Vocal Folds Dynamics

Depth-Kymography
From 2D to 3D in Voice Diagnostics

Frits F.M. de Mul, Nibu A. George, Qingjun Qiu, Harm K. Schutte

Groningen Voice Research Lab.
University of Groningen, University Medical Center UMCG
Kolff Institute - Department of Biomedical Engineering BMSA
Groningen, the Netherlands.

www.demul.net/frits

Version 2

Depth Kymography
from 2D to 3D in Voice Diagnostics

- **First Video-kymography project**:
  "Voice Diagnostics in a New Perspective"
- **Goal:**
  To develop and apply a new type of video-camera
  to image Vocal Folds and
  their **horizontal** positions and movements
  in patients.
- **This (second) project:**
  To measure **vertical** positions and movements
  of vocal folds as well.
  - Experimental: develop instrumentation
  - Numerical: develop simulation of dynamics
  - Develop method to compare measurements and simulations
- **Project financed by Dutch Technology Foundation NWO/STW: no. 6633**

Publications :

1. New Laryngoscope for quantitative high-speed imaging of human vocal folds vibration in the horizontal and vertical direction
   Nibu A. George, Frits F.M. de Mul, Qingjun Qiu, Gerhard Rakhorst and Harm K. Schutte, Journ.Biomed.Optics, 13(6), 064024 (2008)

2. Depth Kymography: high-speed calibrated 3D imaging of human vocal fold vibration dynamics
   Nibu A. George, Frits F.M. de Mul, Qingjun Qiu, Gerhard Rakhorst and Harm K. Schutte, Phys.Med.Biol. 53 (2008) 2667-2675

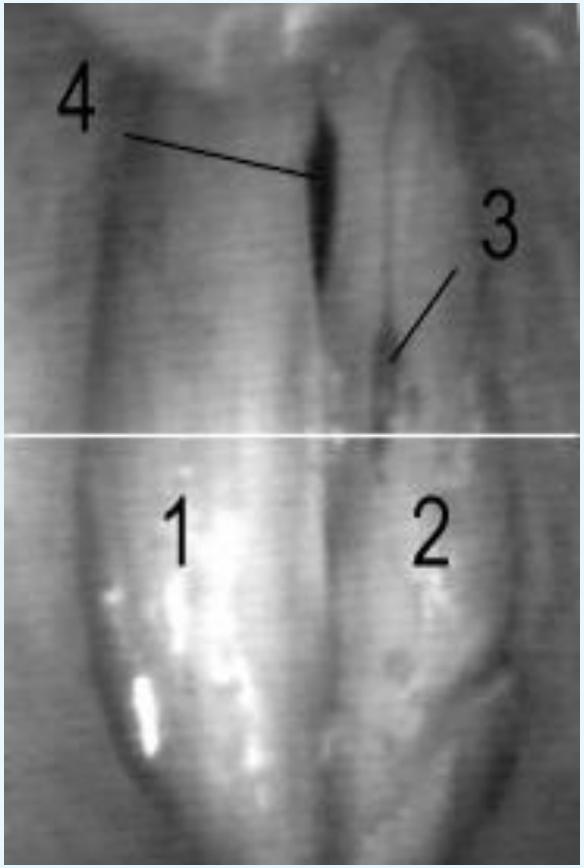
3. Depth Kymograhpy of Vocal Fold Vibrations: part II. Simulations and direct comparisons with 3D profile measurements
   Frits F.M. de Mul, Nibu A. George, Qingjun Qiu, Gerhard Rakhorst and Harm K. Schutte, Phys.Med.Biol. 54 (2009) 3955-3977.

References: in these papers.

More details and the simulation program can be downloaded from www.demul.net/frits

Contents:

Vocal Folds: top view



1,2: Right and left vocal fold

3: Blood vessel

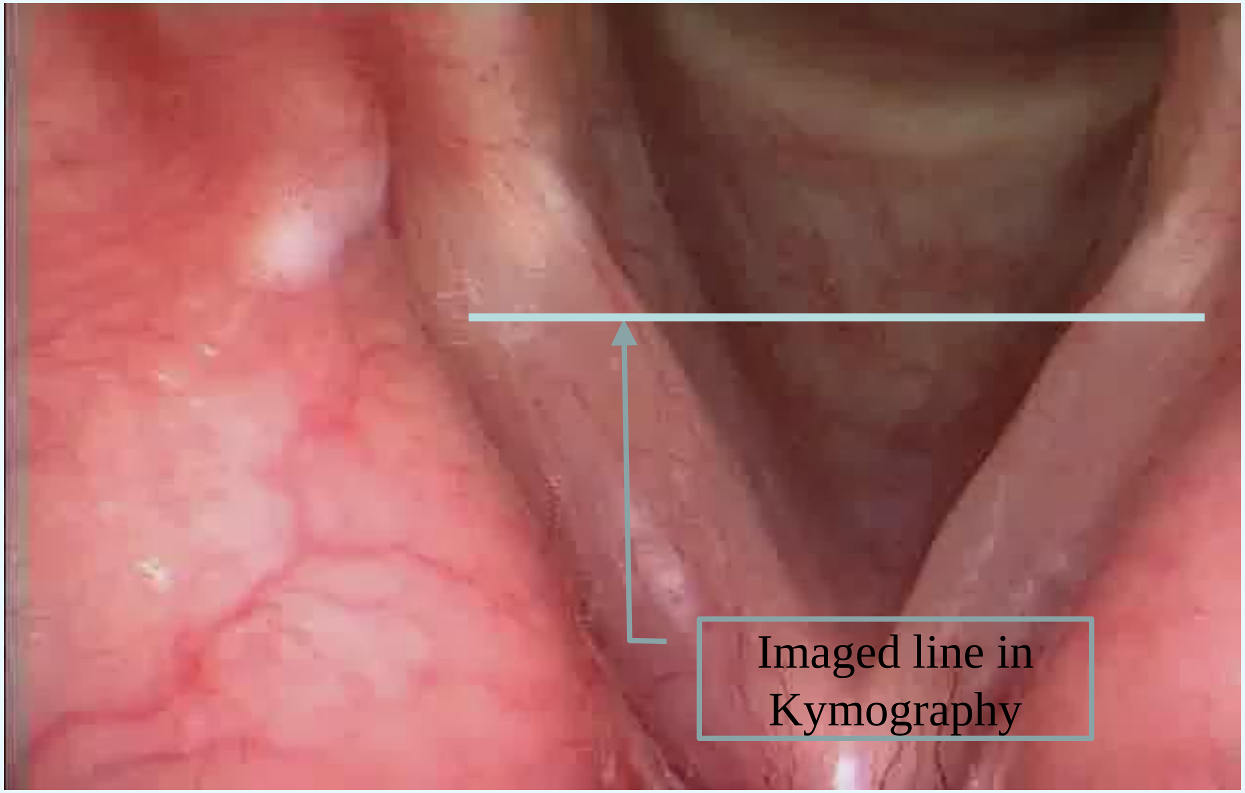
4: Glottis: opening between folds, partly or completely closed during phonation

Imaged line in Videokymography

Depth Kymography
from 2D to 3D in Voice Diagnostics

Vocal folds:
top view

Stroboscopic image

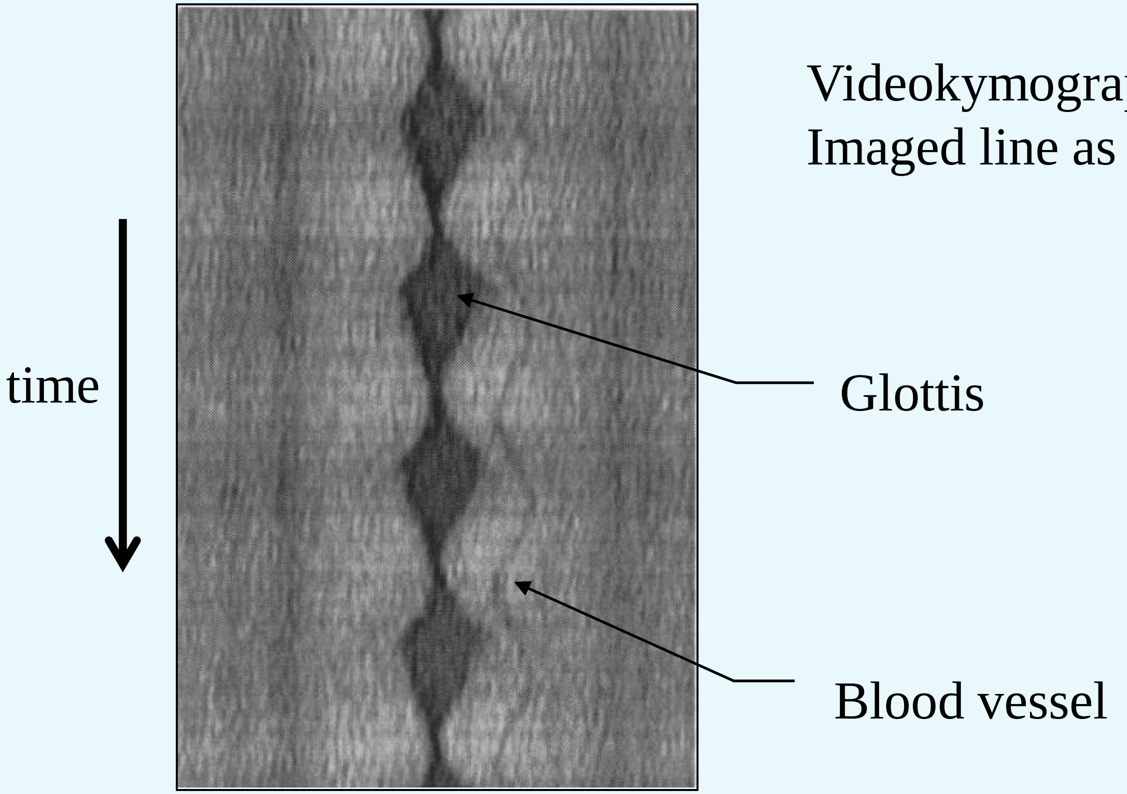


Model:
Vocal folds consist of 2 x 2 masses:
left/right and upper/lower

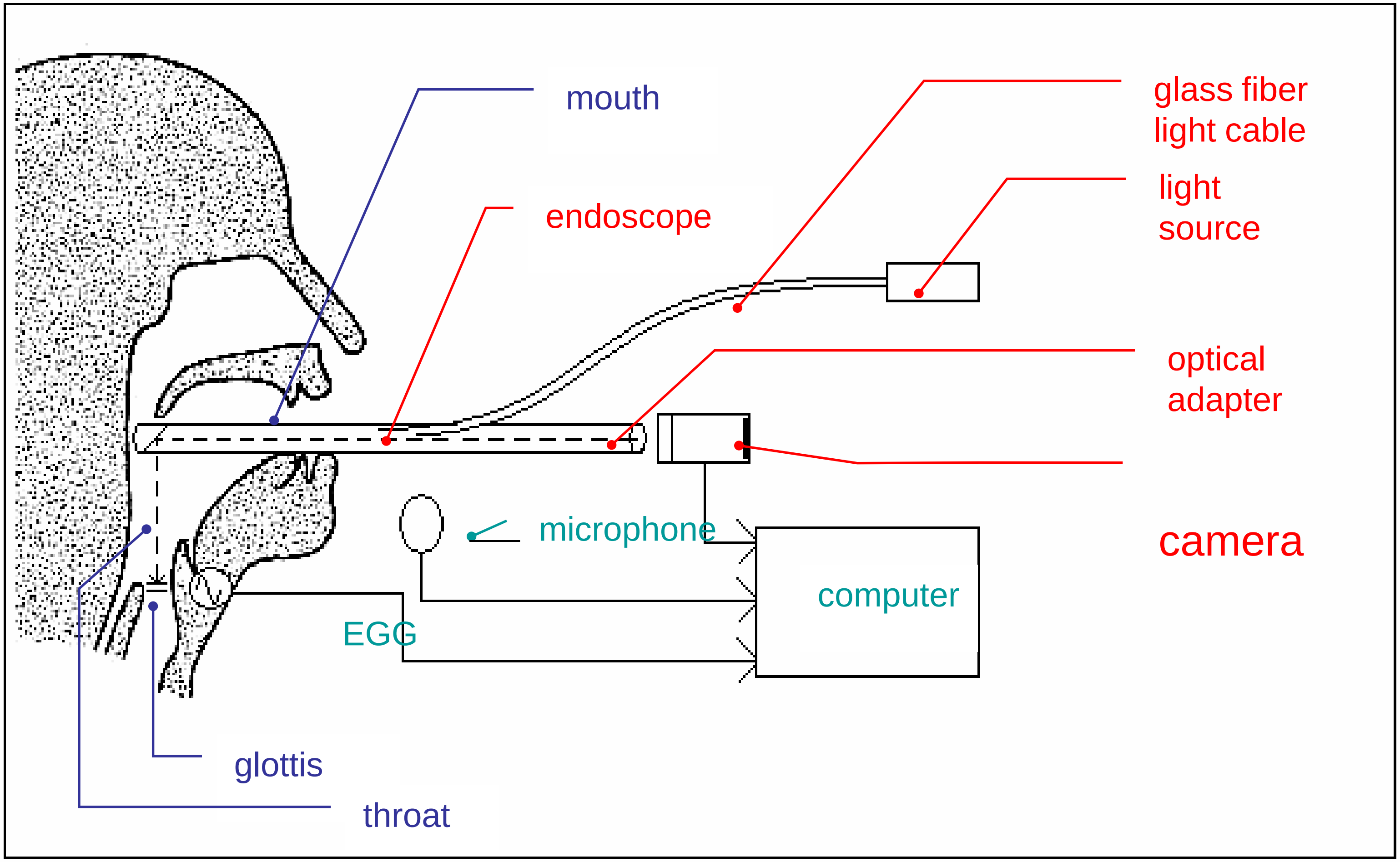
Contents:

