# Verification of the quasi-steady approximation for sound generation by confined pulsating jets

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The 3rd Biennial ICVPB Meeting
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# For more information:

**see web site at:**
**http://widget.ecn.purdue.edu/%7Evoice/**

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# Acknowledgements


## Sponsor

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## Graduate Students

- Zhaoyan Zhang (Postdoc, U. Maryland)
- Scott Thomson (Ph.D., summer 2003)
- Jong Beom Park

## Collaborators

- Steve H. Frankel, Assoc. Prof.

## Technical Assistance

- Gilbert Gordon

# Objectives

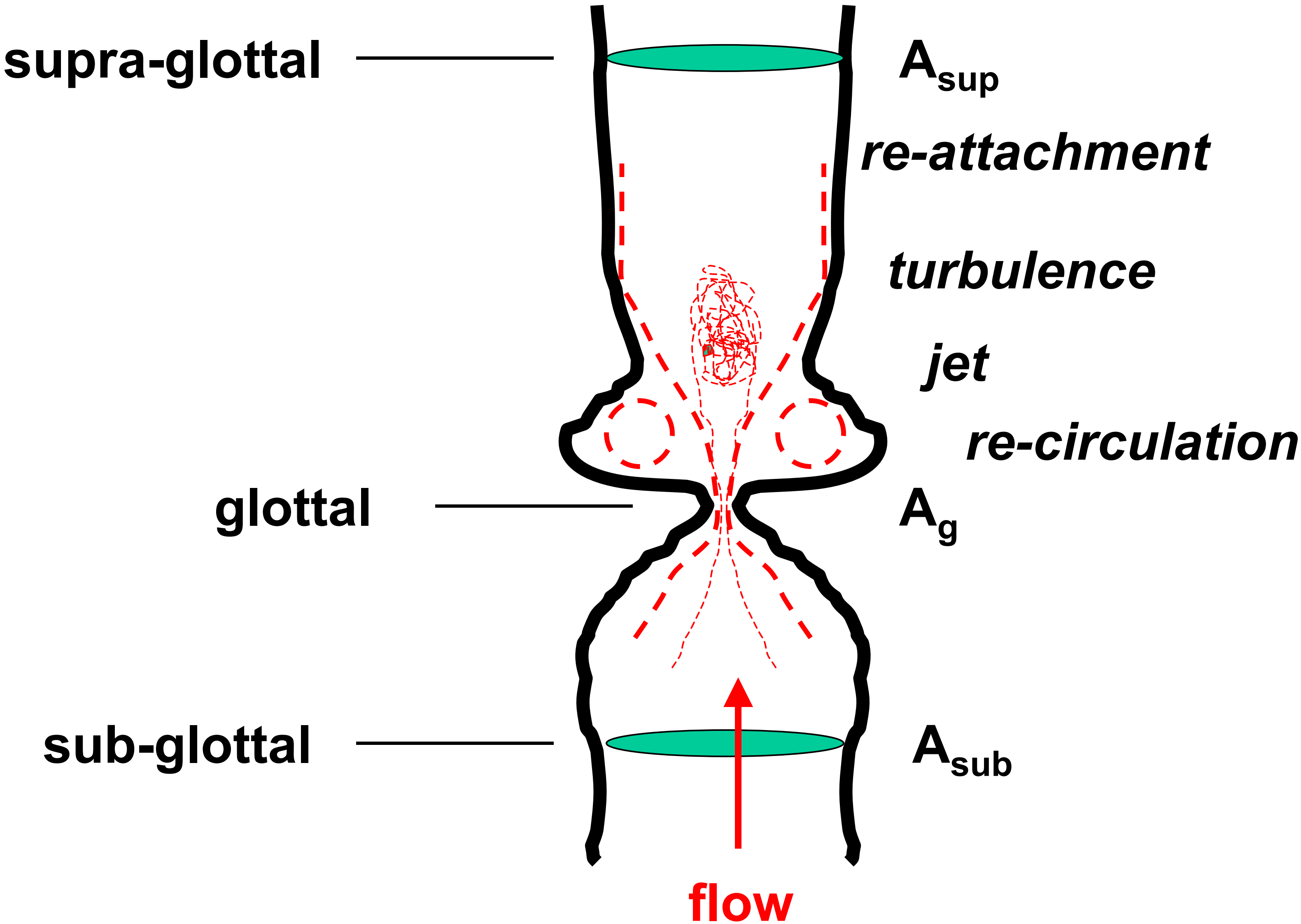
## Investigate the range of validity of the quasi-steady approximation

- Periodic Component
- Random, broadband component

## Gain a better understanding of the sound generation mechanisms

- periodic and broadband components
- steady and pulsating confined jet flows

# Intra-Glottal Flows



# Bernouilli's equation

$$p_{sub} - p_{sup} = \frac{1}{2}\rho_0 U_c^2$$

**assumptions:**

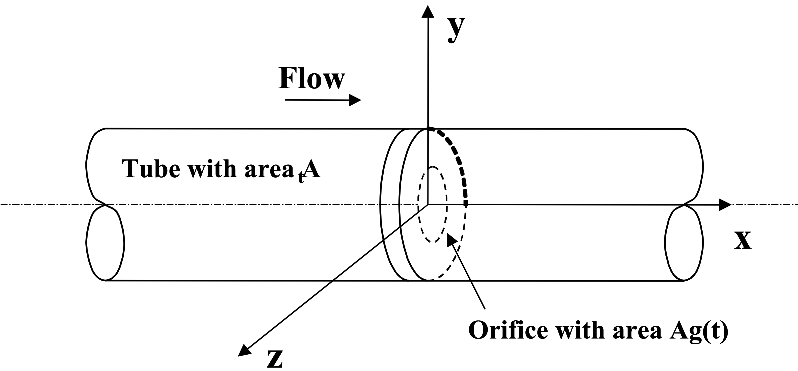
- **irrotational**
- **flow incompressibe**
- **along a streamline**
- **viscous effects neglected**
- **acceleration effects neglected**

# Bernouilli's Obstruction Theory

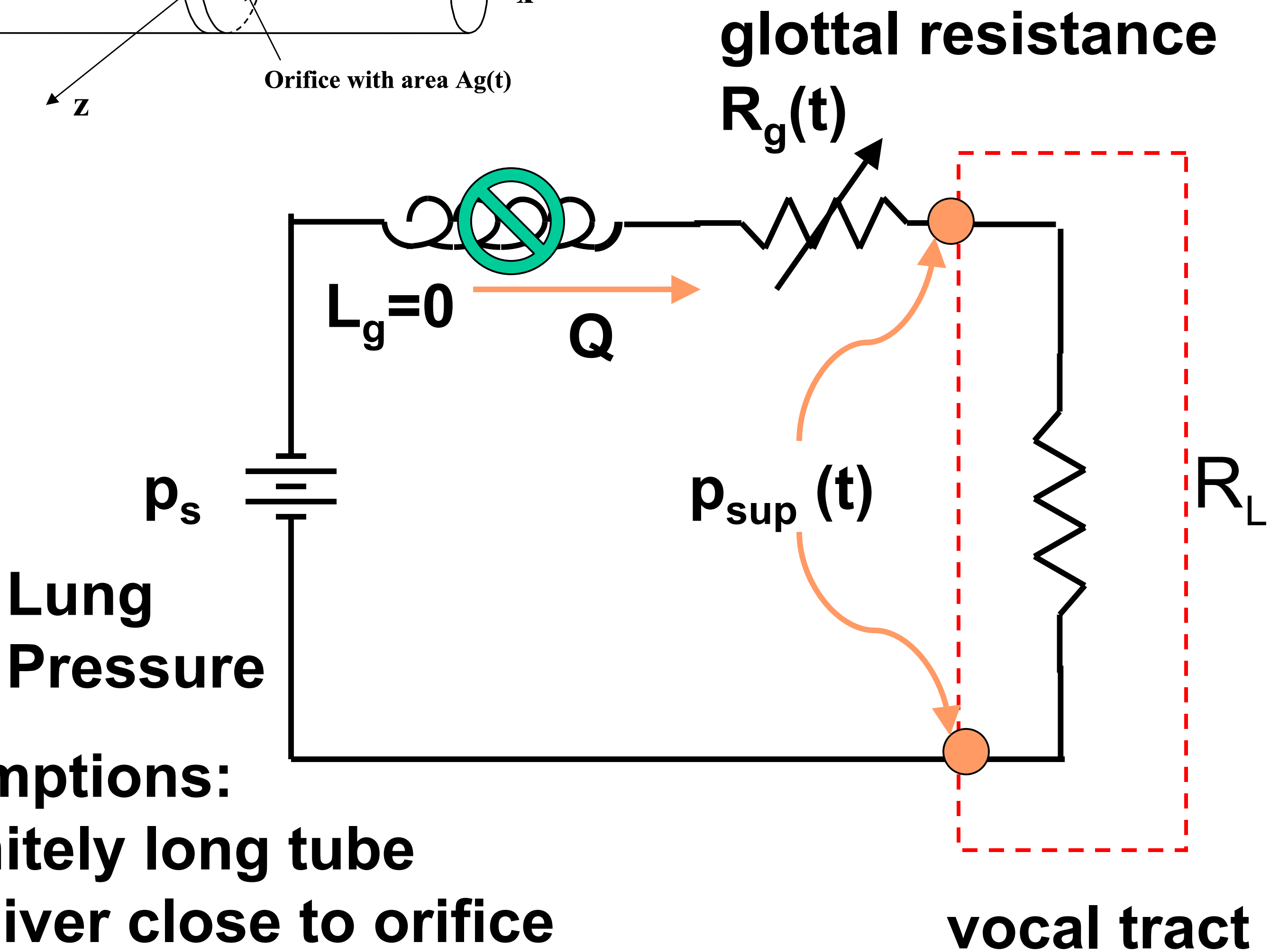
$$Q = KA_g \sqrt{\frac{2(p_{sub} - p_{up})}{\rho_0}}$$

**assumptions:**

- **large area ratio $A_{sub}/A_g$**
- **flow coefficient K combines discharge coefficient and approach velocity factor**
- **K=K(shape, area, inflow+outflow condition)**
- **same as Bernouilli's equation**
- **all variable instantaneous (except density)**




# Simplified Circuit




$$R_L = \frac{\rho_0 c_0}{A_{tube}}$$

**assumptions:**

- **infinitely long tube**
- **receiver close to orifice**
- **negligible inductive effects**

# Glottal Resistance

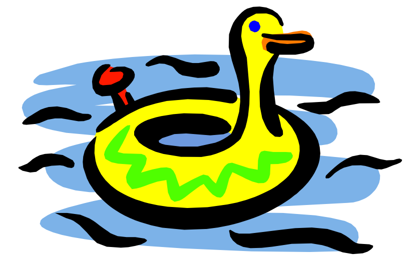
$$R_g = \frac{p_{sub} - p_{up}}{Q} = \frac{p_{sub} - p_{up}}{KA_g \sqrt{\frac{2(p_{sub} - p_{up})}{\rho_0}}}$$

- $K = K(A_g, p_{sub} - p_{sup})$
- direct measurement of $A_g$, $p_{sup}$, $p_{sub}$ sufficient to calculate $R_g$
- ***quasi-steady approximation states that for given geometry, $A_g$ and $\Delta p$, $R_g$ is the same for steady or pulsating flows***

# Non-Stationary Phenomena

- $d\phi/dt$
- Vorticity shedding
- Large scale turbulent structures
- Flow induced by motion of wall

# Rubber Dynamic Physical Models



## Advantages

- real size (no need for scaling)
- allow acoustic and simple flow measurements
- orifice shape easy to modify
- easy to add complexity to model geometry

## Disadvantages

- real size (can't easily perform detailed flow measurements for validation of CFD)
- some shape distortion at high frequency

