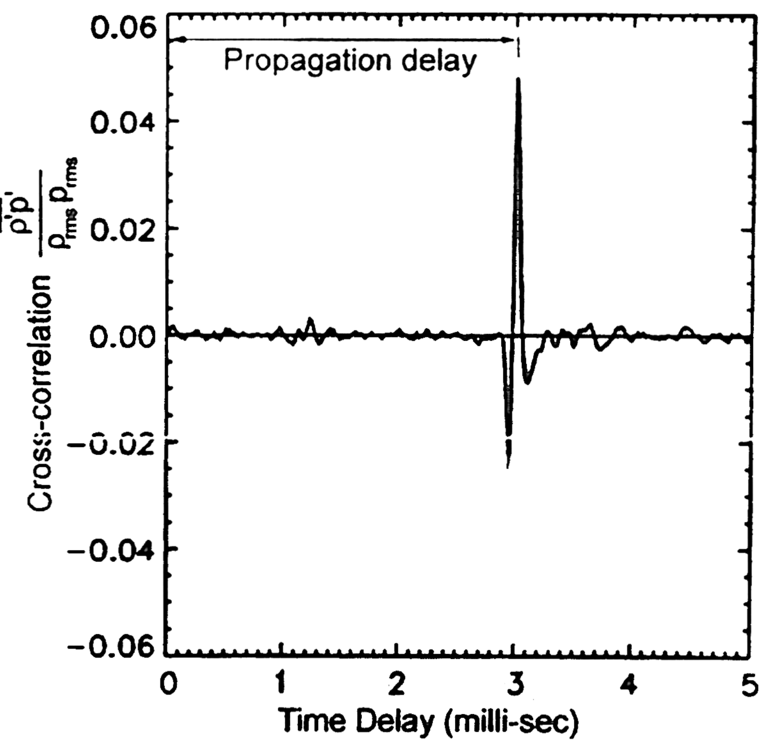
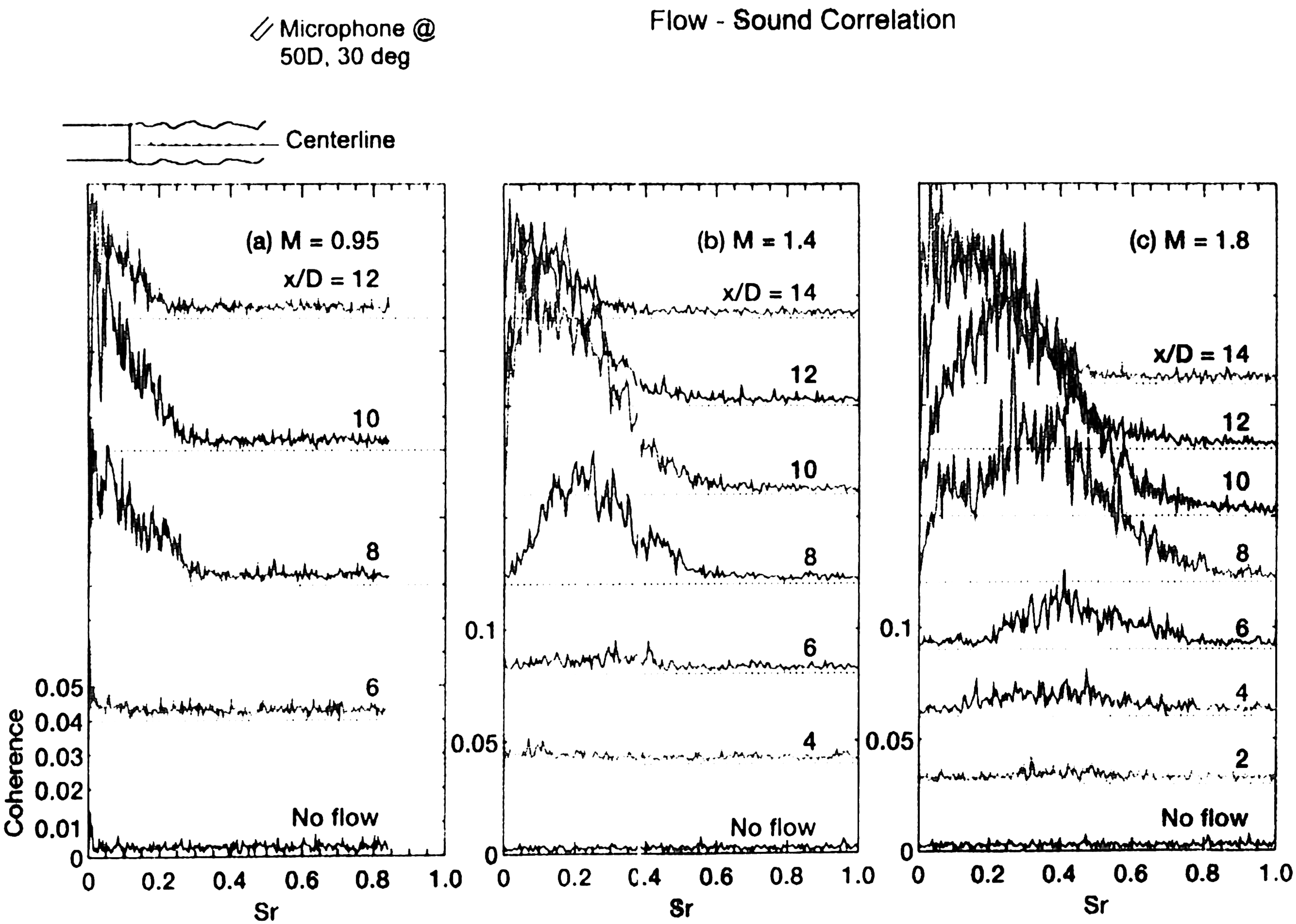