Vocal Folds: top view

Videokymography:
Imaged line as a function of time



2D-Videokymography system



2D-Videokymography system

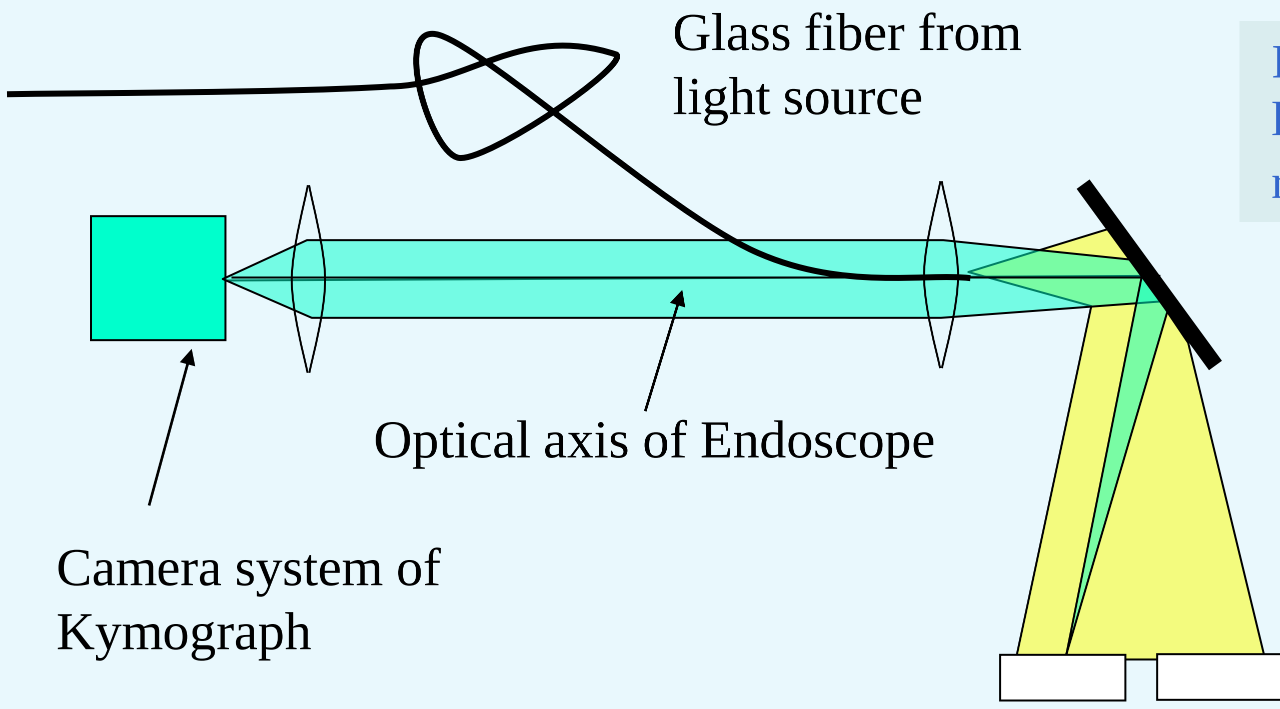
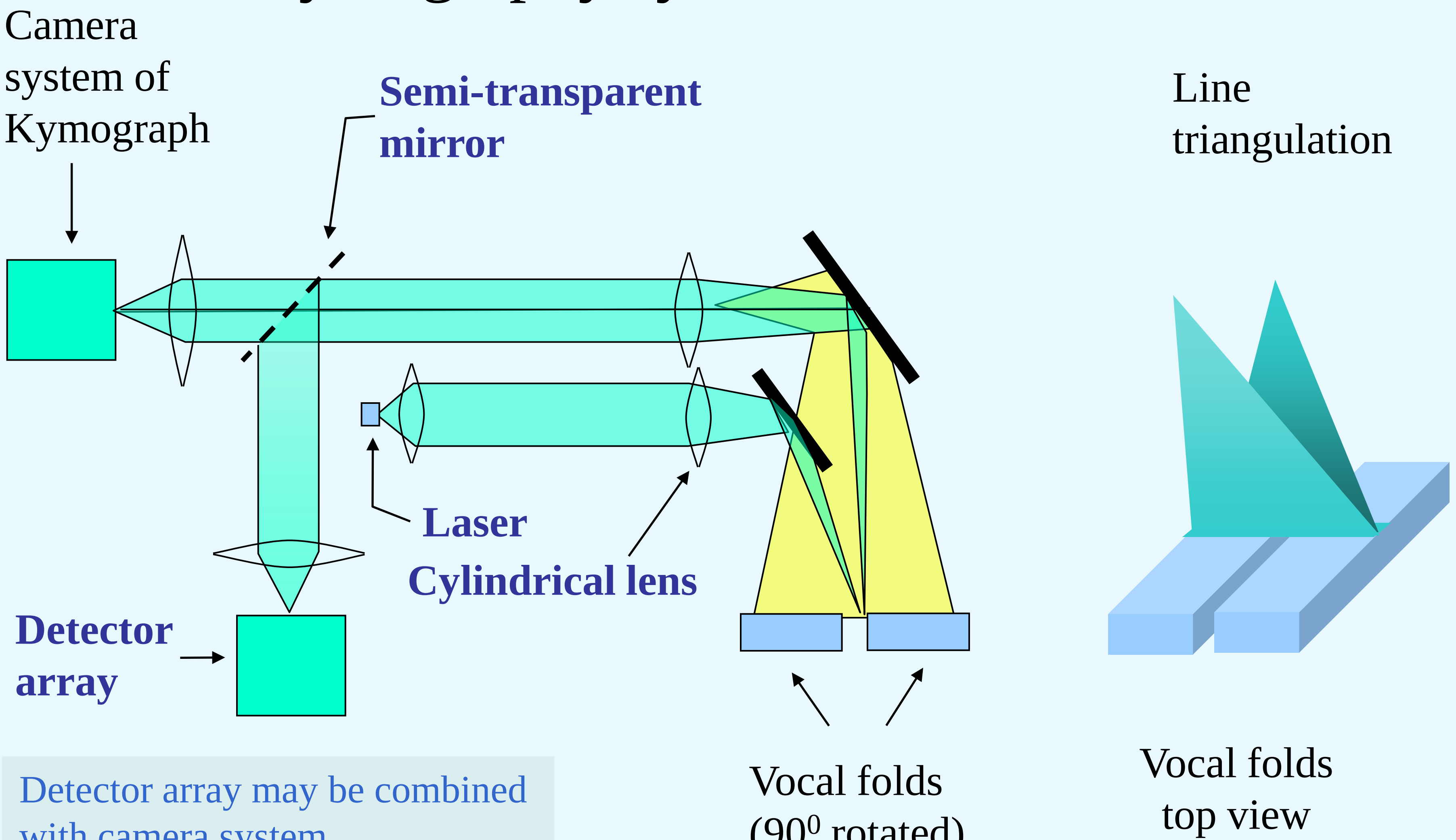


Image of one camera line is recorded repeatedly.

NB. In this figure
the vocal folds are drawn after rotation over 90^0.
(In reality the glottal midline is parallel
to the endoscope axis).

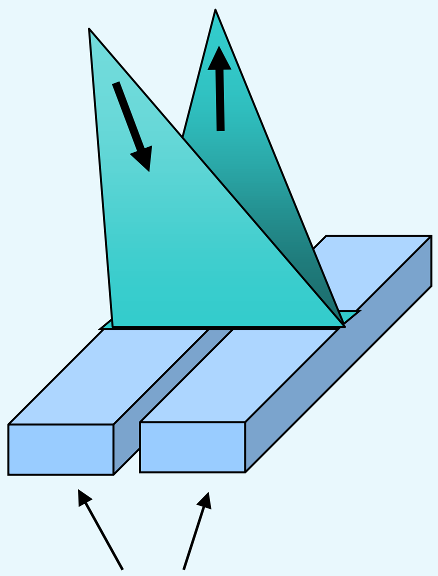
Contents:

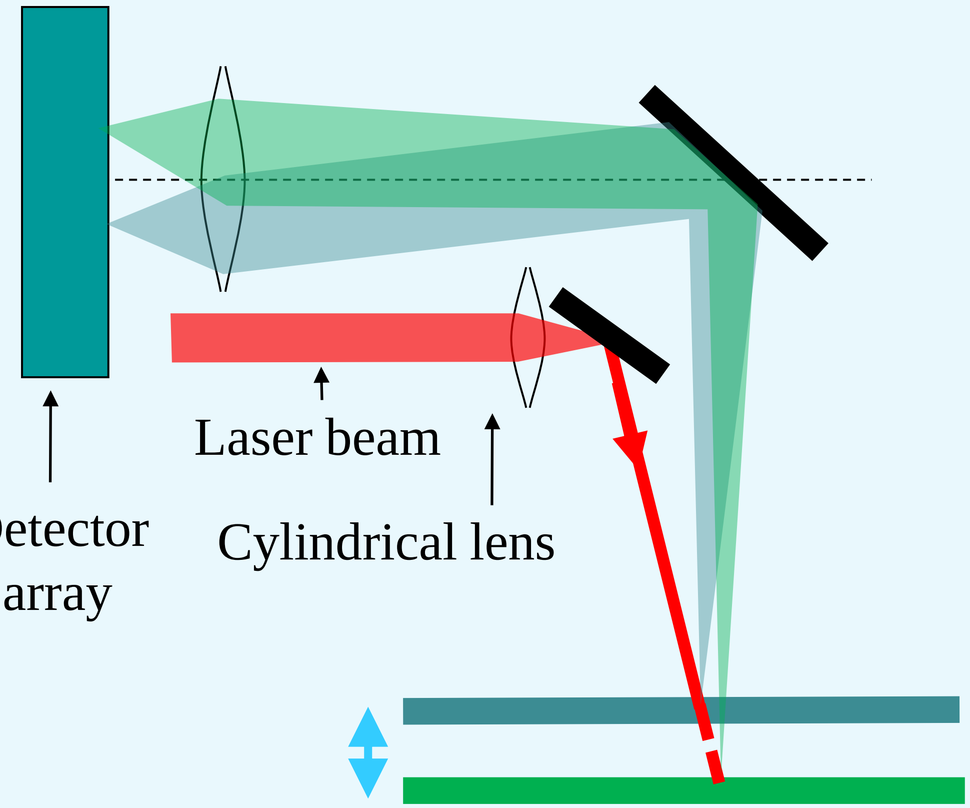
Videokymography system with 3D-extension



Detector array may be combined with camera system.