# Experimental Facility

**Inertial base (concrete slab)**

**Two large electro-dynamic shakers+power amplifiers**

**Rectangular Acrylic test sections**

- anechoic terminations
- open tubes of different lengths

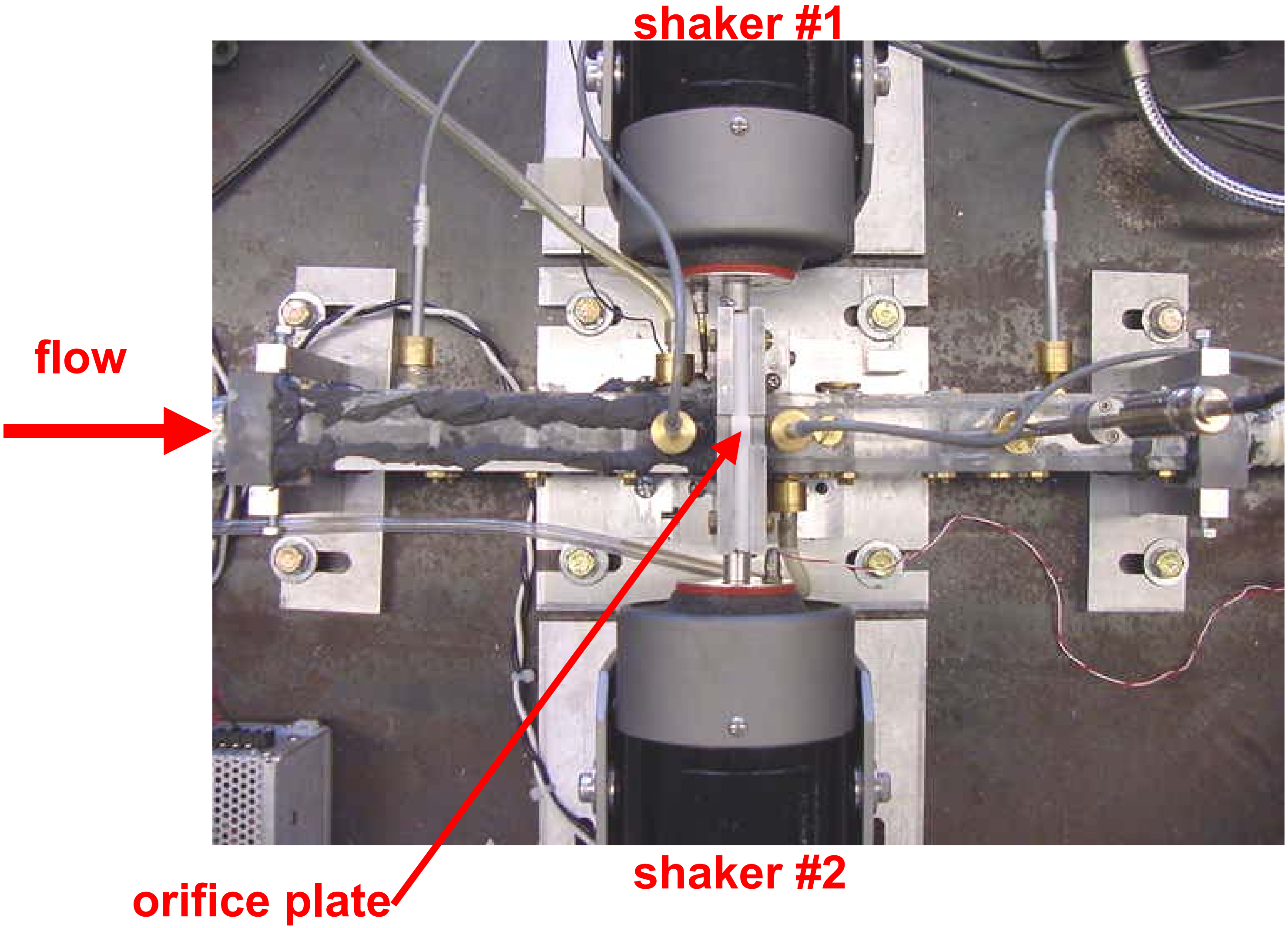
**Flow supply and controller**

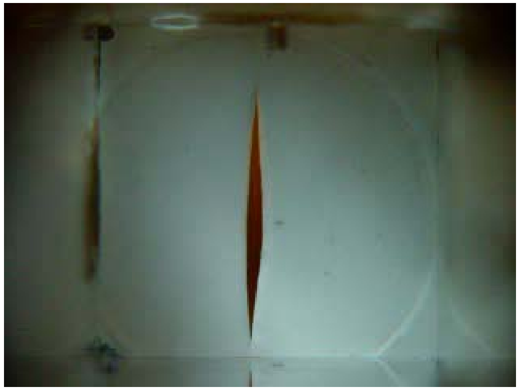
- air, helium, and $CO_2$ mixtures

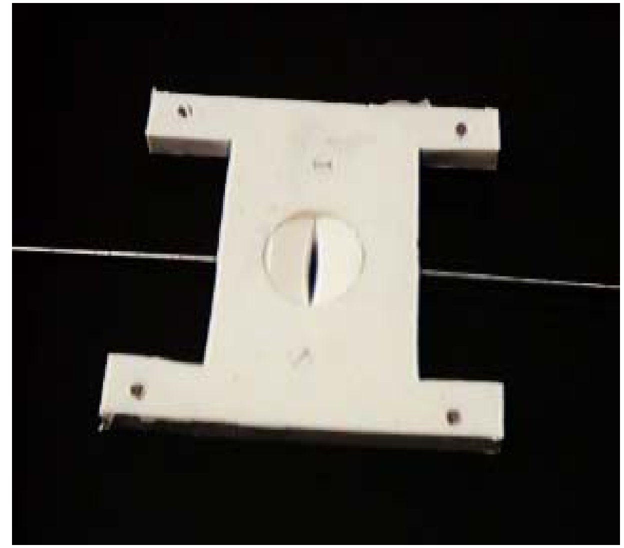
**Rubber glottis models (real size)**

- molds machined using Stereo Lithography
- geometry defined using CAD (proE)
- three geometries (convergent, straight, and divergent)

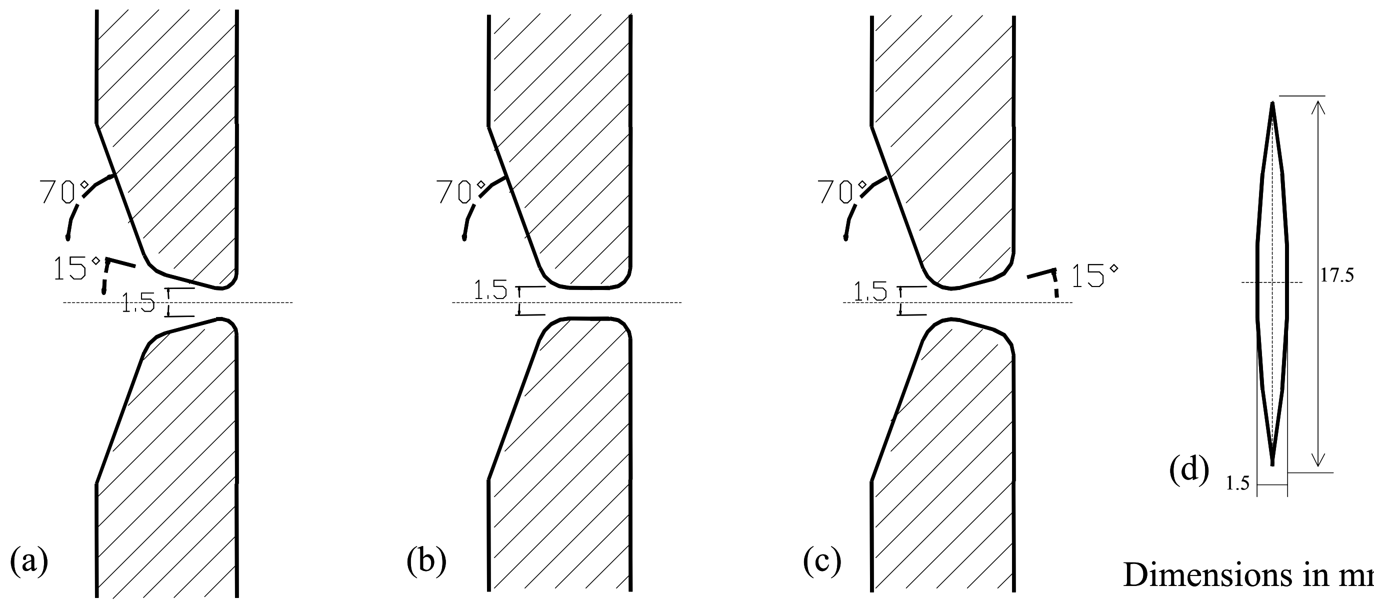
**Belt mechanical drive used for flow visualization**