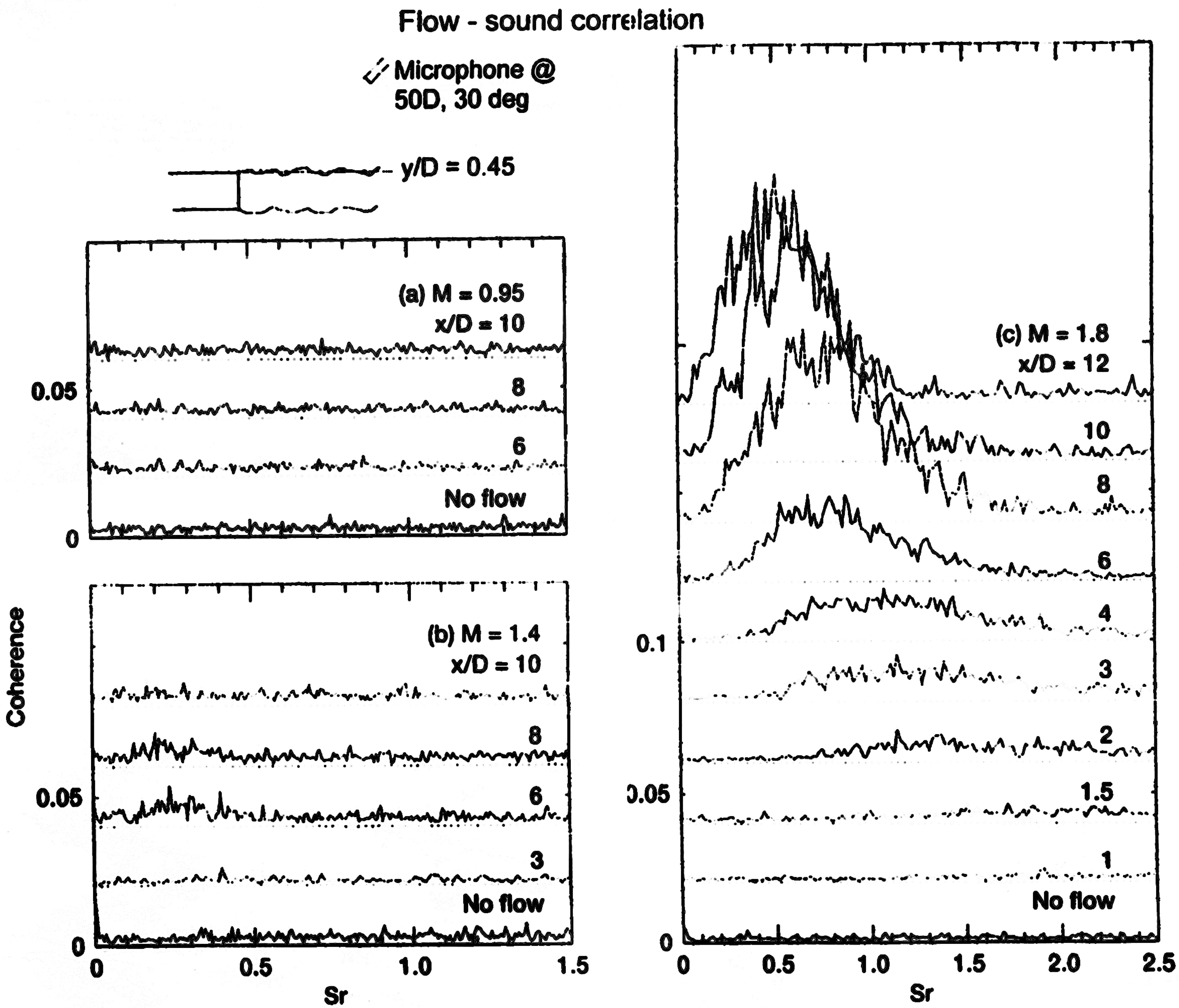
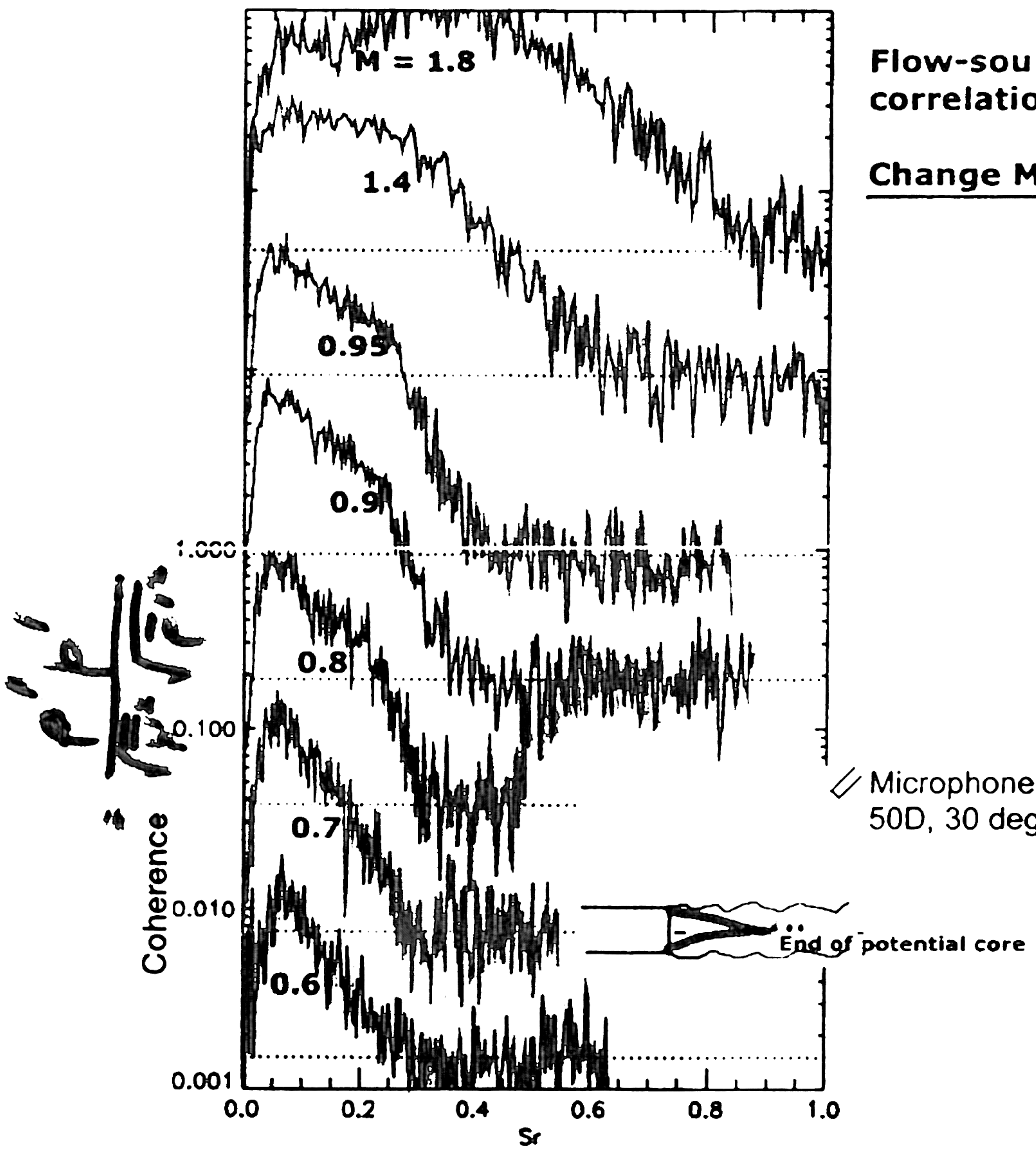