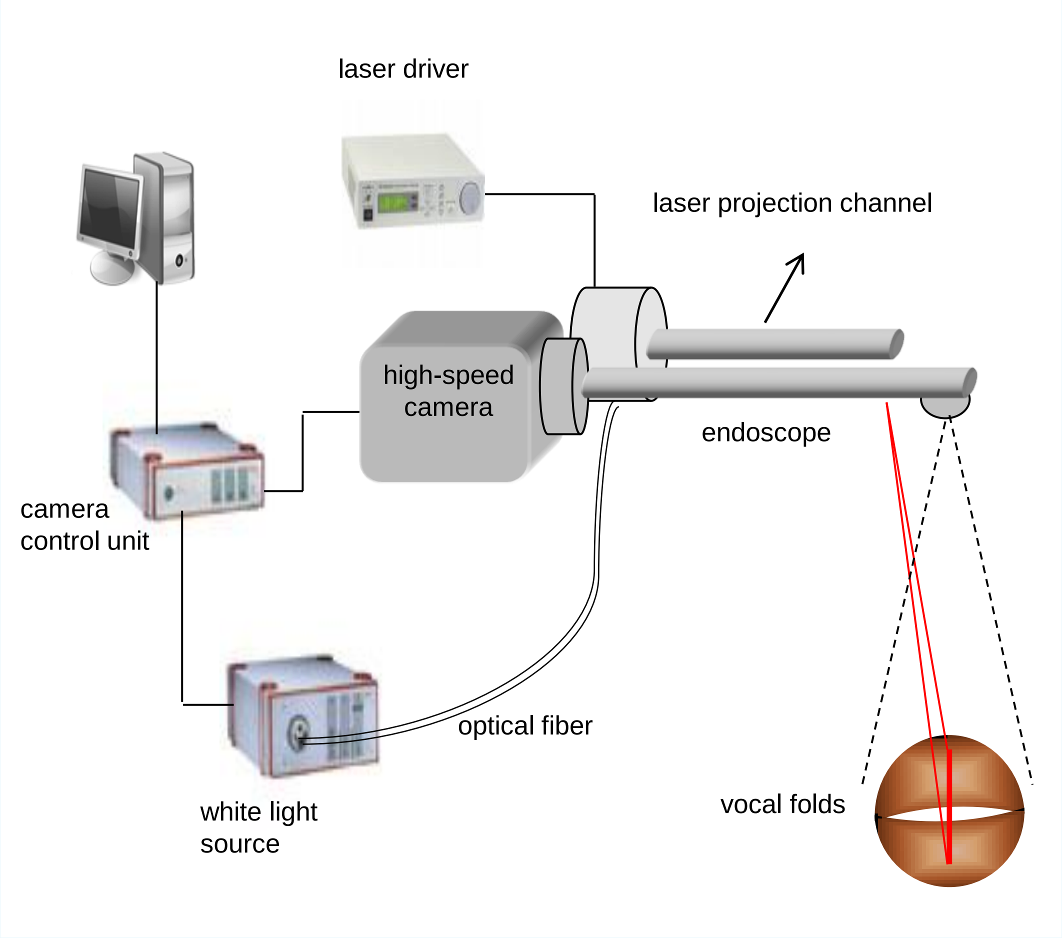
Videokymography system with 3D-extension





Practically favourable setup compared with perpendicular incidence of laser beam

Videokymography system with 3D-extension



Resolution: 50 µm
(hor. & vert.)

Videokymography system with 3D-extension

System characteristics:

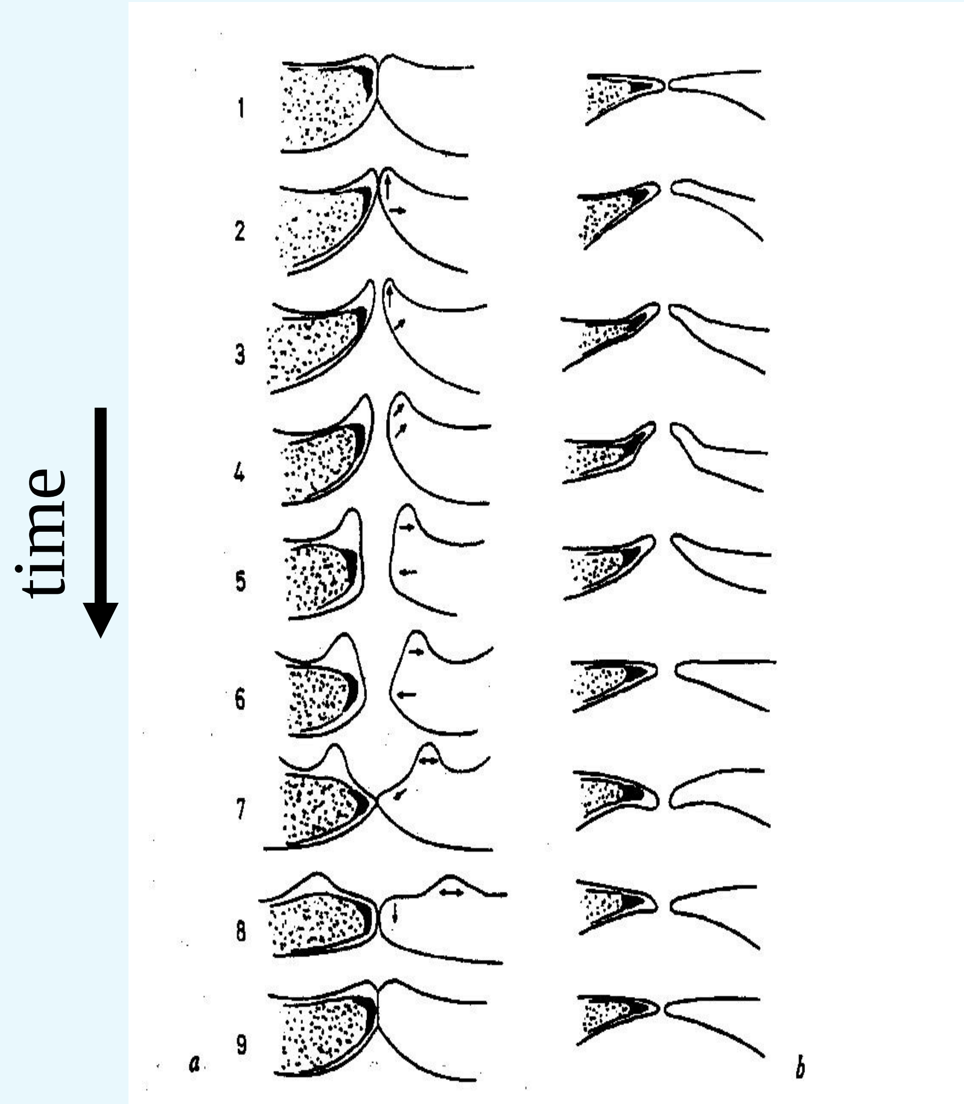
Laser : 658 nm, 90 mW (on vocal folds: 14 mW)

Laser line on vocal folds : 18 mm x 0.4 mm

Triangulation angle : 7 ^{o}

Camera systems: (may be combined using filtering)

1. High-speed camera (Wolf)
   4000 fps, color, 256 x 256 pixels @ 13 x 13 μm^2
2. Position-sensitive linear detector array (Hamamatsu)
   256 x 2 pixels @ 13 μm x 1 mm.



From: Hirano (1968)

Vocal Folds Dynamics

one cycle

Left: Modal

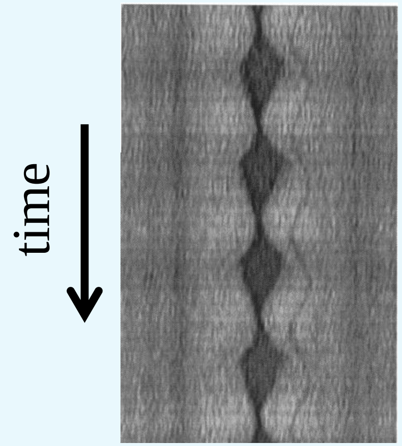
Right: Falsetto

At left side of each:

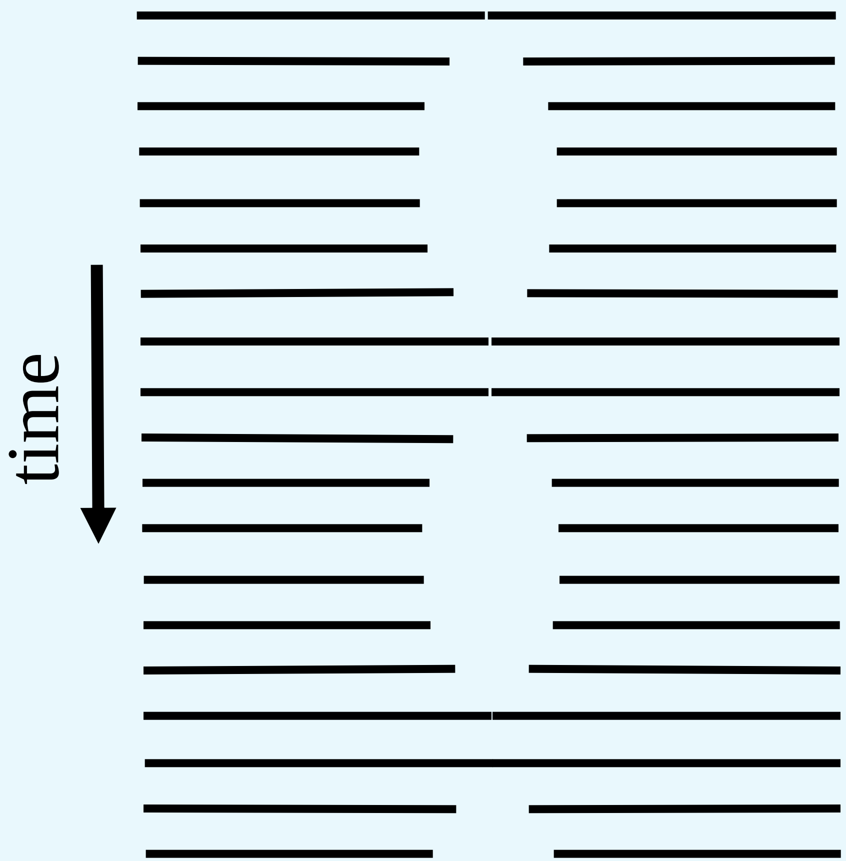
Dotted region: solid lip

Open region: mucosal lip

“Conventional” 2D - Kymography

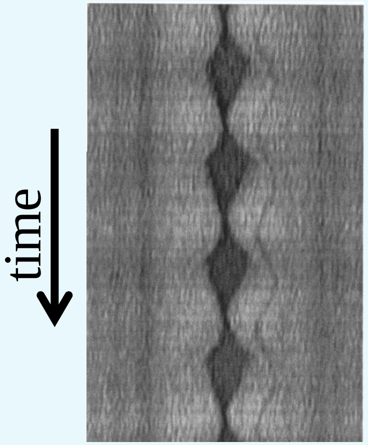


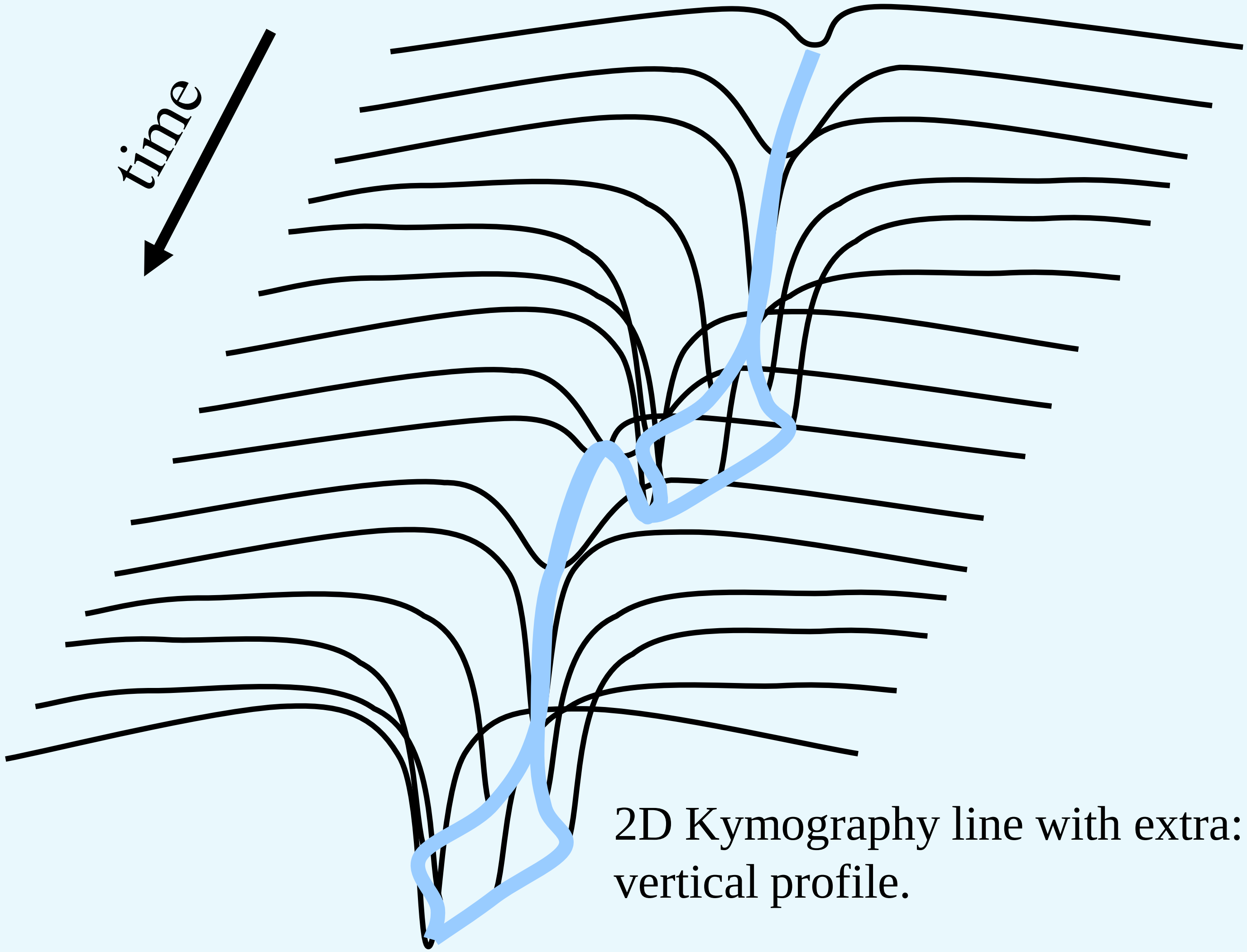
Top view - imaged line as *f* (time)



Depth Kymography
from 2D to 3D in Voice Diagnostics

What do we want to see?