shaker #1
flow
orifice plate
shaker #2



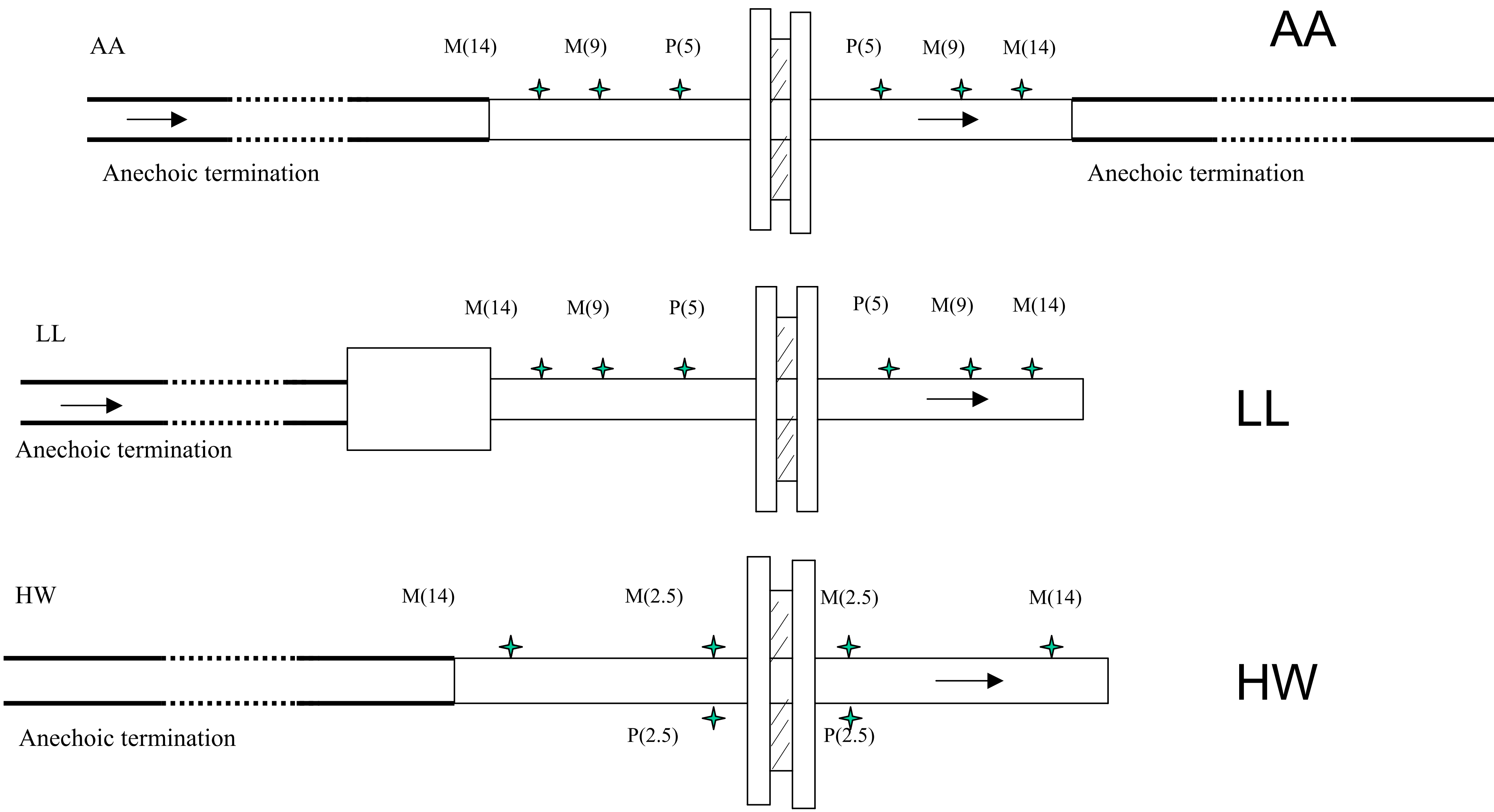


**100 Hz**

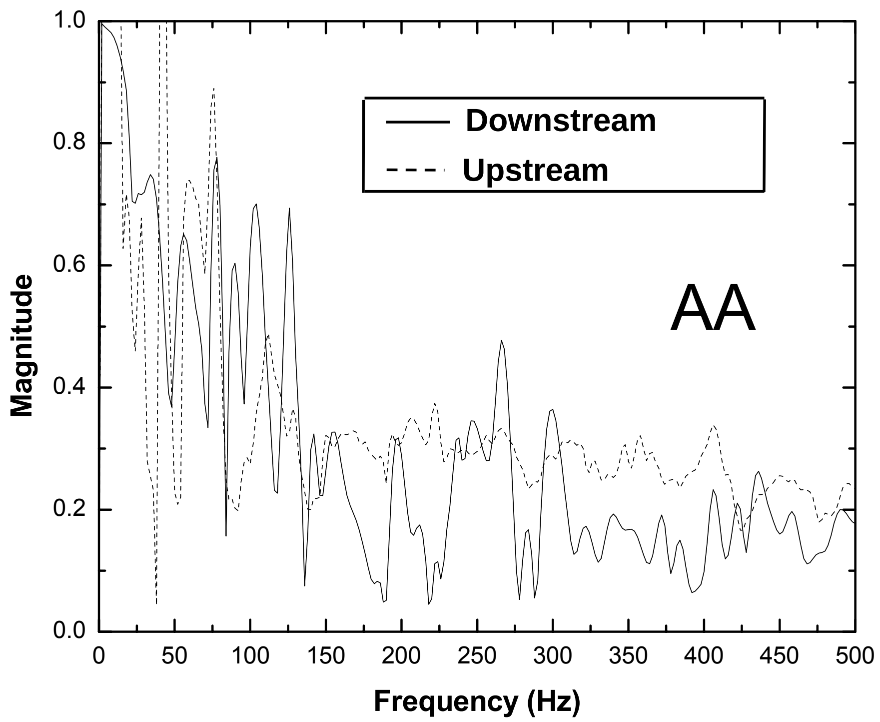


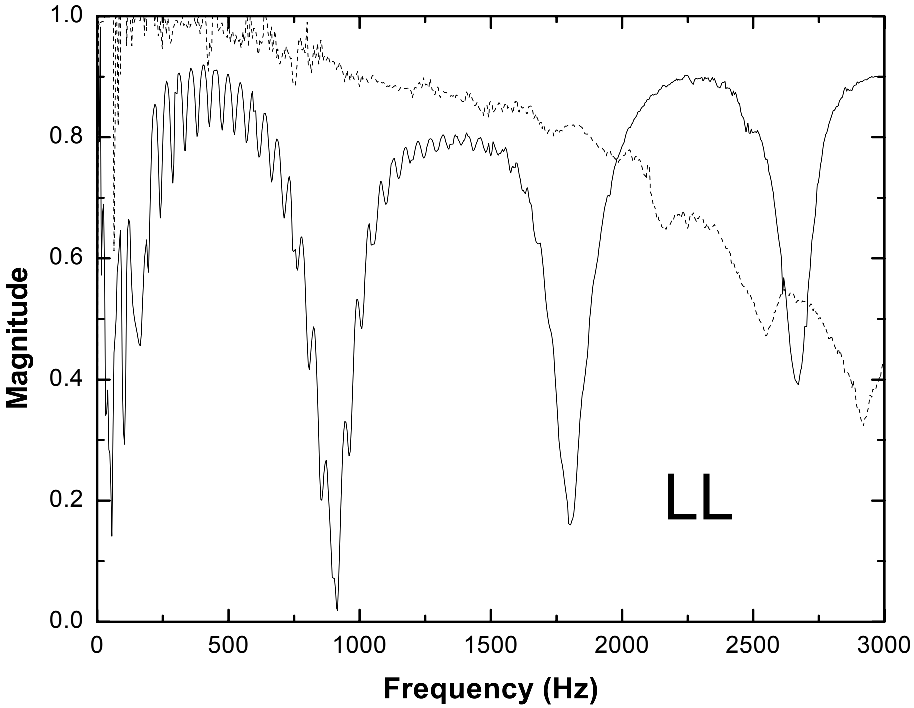

Dimensions in mm

# Tube configurations



# Reflection coefficients

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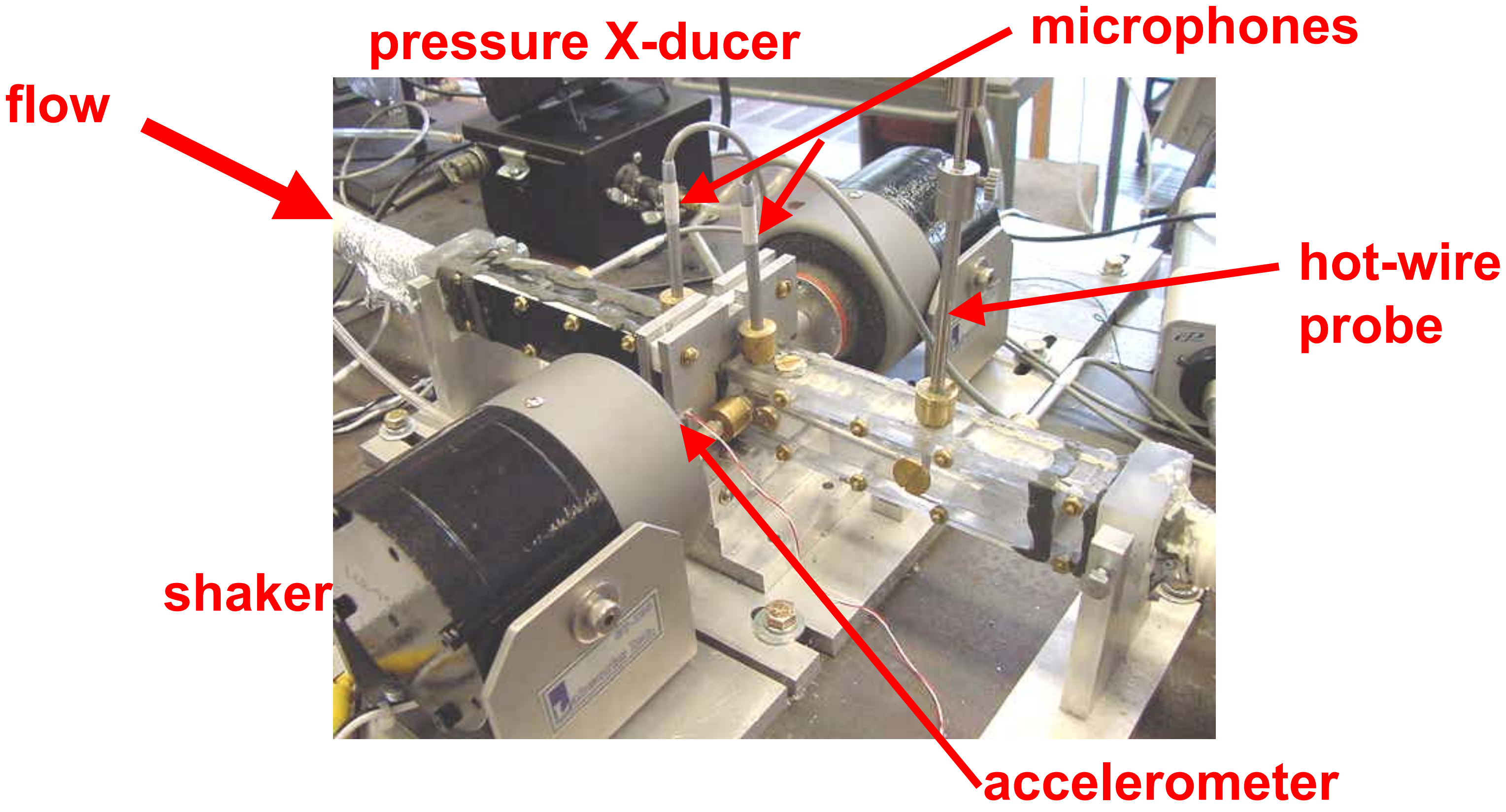
# Instrumentation

- Two pairs of phased-matched microphones
- Precision manometer
- Precision gas flow meter
- Photoelectric detector and light source
- Accelerometers
- Hot-wire anemometer (up to 6 channels)
- Data acquisition systems
- Smoke generator
- High-speed camera (NAC)