0.06
Propagation delay
0.04
0.02
0.00
−0.02
−0.04
−0.06
0
1
2
3
4
5
Time Delay (milli-sec)
Cross-correlation $\frac{\overline{\rho' p'}}{\rho_{rms} p_{rms}}$


Flow - Sound Correlation
Microphone @ 50D, 30 deg
Centerline
(a) M = 0.95
x/D = 12
10
8
6
No flow
(b) M = 1.4
x/D = 14
12
10
8
6
4
No flow
(c) M = 1.8
x/D = 14
12
10
8
6
4
2
No flow
Coherence
0
0.01
0.02
0.03
0.04
0.05
0.1
0.2
0.4
0.6
0.8
1.0
Sr


Flow - sound correlation
Microphone @
50D, 30 deg
y/D = 0.45
(a) M = 0.95
x/D = 10
8
6
No flow
0.05
0
(b) M = 1.4
x/D = 10
8
6
3
No flow
Coherence
0.05
0
0
0.5
1.0
1.5
Sr
(c) M = 1.8
x/D = 12
10
8
6
4
3
2
1.5
1
No flow
0.1
0.05
0
0
0.5
1.0
1.5
2.0
2.5
Sr



Flow-sound correlation

Change M

Microphone @ 50D, 30 deg

M. Goldstein References

1. Goldstein, M. E. Aeroacoustics, McGraw-Hill 1976.

2. Olsin (Only published in Aeroacoustics Pg. 105).

3. Goldstein, M. E. (1984) Aeroacoustics of Turbulent Shear Flows, Annual Reviews of Fluid Mechanics Vol. 16, Pg. 263-286.

4. Goldstein, M. E. (1999) Program and Abstracts of the 6th International Congress on Sound and Vibration, Copenhagen "Some Recent Development in Jet Noise Modeling."