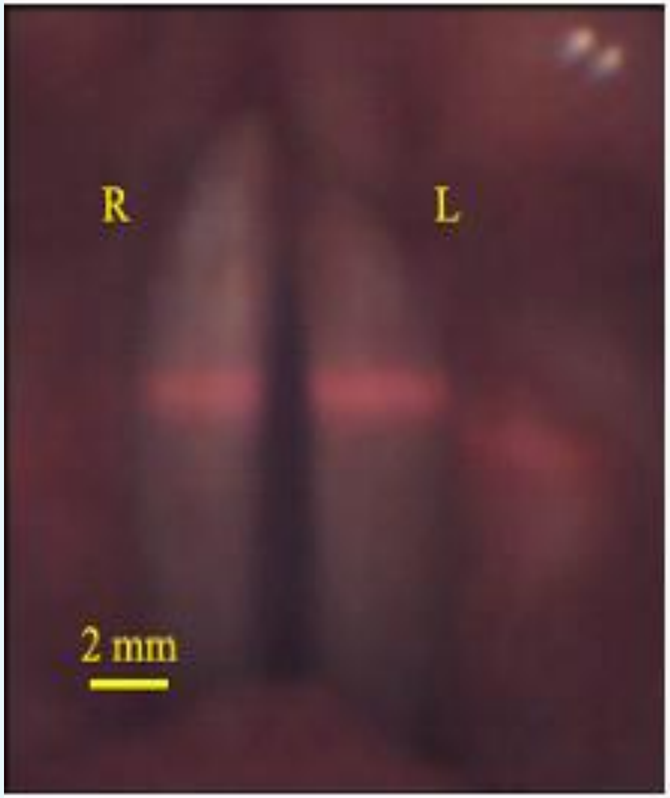




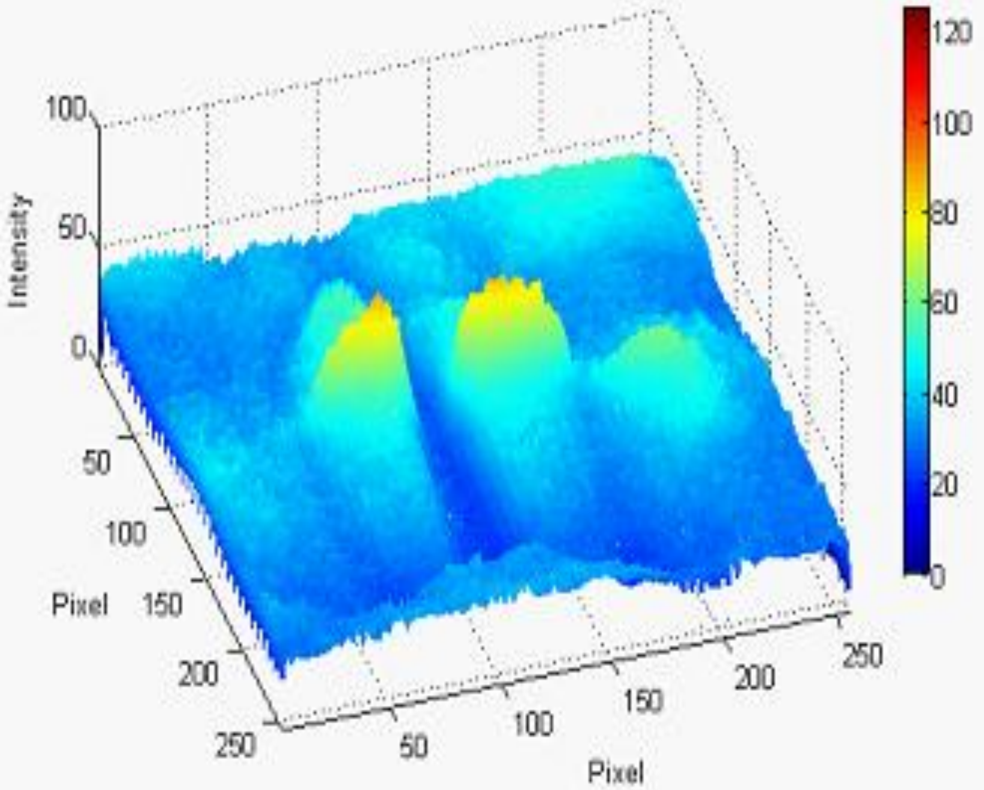
2D Kymography line with extra:
vertical profile.

Depth Kymography
from 2D to 3D in Voice Diagnostics

Example of results:

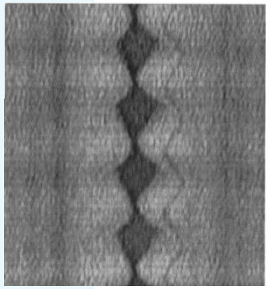


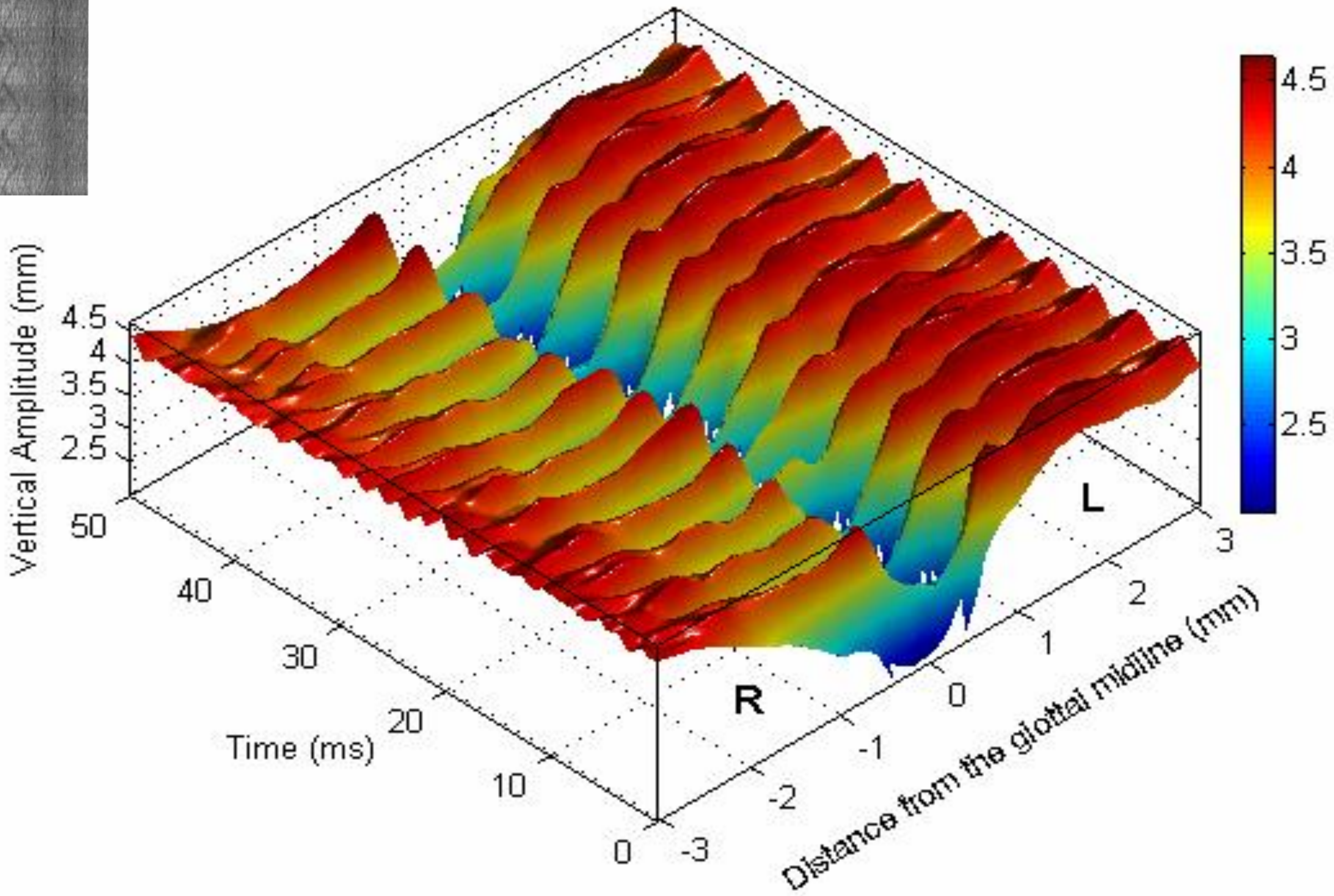
Vocal folds with
laser line image



Corresponding
Depth Kymography plot

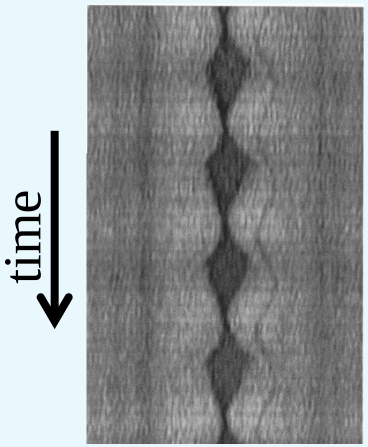
Depth Kymography
from 2D to 3D in Voice Diagnostics

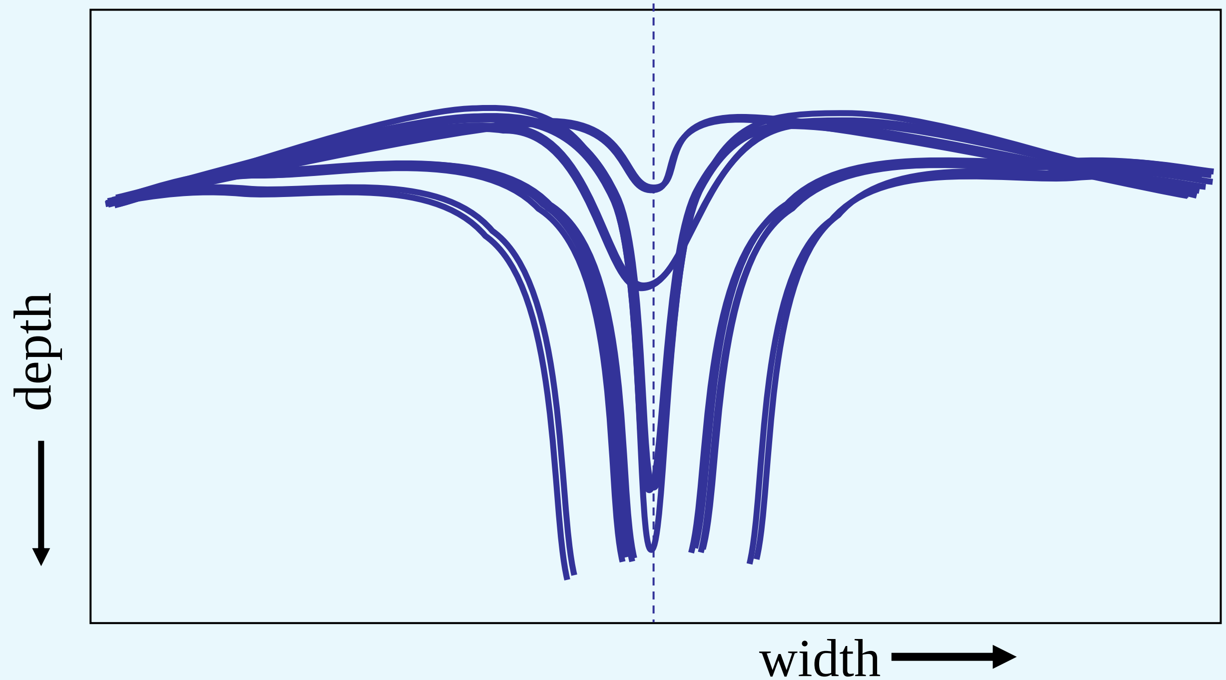




Depth Kymography from 2D to 3D in Voice Diagnostics

Movie: what do we want to see?