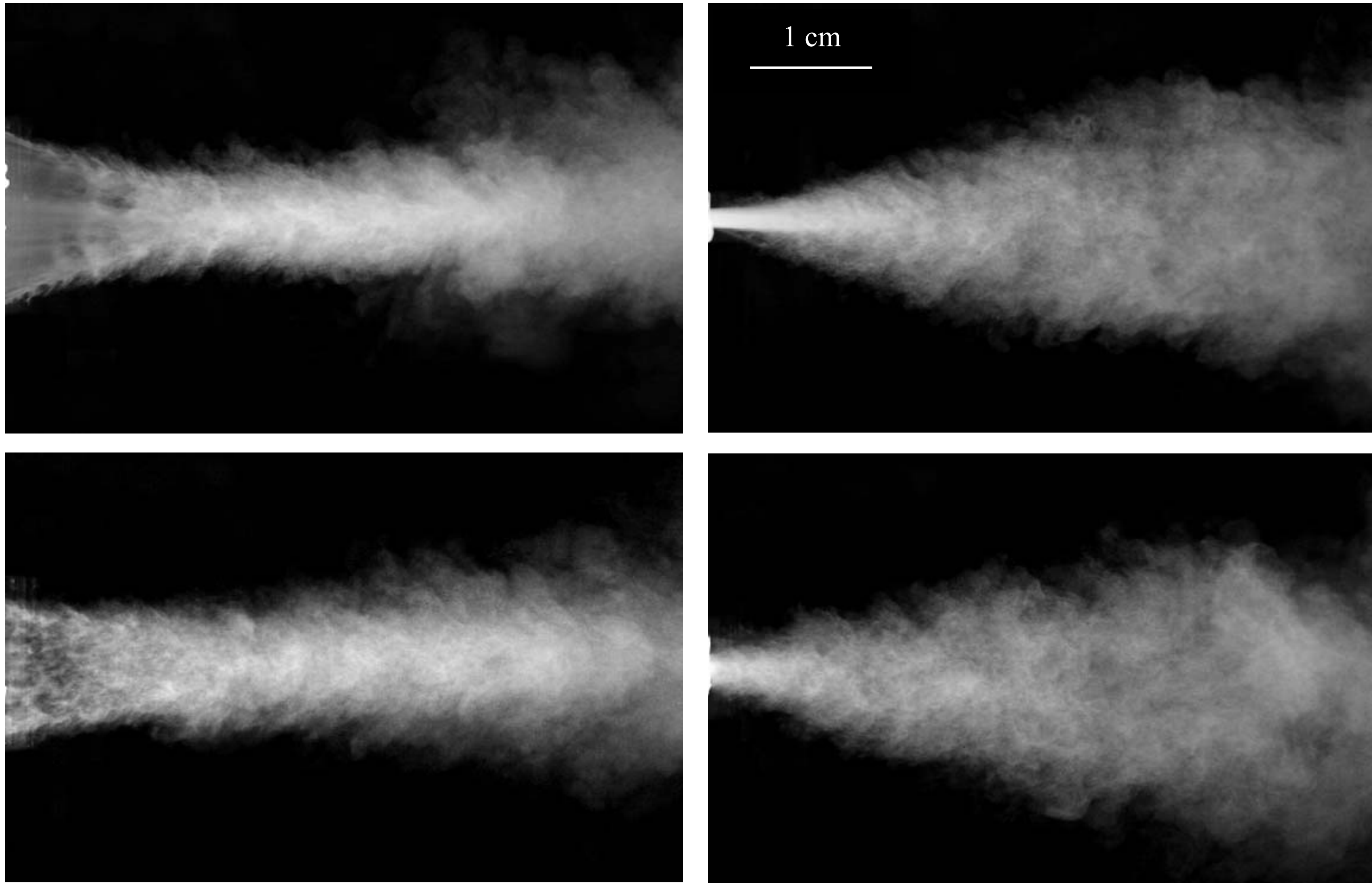

pressure X-ducer
microphones
flow
hot-wire
probe
shaker
accelerometer

# Flow Visualization

**steady open jet, 4 cm $H_2O$**

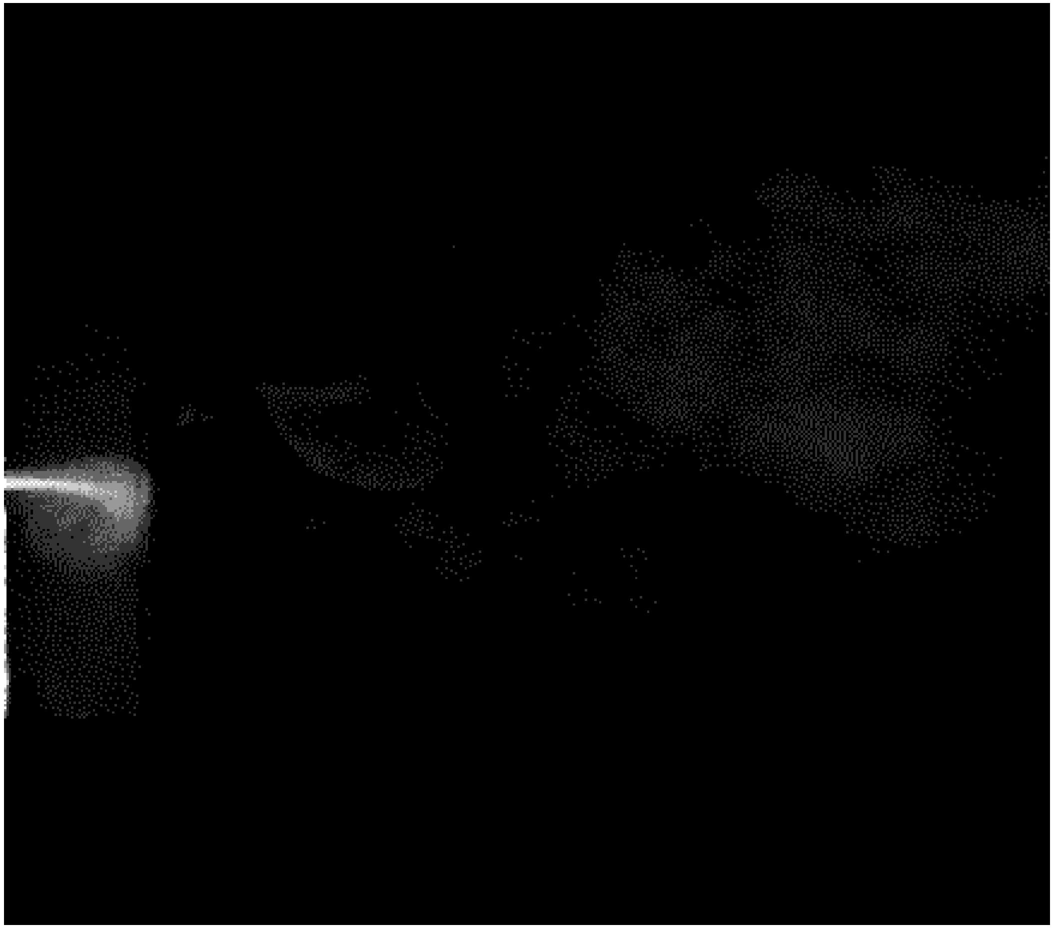
converging

diverging




span view

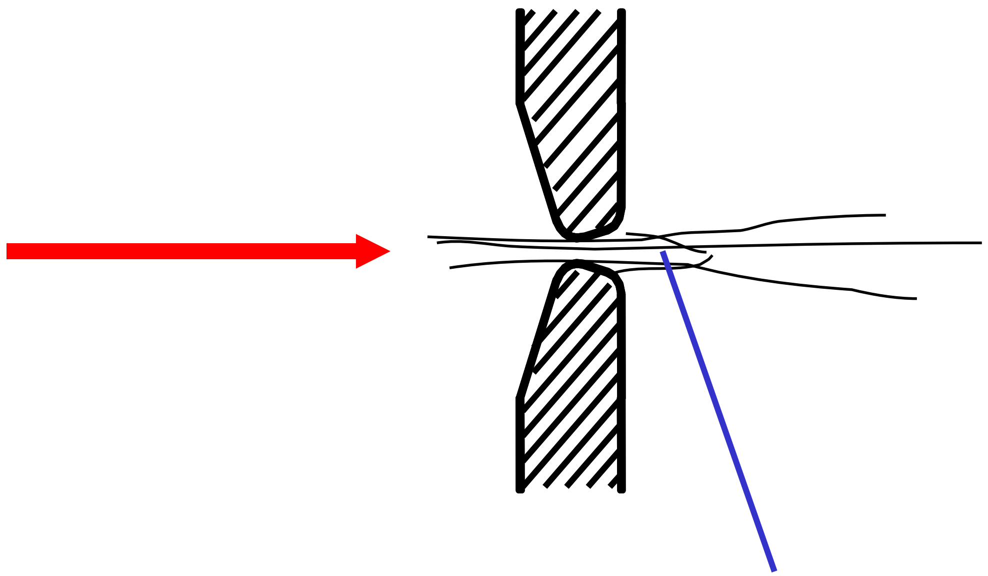
width view




1
2

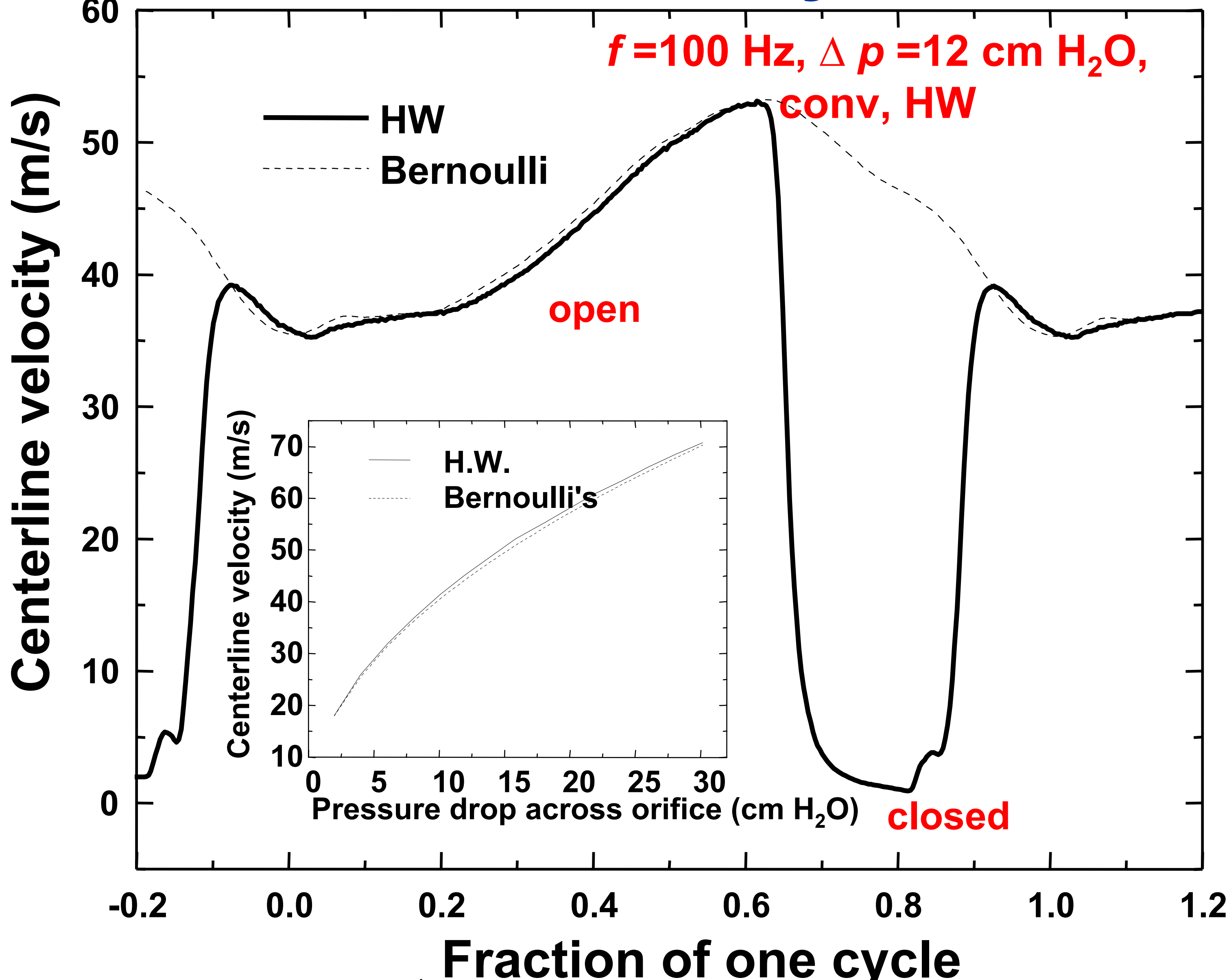
# Bernouilli's Equation

## Direct verification



**hot-wire anemometer**

# Hot-wire velocity data



# Bernouilli’s Obstruction Theory

## Indirect Method

- can’t easily measure instantaneous flow rate
- use inverse filter method
  - equivalent monopole strength

# Assumptions

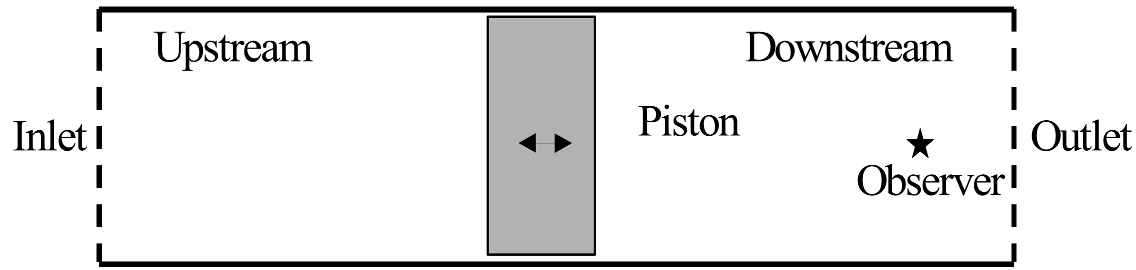
- flow through orifice at any instant same as steady incompressible flow for same wall geometry and inlet boundary condition
- monopole source
- plane waves
- source strength is fluctuating volume velocity at orifice

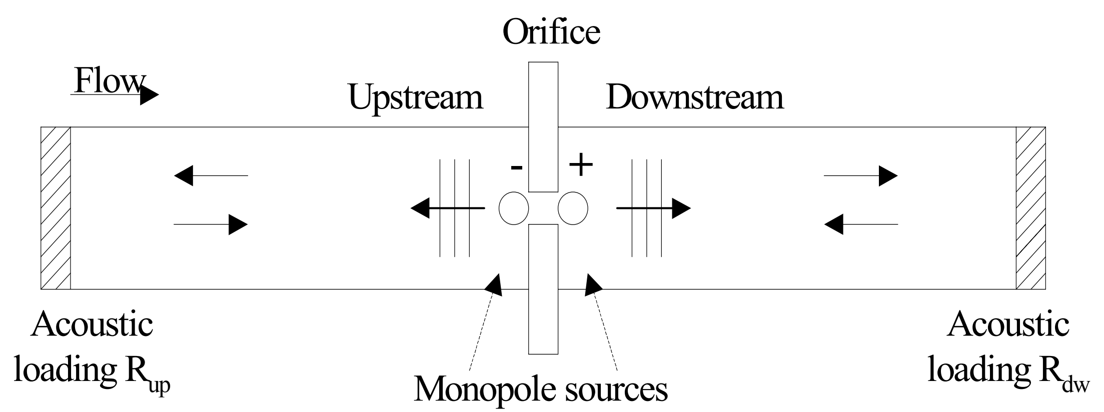
# Procedures

- iteration method
- Predict sound pressure using Bernouilli's equation (steady form), using measured orifice area, mean pressure drop across the orifice, and orifice discharge coefficients measured statically
- Reflections accounted for using signal processing techniques (deconvolution)
  - two-microphone method
  - low-pass filter

# equivalent monopole source model

- Dipole source due to unsteady pressure drop
- similar to vibrating piston
- Decompose into two monopole sources with equivalent source strength, each radiating to one side of the orifice
- two equivalent monopole sources equal in strength and opposite in phase



$$\Delta p(t) = \Delta p_0 + p'_{up}(0,t) - p'_{dn}(0,t) = \tfrac{1}{2}\rho_0 U_c^2$$

$$Q = C_d A_g U_c$$

$$u'_{up}(0,t) = \int \frac{B_{up}(0,\omega)}{\rho_0 c}\{e^{j(\omega t - kL)} - R \cdot e^{j(\omega t + kL)}\} d\omega = -\frac{1}{A_t}\{Q(t) - Q_0\}$$

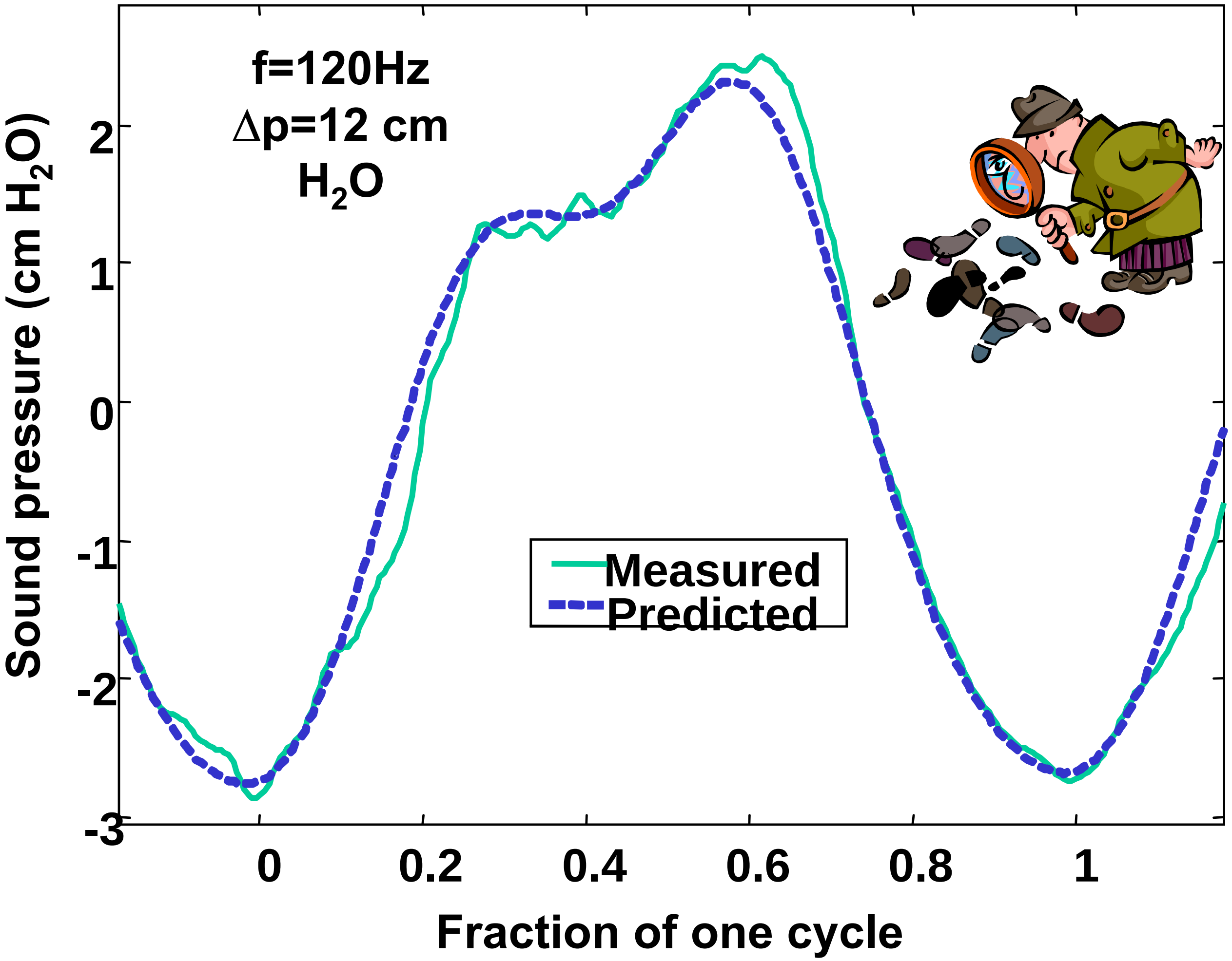
$$u'_{dn}(0,t) = \int \frac{B_{dn}(0,\omega)}{\rho_0 c}\{e^{j(\omega t - kL)} - R \cdot e^{j(\omega t + kL)}\} d\omega = \frac{1}{A_t}\{Q(t) - Q_0\}$$

$$p'(x,t) = \int B(x,\omega)\{e^{j(\omega t - k(L-x))} + \hat{R} \cdot e^{j(\omega t + k(L-x))}\} d\omega$$

**$C_d$: orifice discharge coefficient obtained in steady flow measurement**
***R*: reflection factor measured using two-microphone method**
***B*: coefficient to be determined**
**$A_t$: orifice area measured using a photoelectric sensor**

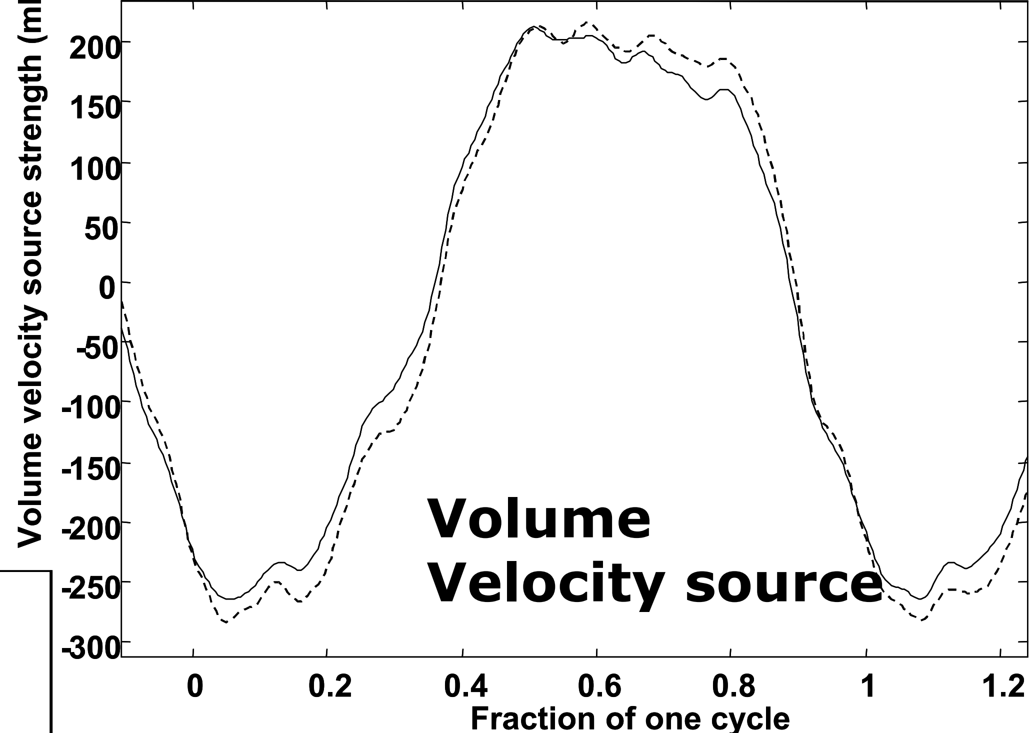
# Typical Result

Comparison between measured upstream sound pressure and prediction from quasi-steady assumption



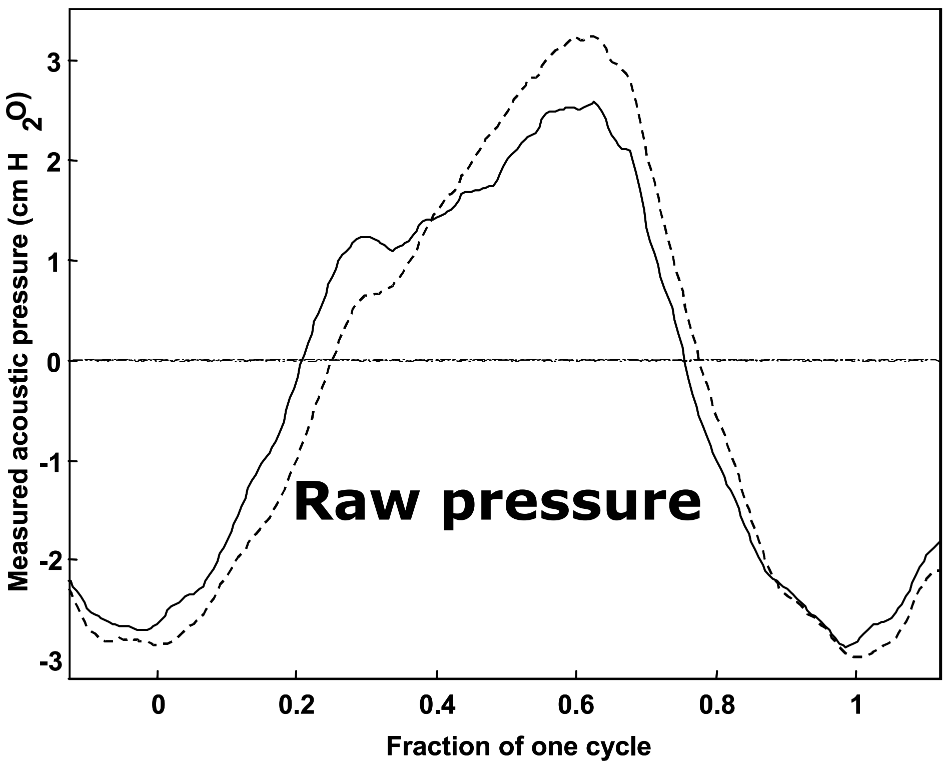
# Results

- $f$=80 Hz, $\Delta p_0$=12 cm $H_2O$, convergent orifice, AA

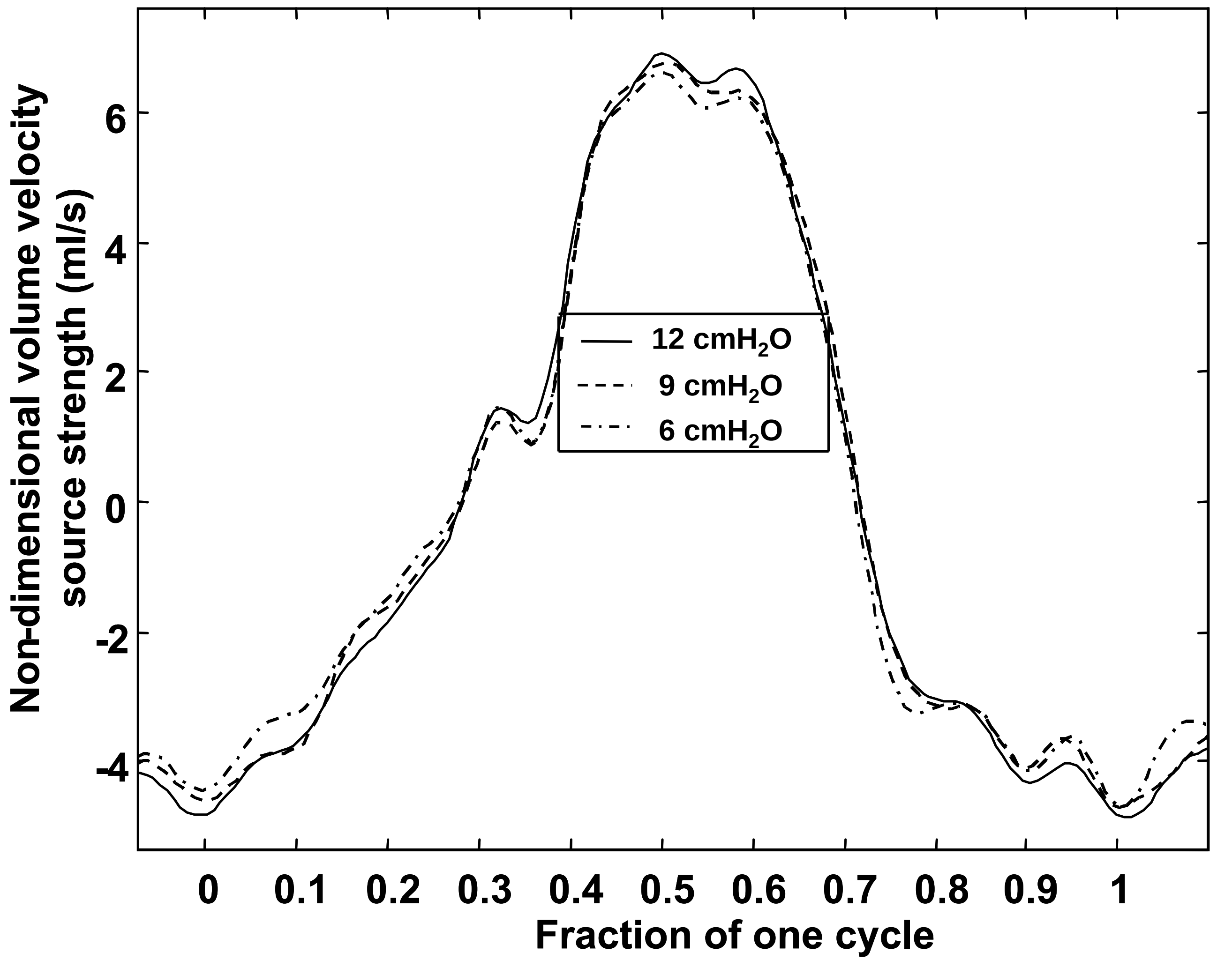



Upstream

Downstream * (-1)