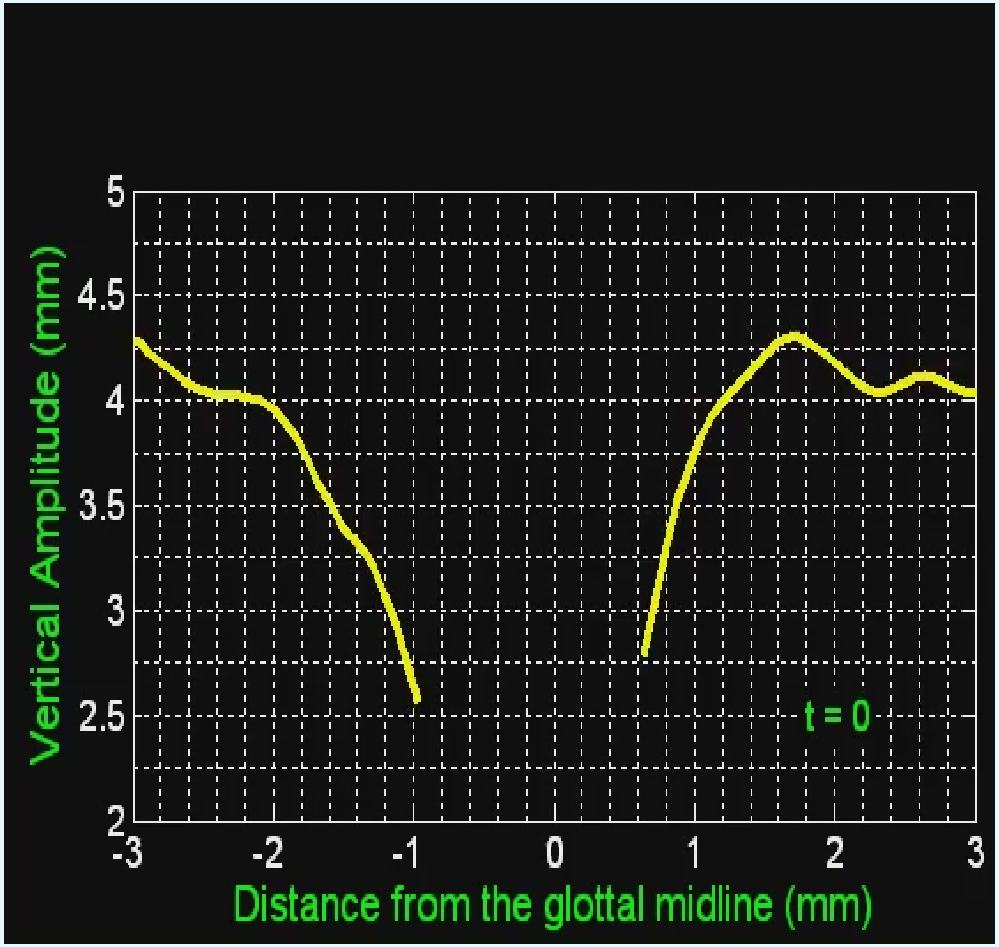




2D Kymography line with extra:
vertical profile.

Depth Kymography
from 2D to 3D in Voice Diagnostics

Results:



Depth Kymography
from 2D to 3D in Voice Diagnostics

IOP PUBLISHING PHYSICS IN MEDICINE AND BIOLOGY

Phys. Med. Biol. 53 (2008) 2667–2675 doi:10.1088/0031-9155/53/10/015

Depth-kymography: high-speed calibrated 3D imaging of human vocal fold vibration dynamics

Nibu A George, Frits F M de Mul, Qingjun Qiu, Gerhard Rakhorst and Harm K Schutte

Groningen Voice Research Lab, Department of Biomedical Engineering, University Medical Center Groningen and University of Groningen, 9700 AD Groningen, The Netherlands

Received 3 December 2007, in final form 17 March 2008
Published 28 April 2008
Online at stacks.iop.org/PMB/53/2667

Abstract

We designed and developed a laser line-triangulation endoscope compatible with any standard high-speed camera for a complete three-dimensional profiling of human vocal fold vibration dynamics. With this novel device we are able to measure absolute values of vertical and horizontal vibration amplitudes, length and width of vocal folds as well as the opening and closing velocities from a single *in vivo* measurement. We have studied, for the first time, the generation and propagation of mucosal waves by locating the position of its maximum vertical position and the propagation velocity. Precise knowledge about the absolute dimensions of human vocal folds and their vibration parameters has significant importance in clinical diagnosis and treatment as well as in fundamental research in voice. The new device can be used to investigate different kinds of pathological conditions including periodic or aperiodic vibrations. Consequently, the new device has significant importance in investigating vocal fold paralysis and in phonosurgical applications.

(Some figures in this article are in colour only in the electronic version)

Awarded

(for the novelty, significance and potential impact on future research)

Contents:

- Numerical simulations:

Vocal Folds Dynamics

- **Goals:**

1. To simulate the **horizontal and vertical motions** of the vocal folds, as functions of time
2. To directly compare measurements and simulations

- **Modeling:**

  - Vocal folds modelled as **two masses**,
  - With **horizontal and vertical freedom**,
  - Connected by **springs and dampers**,
  - Driven by **air pressures**

- **Simulate (as functions of time):**

  - Coordinates
  - Pressures
  - Flows

- Numerical simulations:

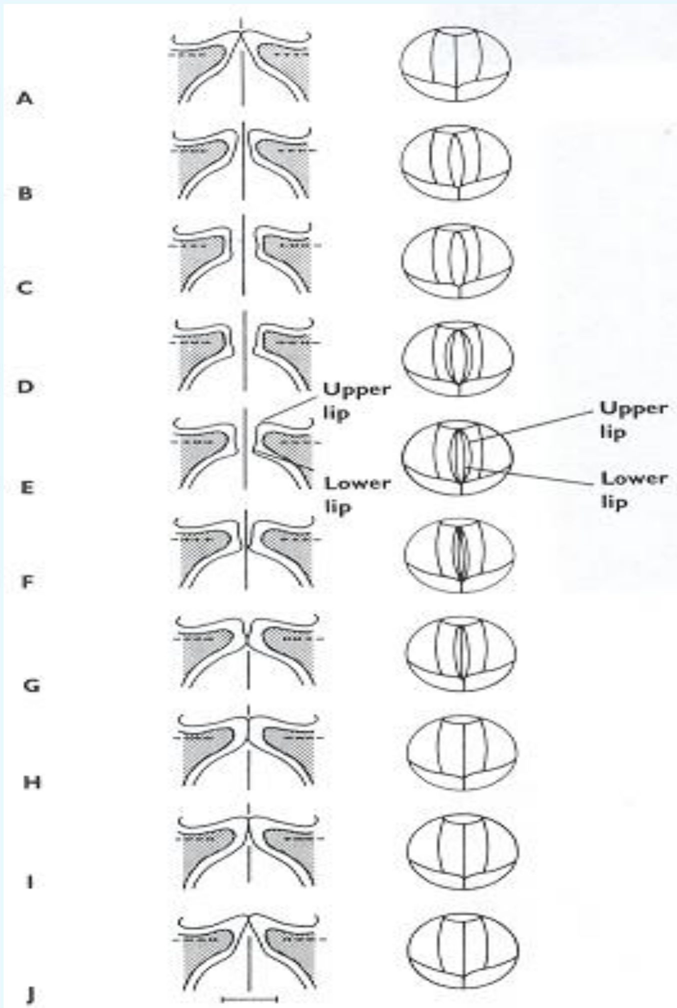
Vocal Folds Dynamics

- Most important references:

- Ishizaka, K. and Flanagan, J.L., *Synthesis of voiced sound from a two-mass model of the vocal cords,* Bell Syst. Tech. Journ. 51, 1972, 1233-1267.
- Titze, I.R., *The human vocal cords: A mathematical model I+II,* Phonetica, 28, 1973, 129-170.
- Koizumi, T., Taniguchi, S., Hiromitsu, S., *Two-mass models of the vocal cords for natural sounding voice synthesis,* J. Acoust. Soc. Amer. 82, 1987, 1179-1192 + corrections

Depth Kymography
from 2D to 3D in Voice Diagnostics

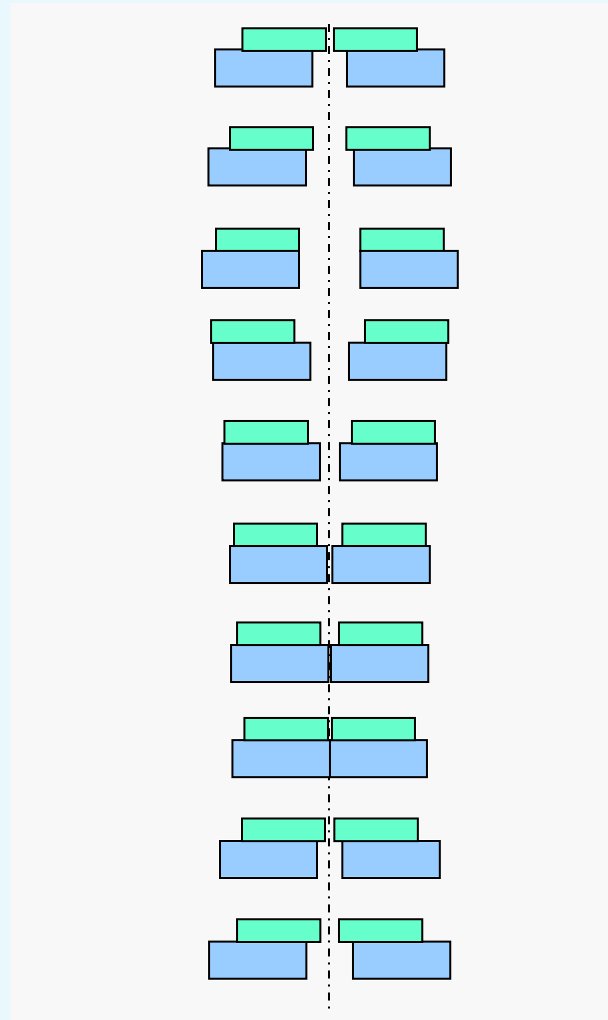
Side view   Top view



time

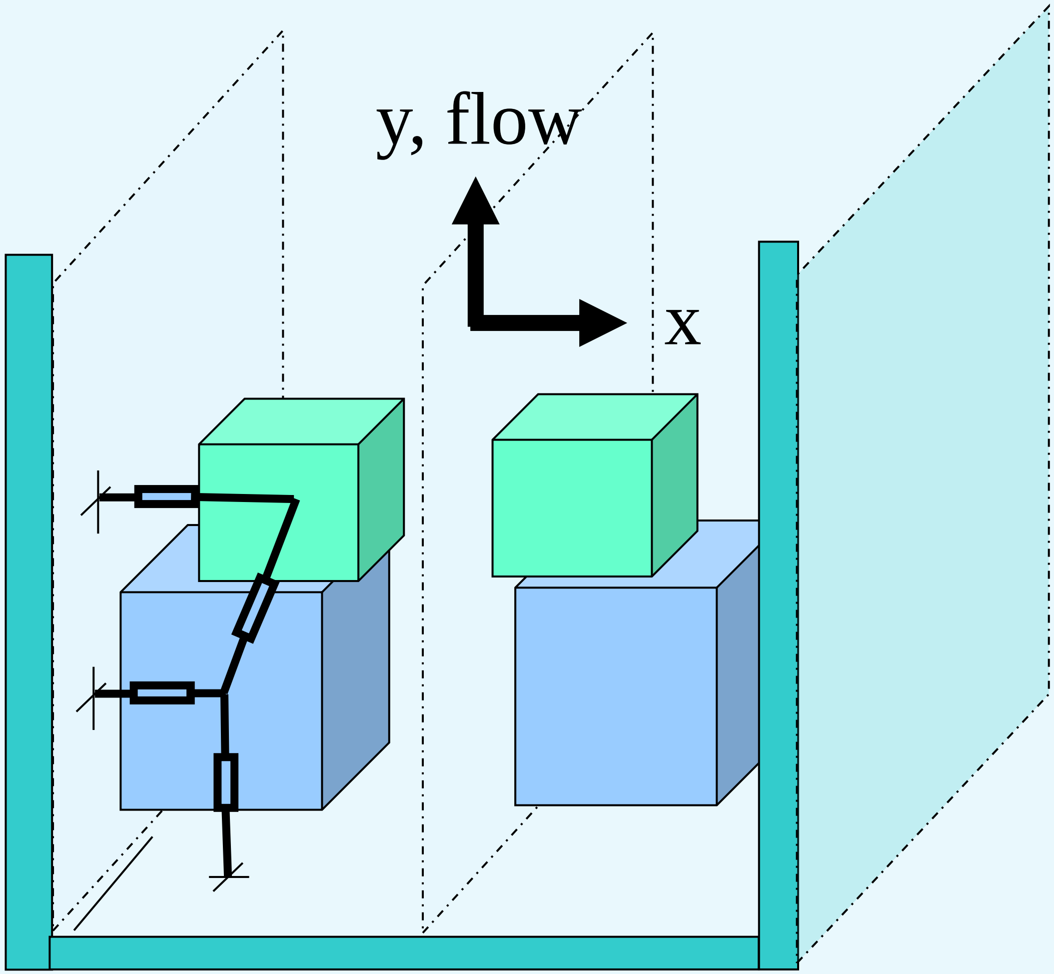
From: Hirano (1968)

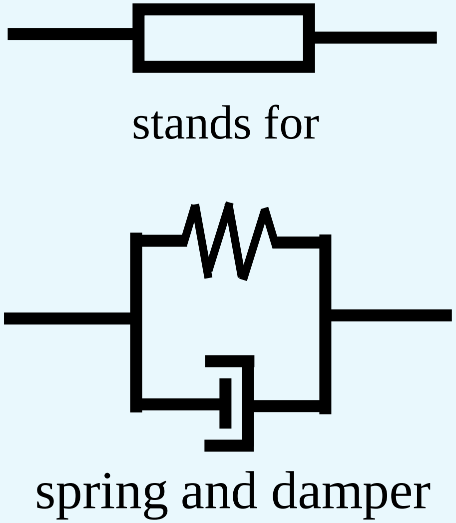
Modeling



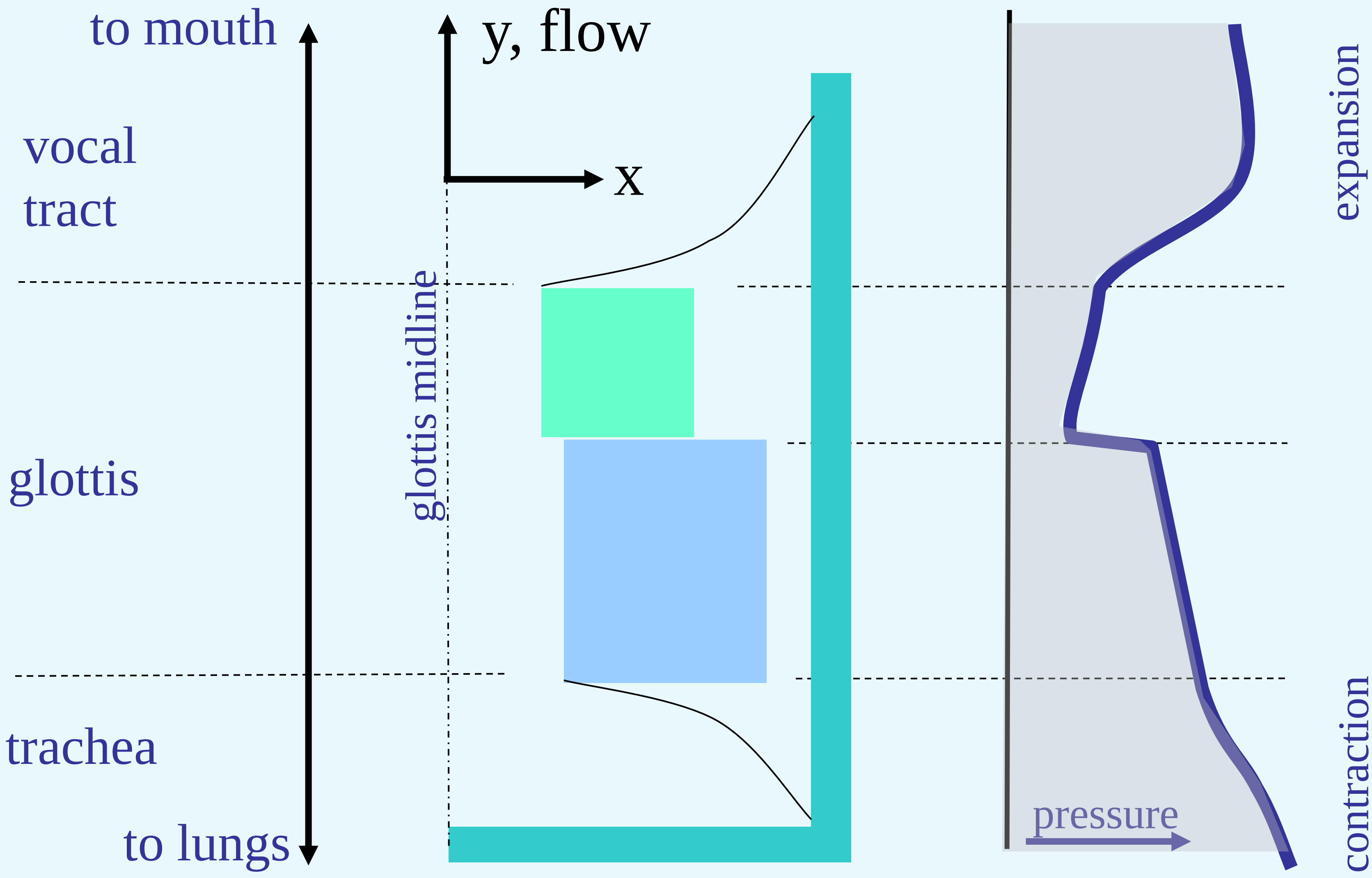
Blocks may also have vertical freedom

2-masses model





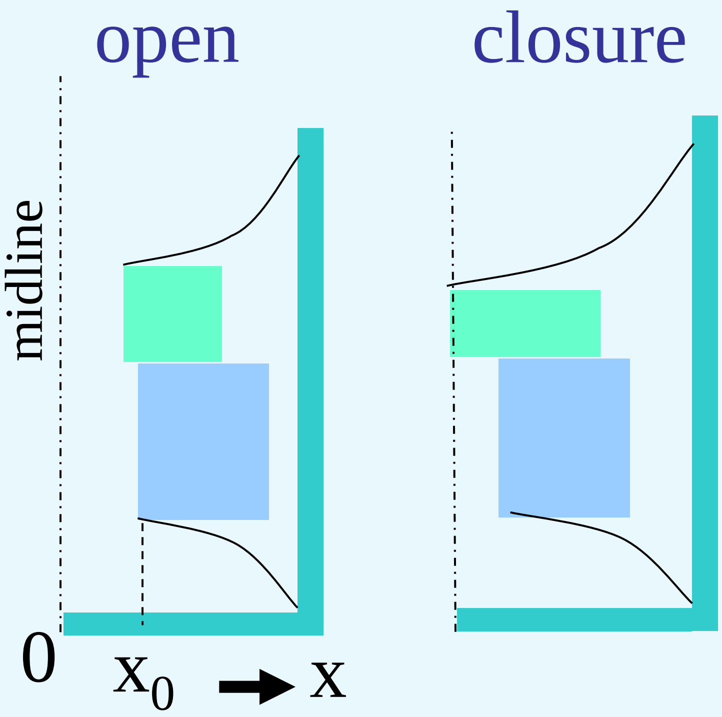
Depth Kymography
from 2D to 3D in Voice Diagnostics

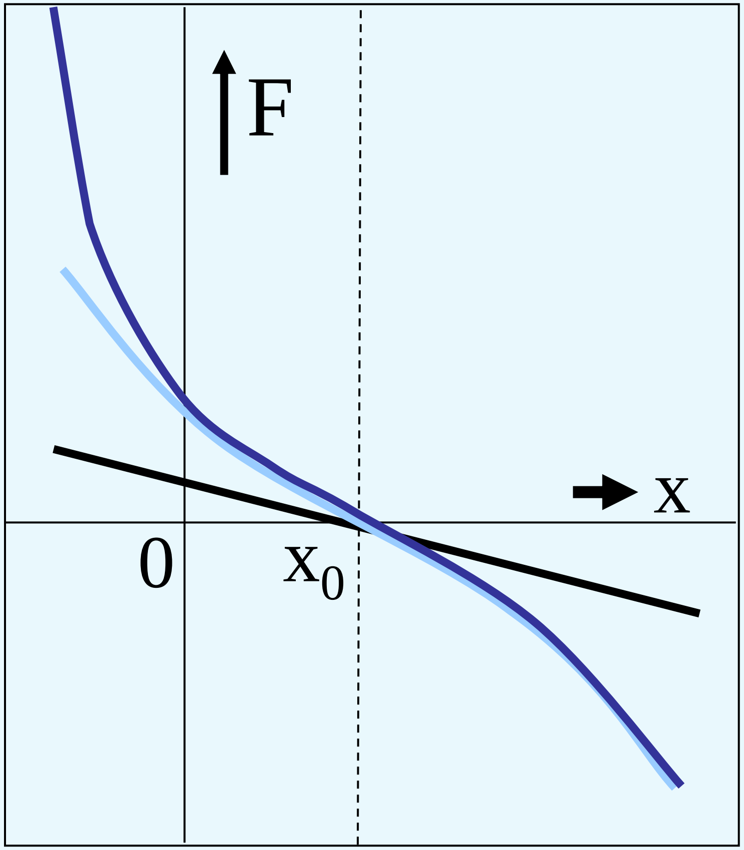


Pressure distribution depends on actual positions of vocal fold masses.

Depth Kymography
from 2D to 3D in Voice Diagnostics

Spring forces:





also for y

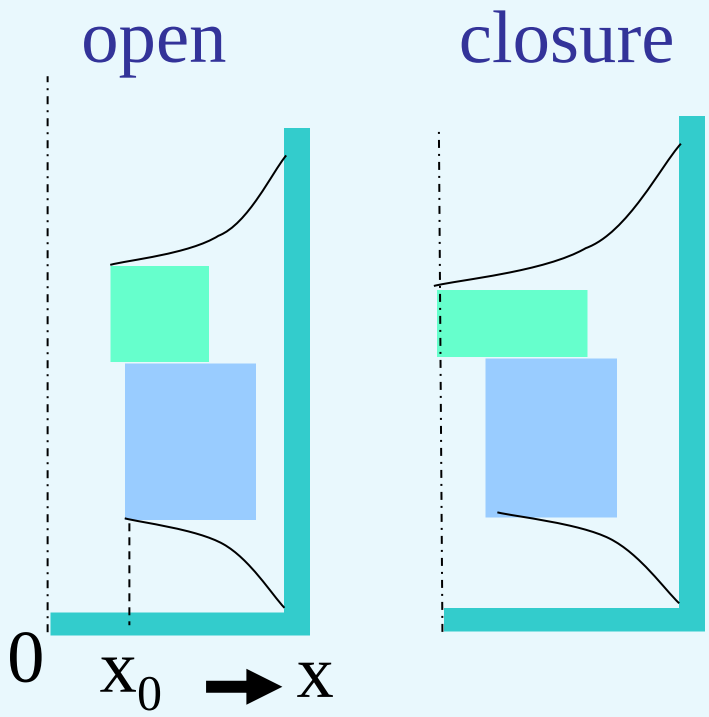
x_{0}, y_0 = position at rest

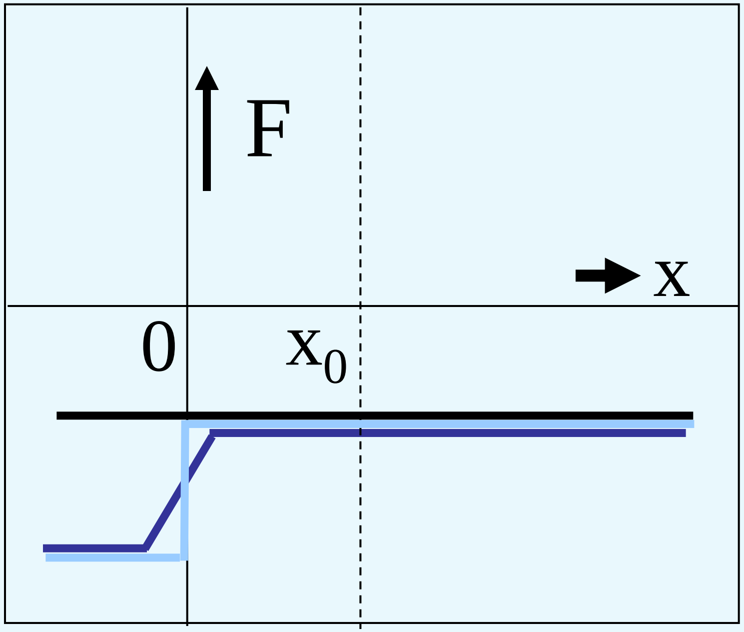
linear term (prop. to displacement)