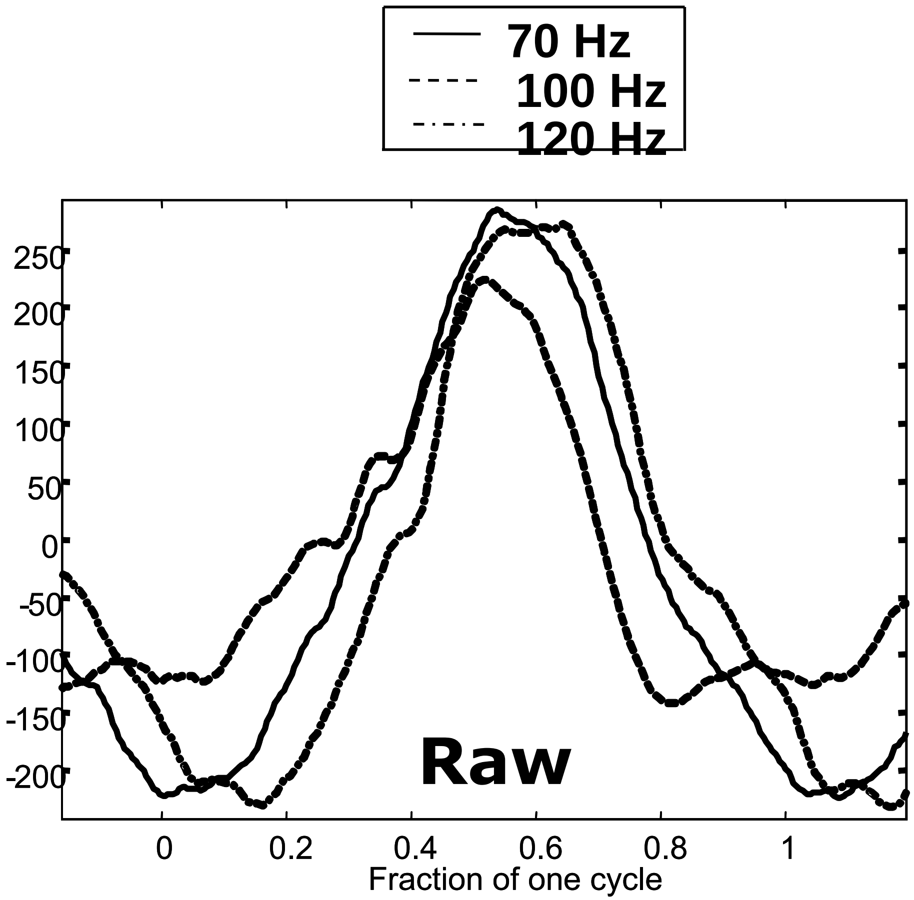


# Effects of Mean Pressure

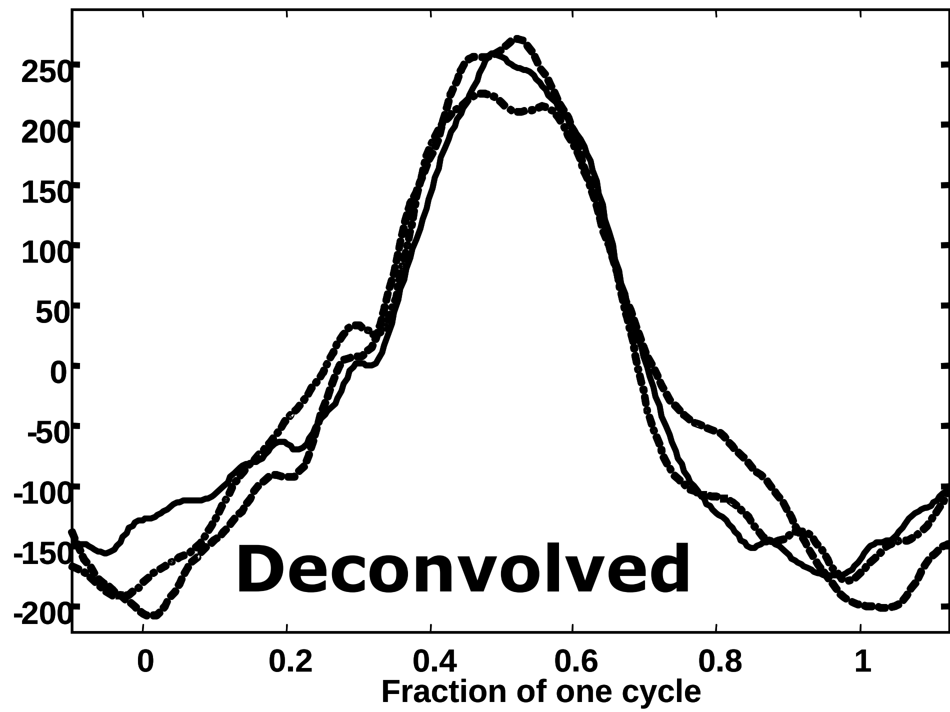



**Volume velocity source at different pressure drop scaled by the square root of the mean pressure drop. Straight orifice, f=120 Hz.**

# Effects of Driving Frequency



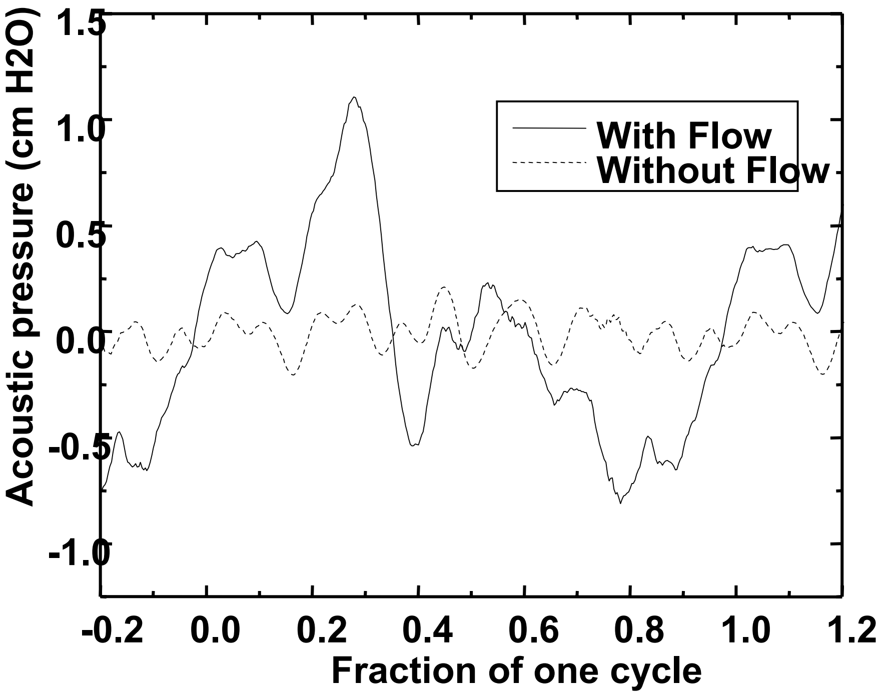

**Convergent orifice**
**$\Delta p_0$=12 cm $H_2O$**




**Volume velocity source strength (ml/s)**

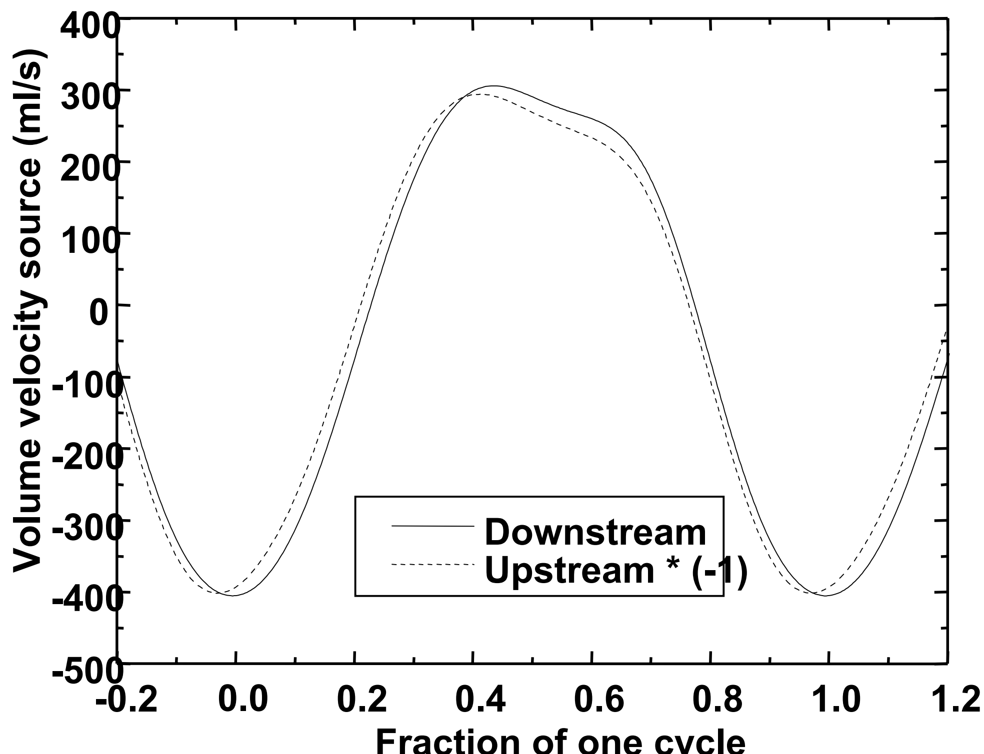
- **Driving frequency has small effect on source strength**
- **consistent with quasi-steady assumption**

# Effects of acoustic loading



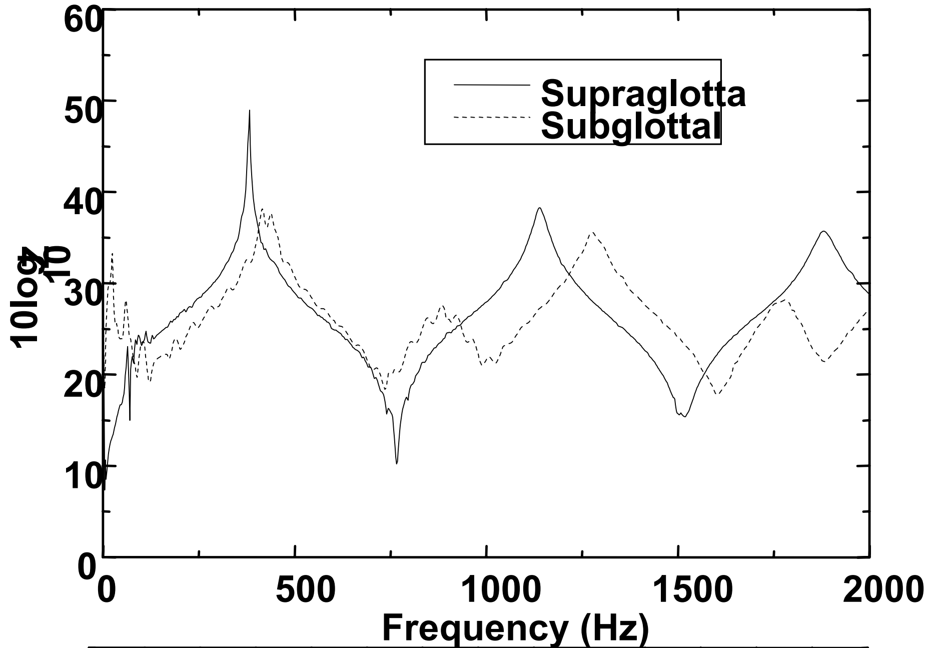

- downstream tube modeled as close-open tube
- velocity node at orifice
- resonance
- monopole ideal velocity source
- monopole source amplified
- dipole source at pressure anti-node

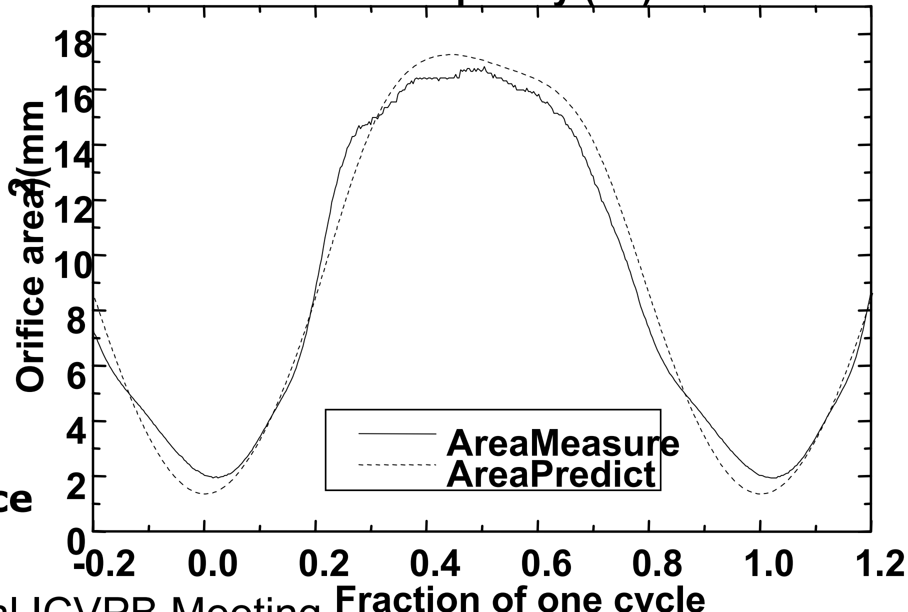
- f=100 Hz, Δp0=12 cm H2O, divergent orifice
- Upstream and downstream volume velocity sources agree well



# Orifice area function

- Resonance in both subglottal and supraglottal systems (first resonance around 450 Hz)
- This causes errors in reflection coefficient measurements and leads to the failure of the iteration method
- Area can still be predicted using measured sound pressure and statically measured orifice discharge coefficient




**f=100 Hz, Δp0=12 cm H2O, divergent orifice**

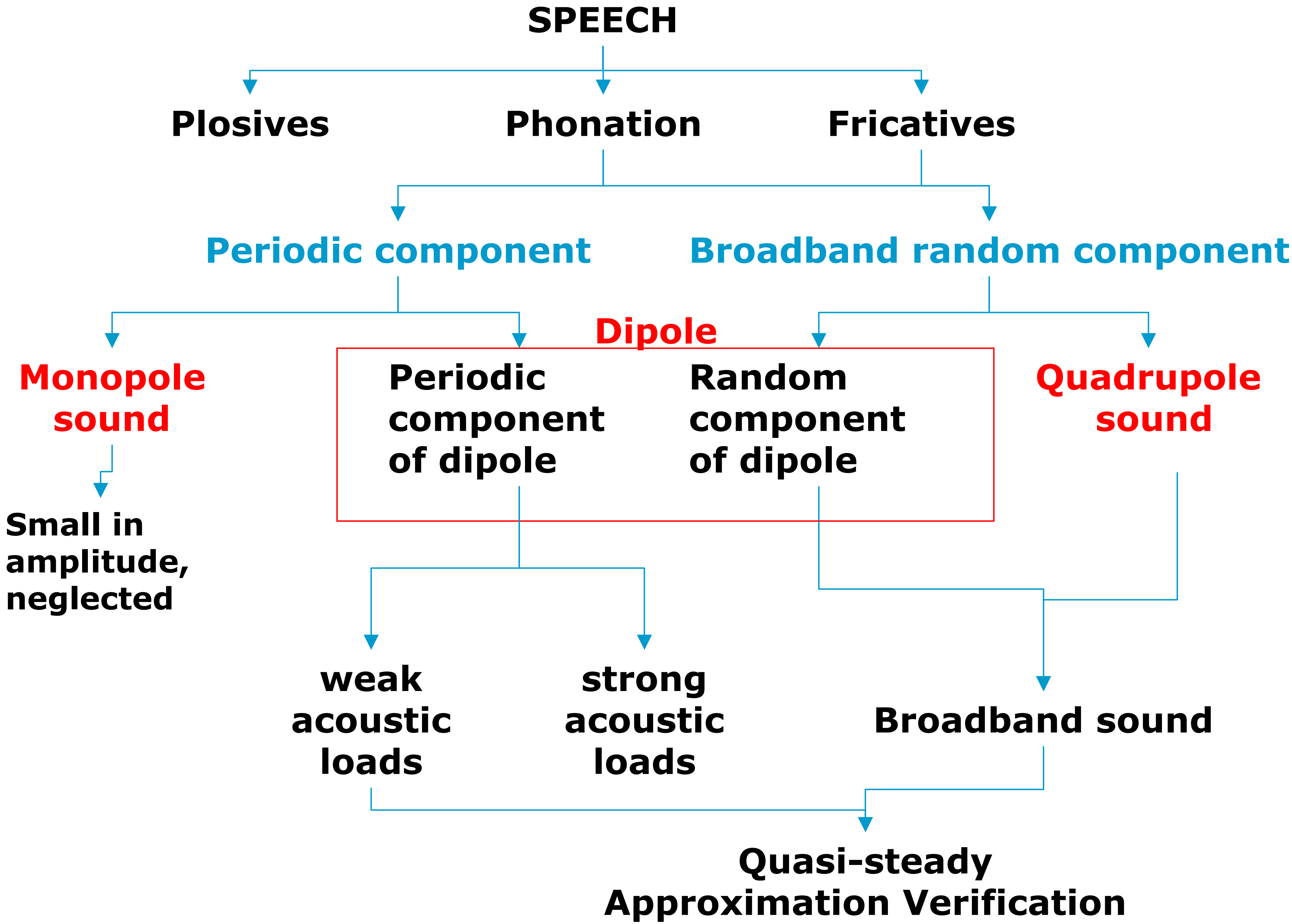
# Tonal Component Results

- Good agreement between measured upstream sound pressure and prediction from quasi-steady assumption
- Quasi-steady assumption valid for different orifice shapes at different operating conditions (driving frequency up to 120Hz)
- Suggests monopole model could be used in conjunction with 3-D incompressible steady numerical models

# Broadband Sound Production by Non-stationary Turbulent Jets

**Periodic component obtained by ensemble-averaging method, and extracted from signals**

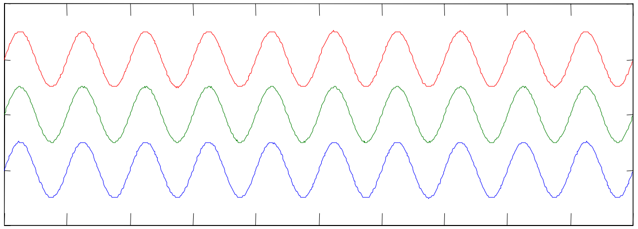
**Statistics of turbulent sound in non-stationary flow at a particular instant compared to those for comparable stationary flow**


SPEECH
Plosives
Phonation
Fricatives
Periodic component
Broadband random component
Dipole
Monopole sound
Periodic component of dipole
Random component of dipole
Quadrupole sound
Small in amplitude, neglected
weak acoustic loads
strong acoustic loads
Broadband sound
Quasi-steady Approximation Verification

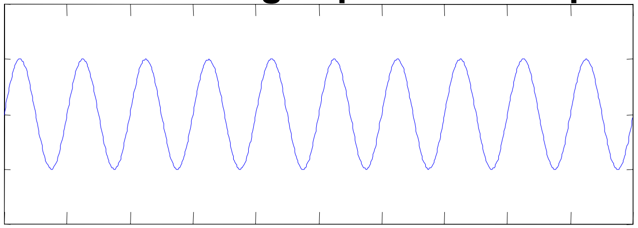
# Broadband Sound in Pulsating Jets

- Orifice area is forced at specific frequency
- Sound pressure is decomposed into a periodic component and a broadband component
- Periodic component obtained by ensemble-average method
- Broadband sound obtained by removing periodic component sound from measured pressure
- Characteristics of broadband sound for non-stationary jet at a particular instant compared to those of stationary jets with same flow and orifice geometry
- Two methods:
  - Probability density function (PDF)
  - Wavelet transform

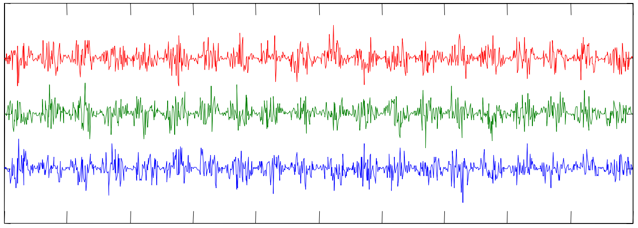
**Measured sound pressure**



**Ensemble-averaged periodic component**

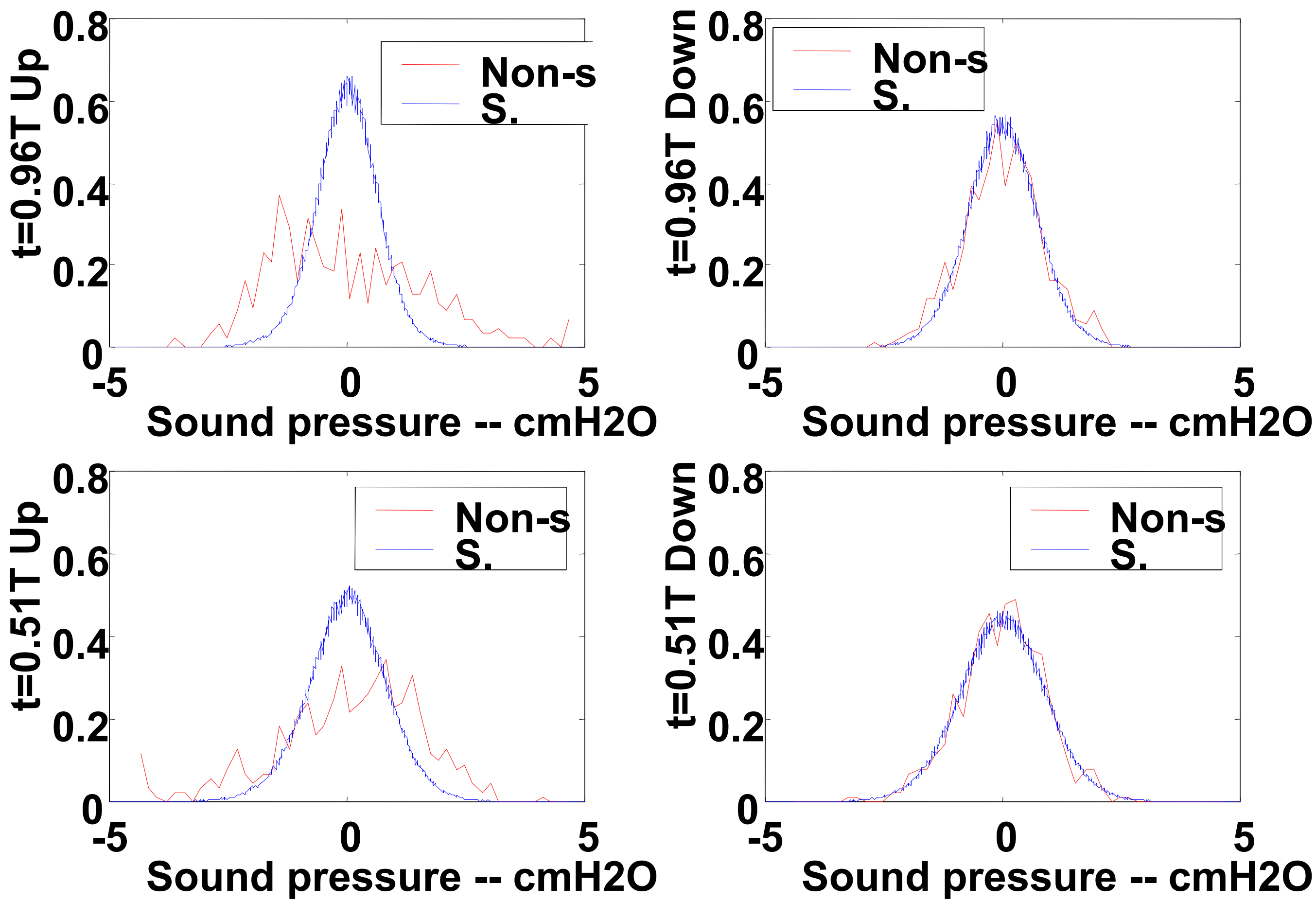


**Turbulence generated sound**



# Broadband Sound Production by Non-stationary Turbulent Jets

Comparison between probability density functions

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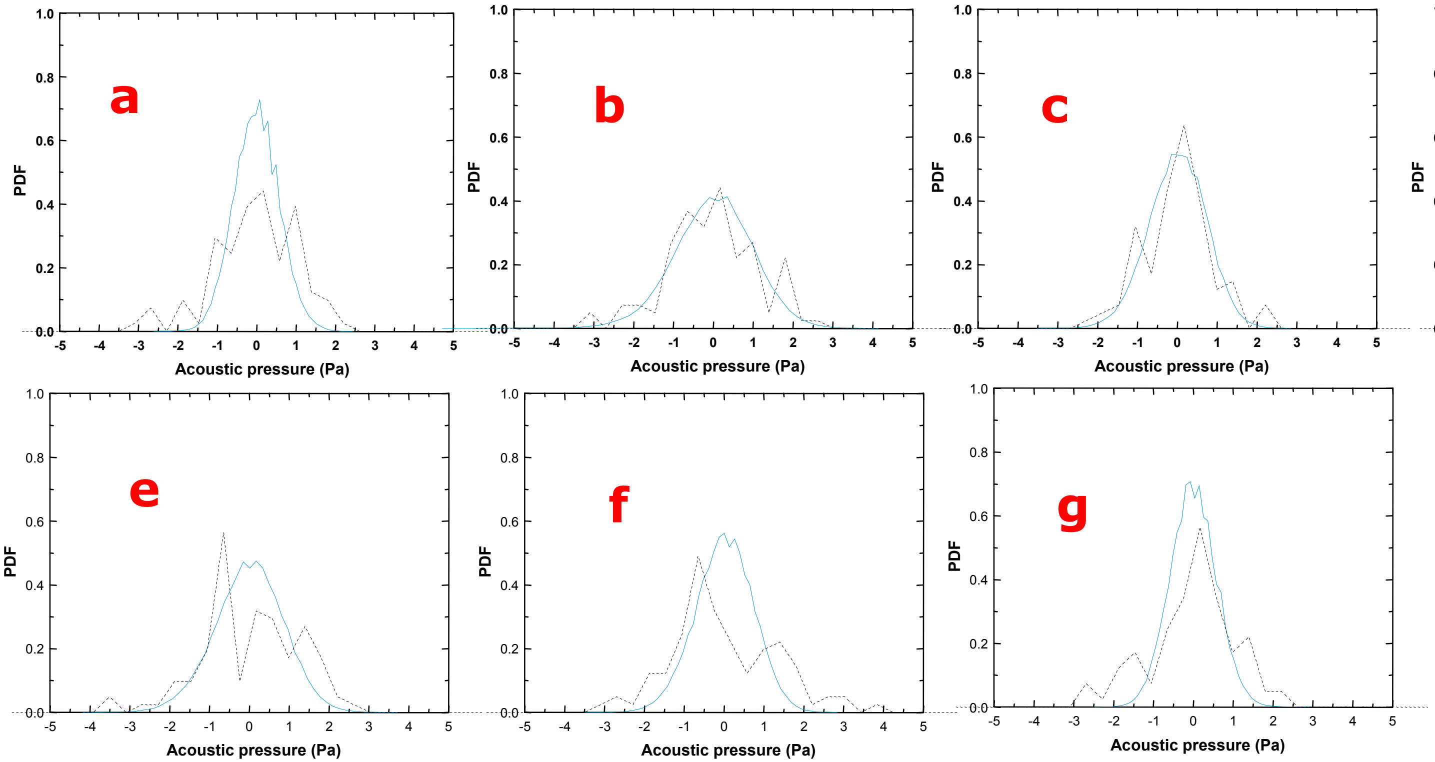
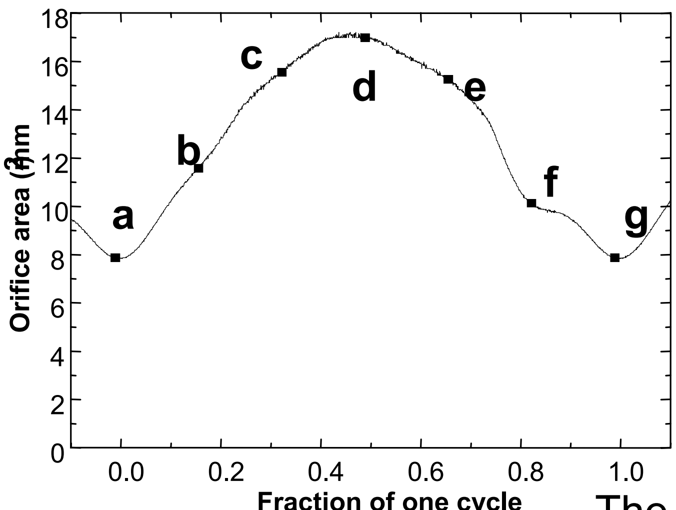
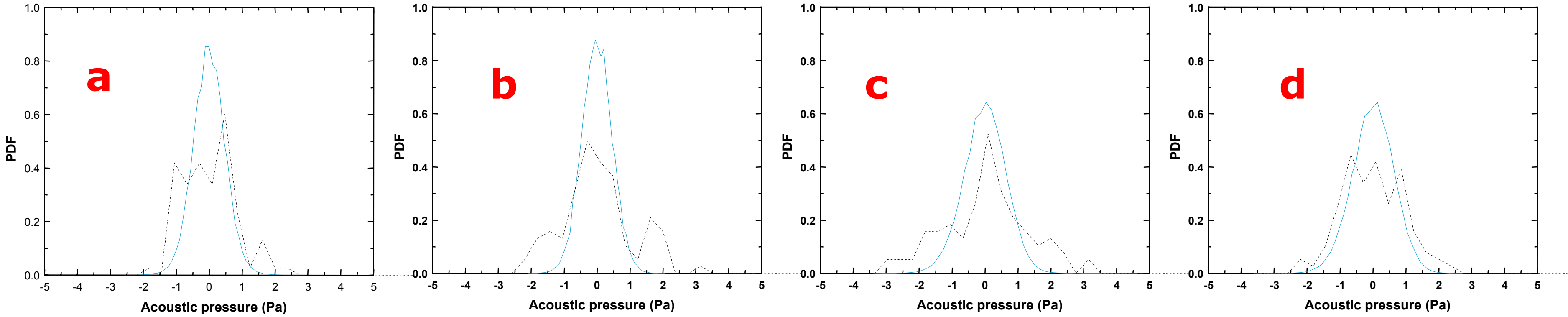
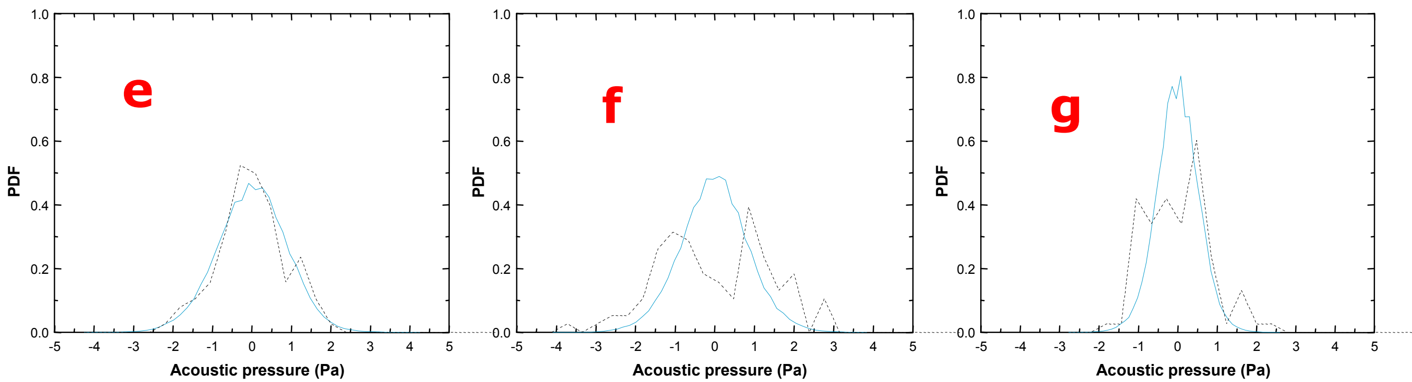