incl. non-linear term

incl. closure term

Damping forces (prop. to velocity)





also for y

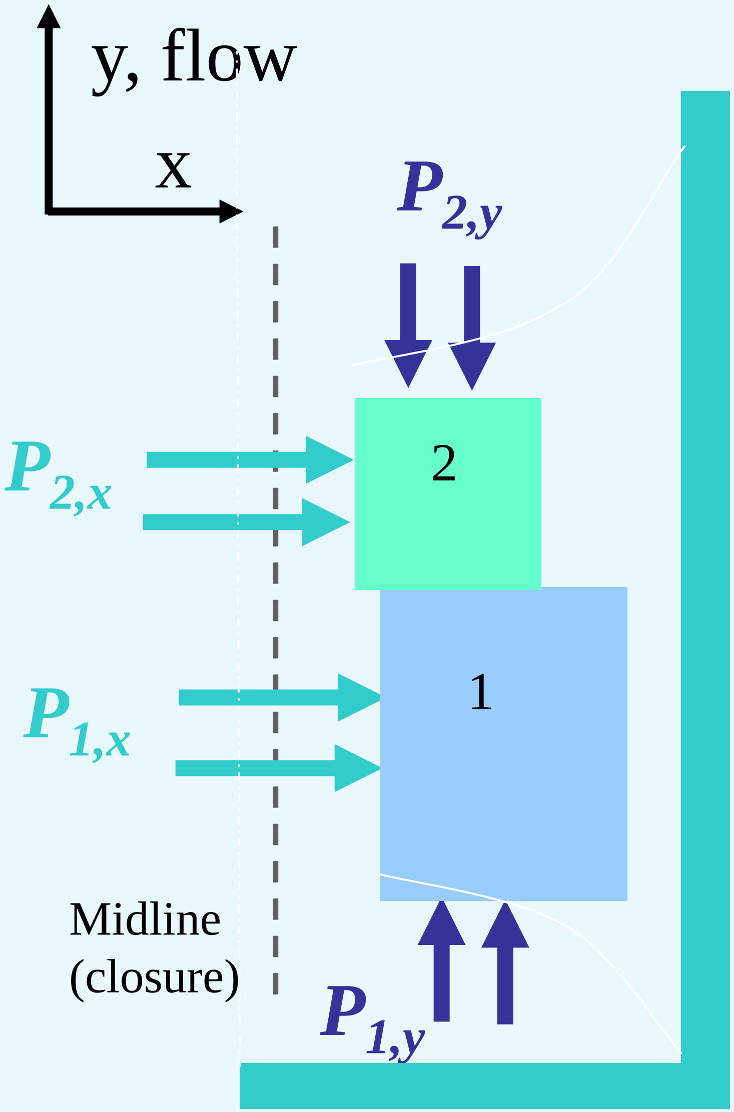
$x_{0,}$, y_0 = position at rest

constant term ~ velocity

incl. closure term

incl. singularity smoothing

Depth Kymography
from 2D to 3D in Voice Diagnostics



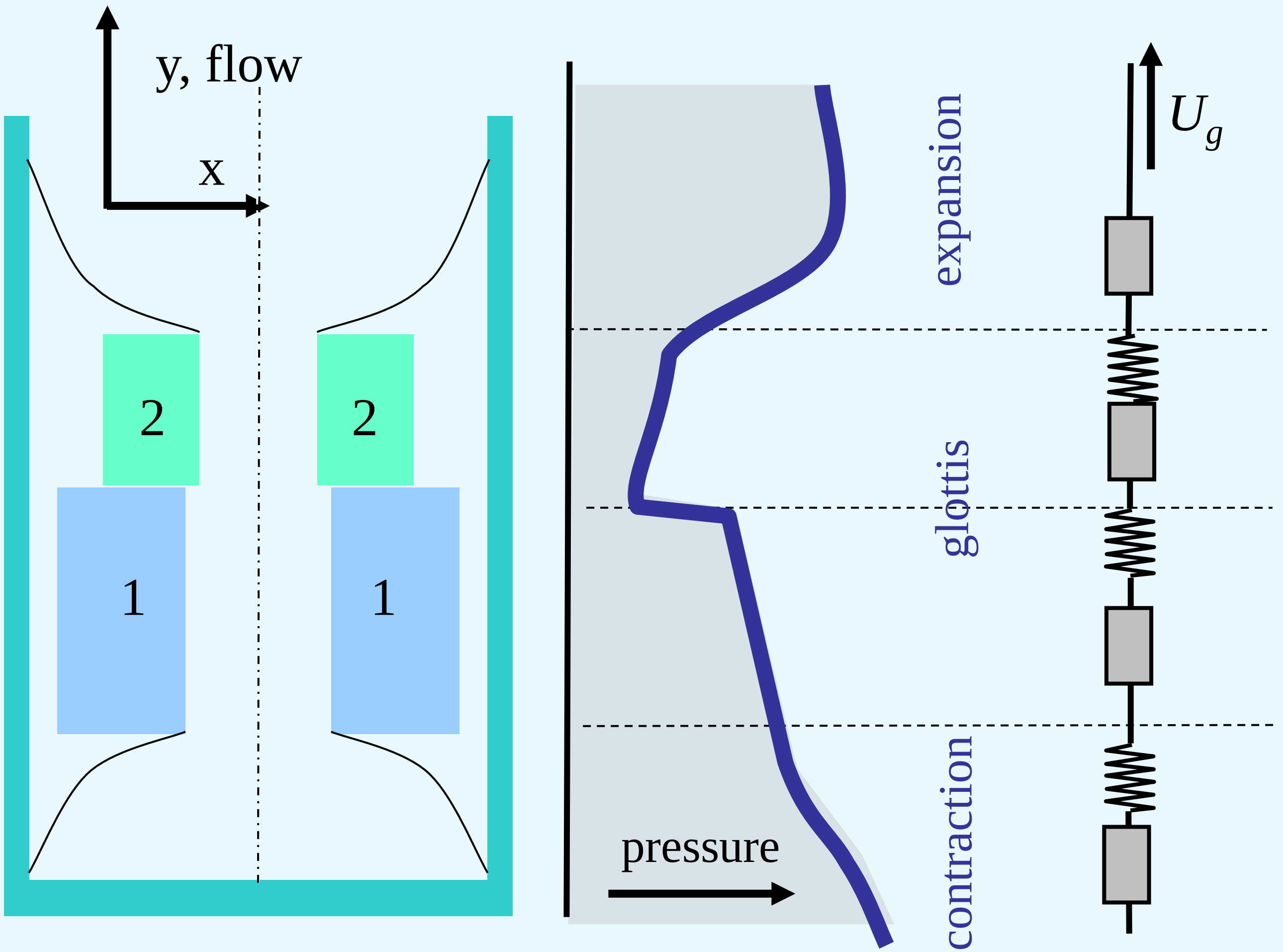
Pressure forces

depend on exposed area

$$F = P.A$$

x- and *y*-positions, thicknesses *d* and widths *w* will vary. see papers for details.

Depth Kymography
from 2D to 3D in Voice Diagnostics



Compartments:

$\Delta P = f(R, L, U, V)$

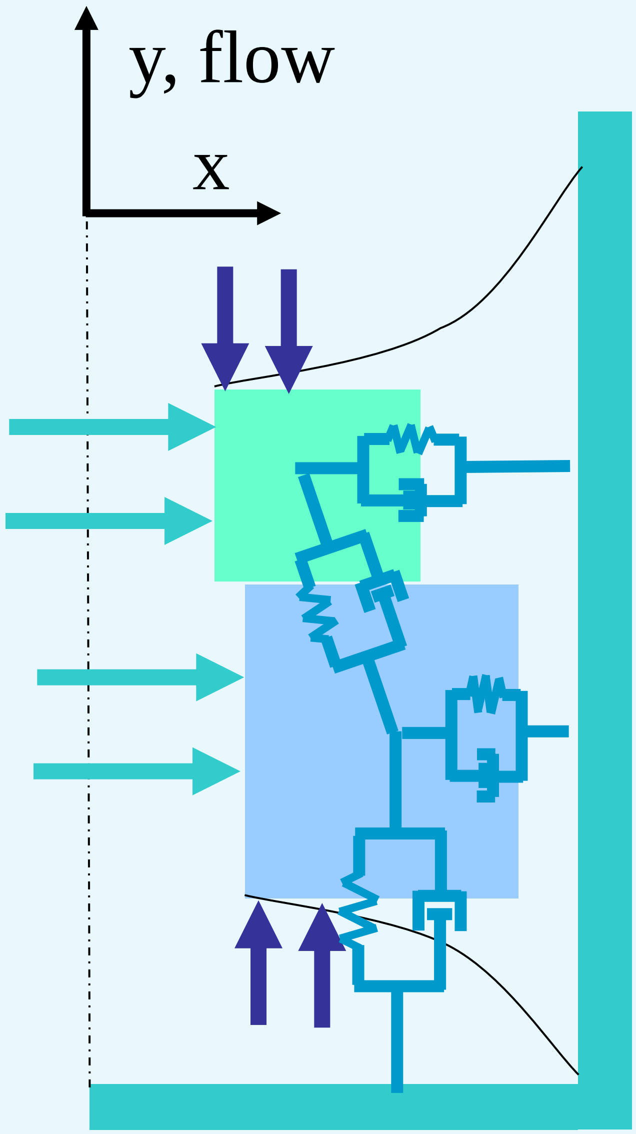
P = pressure [Pa]

U = flow [m^3/s]
$V = dU / dt$

R = flow resistance

L = flow inertia

Pressure distribution depends on actual positions of vocal fold masses.



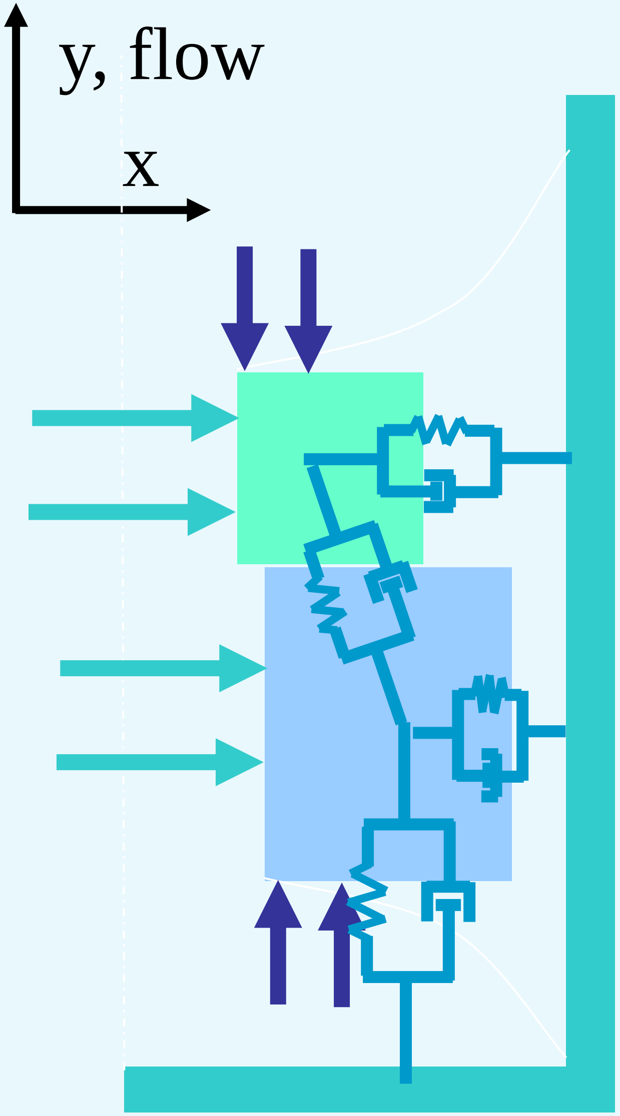
"Combined Model"