**f=20 Hz,**
**$\Delta p_0$=12 cm $H_2O$,**
**Divergent orifice.**

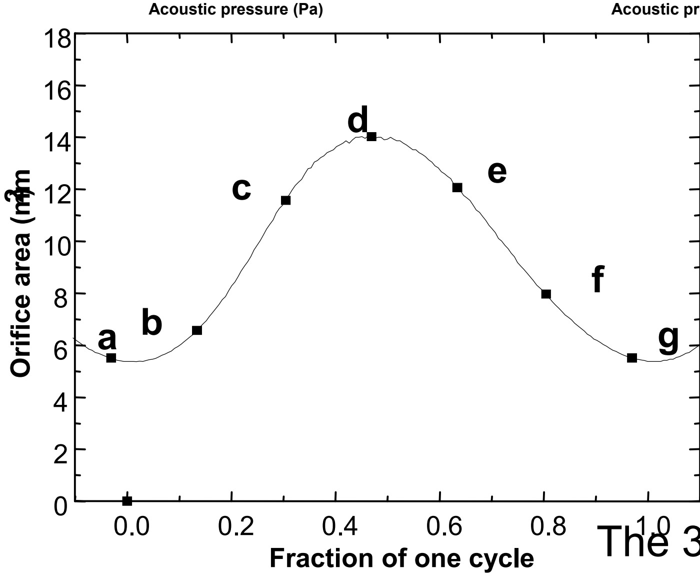



- **Agreement between PDFs evolves during one cycle**
- **Poor agreement during the beginning of orifice opening**
- **Agreement improves as the orifice continues to open**
- **Agreement decreases as the orifice begins to close**




**f=200 Hz,**
**$\Delta p_0$=12 cm $H_2O$,**
**Divergent orifice**

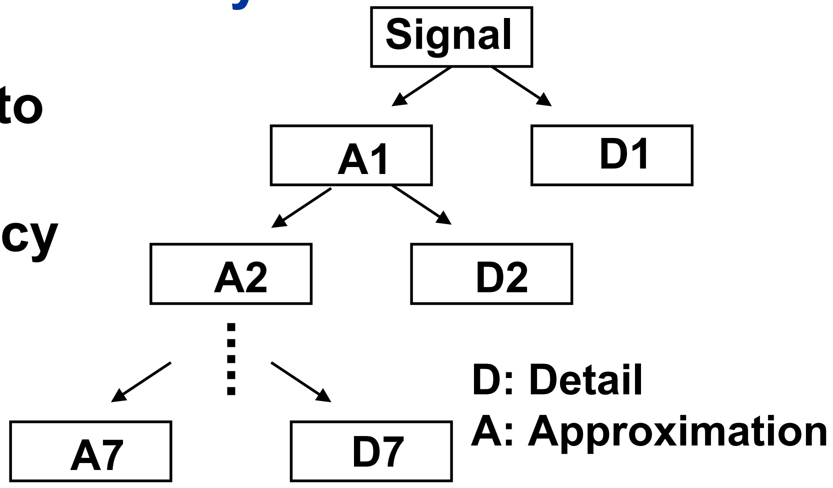



- **As driving frequency increases, general agreement between PDFs decreases, especially during the orifice opening stage**
- **quasi-steady approximation may not be valid for broadband component**

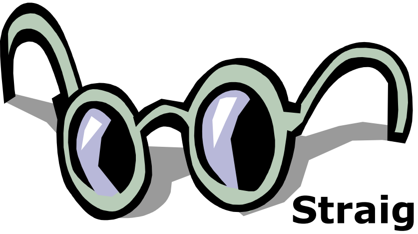
# Wavelet Analysis

- Provides time information as well as frequency information
- In STFT the size of the sliding window is fixed, while in wavelet analysis the window size is changeable, therefore giving same resolution for different frequency component
- Daubechies 1 wavelet (a step function) used (similar results obtained with db2)
- 7-level wavelet transform used in this study

**At each level, signal is decomposed into a *Detail* and an *Approximation*. The *Detail* corresponds to the high frequency component while the *Approximation* corresponds to the low frequency component.**




**S=A7+D7+D6+D5+D4+D3+D2+D1**

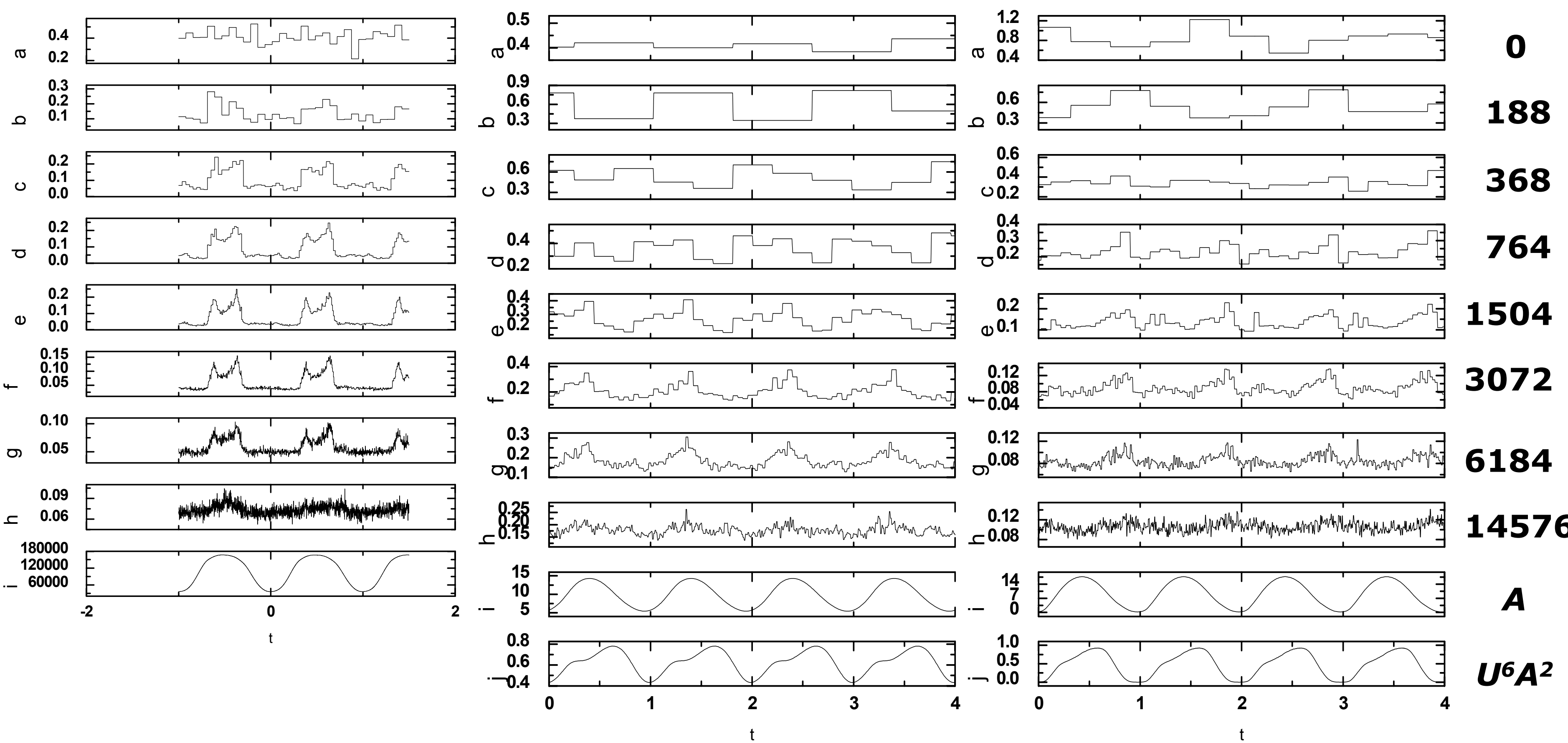


# Wavelet Coefficients

**Straight, 20 Hz, 12 $cmH_2O$**

**Divergent, 200 Hz, 12 $cmH_2O$**

**Convergent, 200 Hz, 12 $cmH_2O$**



# Summary

- Turbulent sound synchronous with modulation of orifice area
- Two peaks during one cycle:
  - first peak may be associated with the developing of the jet
  - second peak associated with the quenching of the flow during closure.
- First peak less apparent for high-frequency component
- For same level of details, first peak becomes less apparent as the driving frequency increases

# Conclusions

- **quasi-steady approximation verified in confined jets for tonal sound component across various flow conditions, orifice geometries, and acoustic loads**
- **non-stationary broadband investigated using PDF comparisons and wavelet analysis**
- **broadband sound generation appears to be non-stationary (not quasi-steady)**

# Ongoing Work

## Validation of quasi-steady assumption

- Coanda Effect
- Complex geometries (pathological)

## Acoustic scaling laws

- Tonal and broadband
- Evaluate impact on articulatory speech synthesis

## Adina Simulations

# For more …

Zhaoyan Zhang, "Experimental study of sound generation by confined jets with application to human phonation," Ph.D. Dissertation, Purdue University, 2002.
Cheng Zhang, "____," M.S.M.E. Thesis, Purdue University, 2002.
Wei Zhao, "A numerical investigation of sound generated from subsonic jets with application to human phonation," Ph.D. Thesis, Purdue University, 2000.