- **6 System coordinate variables + 2 masses:**
  for both masses:
  x- and ***y***-positions, thicknesses ***d***
- **4 Equations of motion *E***
  (for ***x*** and ***y*,** for both masses):

$$E \equiv \frac{d}{dt}(mv) - \sum F = 0$$

$$E \equiv \frac{dm}{dt}\frac{dx}{dt} + m\frac{d^2x}{dt^2} - \left(F_{springs} + F_{dampers} + F_{pressures}\right) = 0$$

- **2 Additional constraining equations:**
  1. Conservation of total mass
  2. y_1, y_2, d_1 and d_2 connected
- **=> 6 Independent variables**



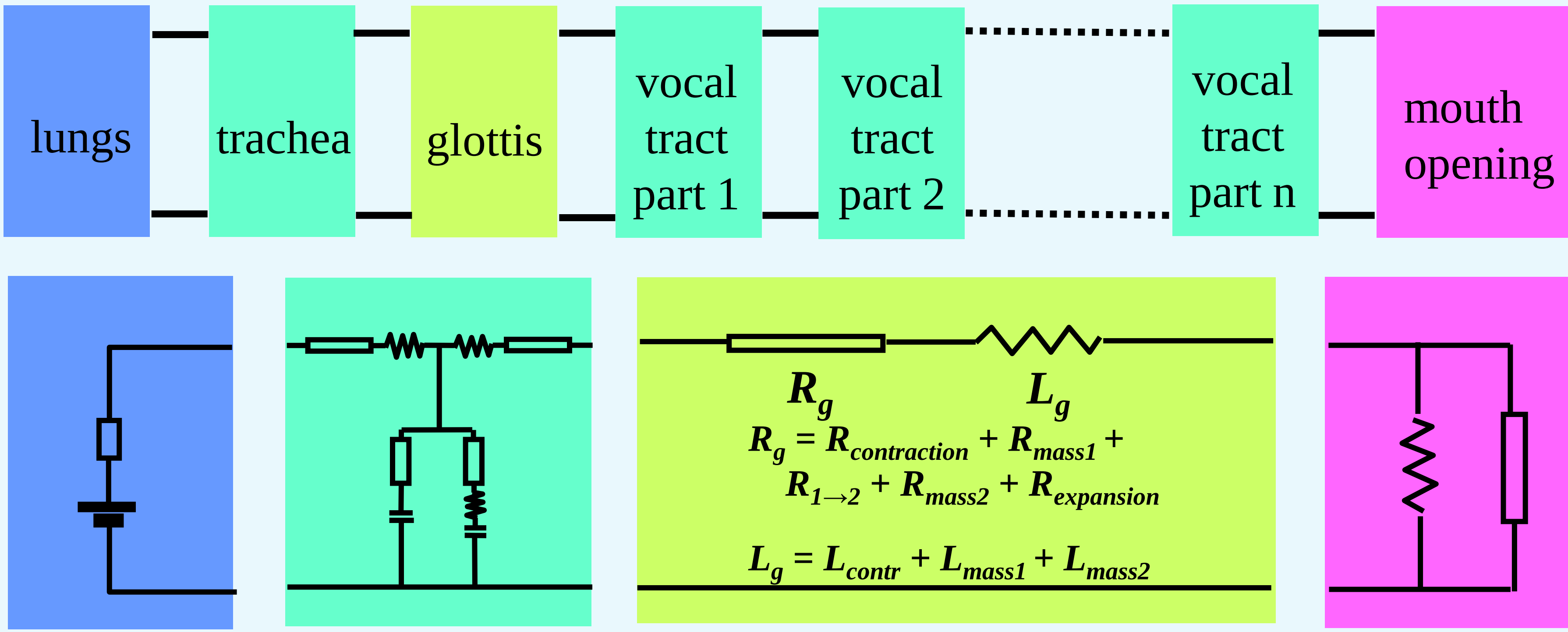
Combined Model

Older models: (see ref.)

1. Ishizaka & Flanagan:
   - Only x-dependence
   - Fixed depths (*d*) and widths *(w)*
   - Forces not in center-of-masses

2. Koizumi:
   - No wall connection for upper mass
   - Forces not in center-of-masses

Electrical analogon for pressures and flows

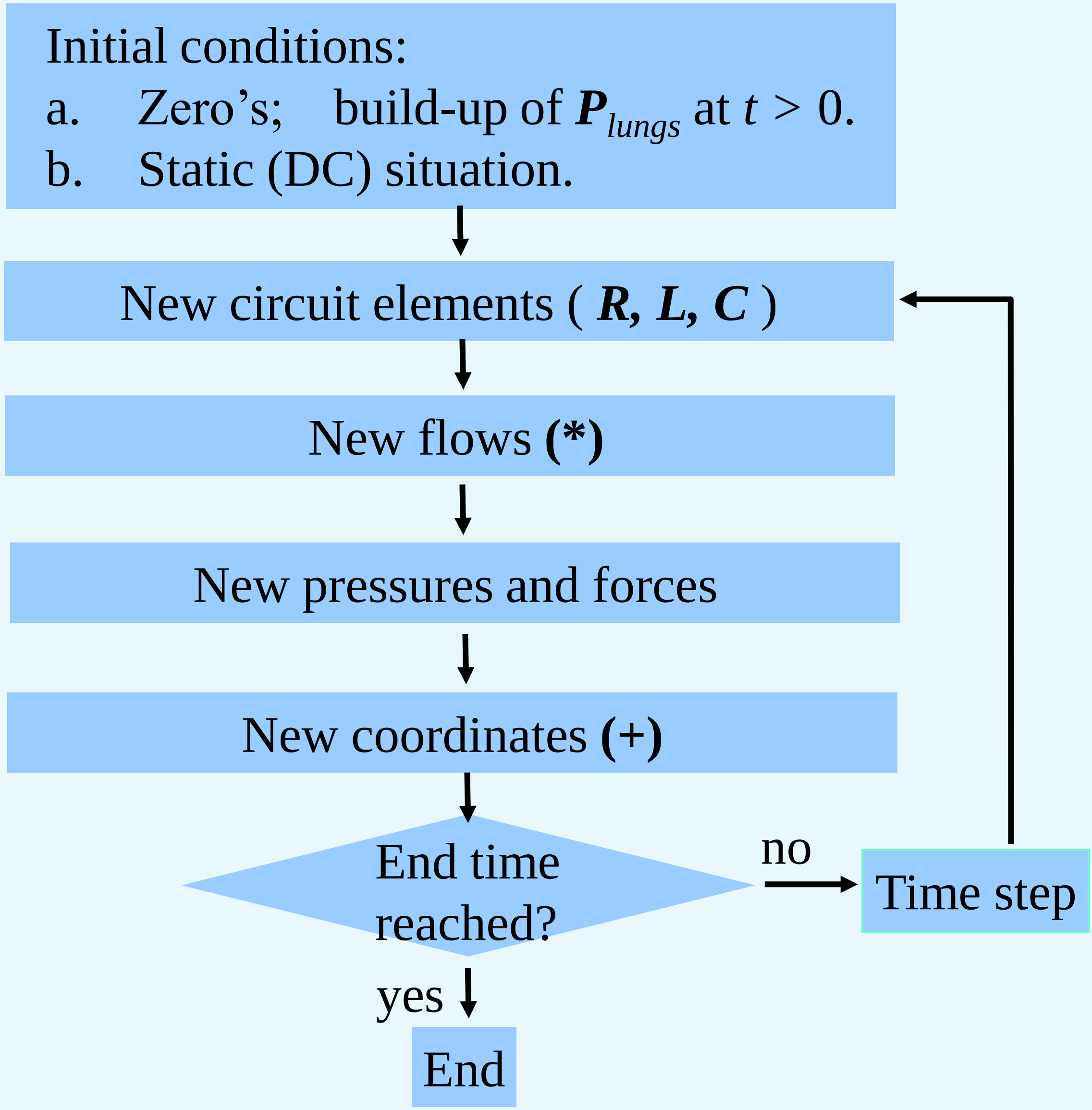


After: Izhizaka & Flanagan and Titze.

All **resistances, compliances and inertias**:
expressions describing air flow in tubes as *f* (length, diameter, density, etc.).
(details: see papers)

Vocal tract: components dependent on vowel characteristics (≈ 45 compartments.)

Static situation (DC): all inertia's (***L***) = 0 and all compliances (***C***) = ∞.



Calculations

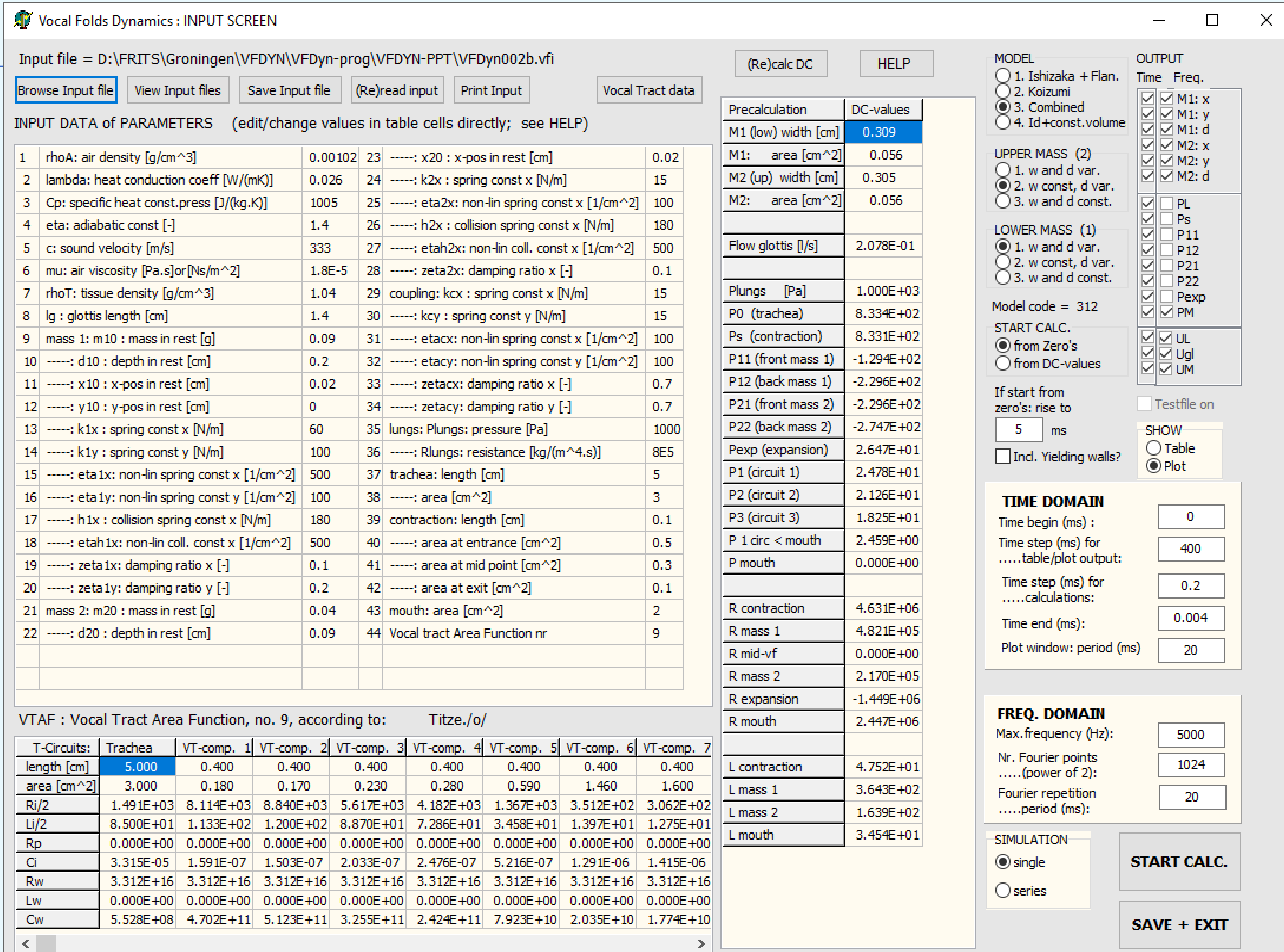
(*) Electrical analogon of coupled circuits:
set of 2.(n+2) linear equations to solve
(n = no. of vocal tract compartments)

(+) 4 coupled non-linear equations of motion,
with 2 additional constraining equations
(total mass, and ***y***-positions);
iterative approach.

Depth Kymography
from 2D to 3D in Voice Diagnostics

Input parameters of the simulations
(partly following Ishizaka/Flanigan, Titze, Koizumi, and others).

parameter	*parameter*
general: rhoA: air density [g/cm^3] lambda: heat conduction coeff [W/(mK)] Cp: specific heat const.press [J/(kg.K)] eta: adiabatic const [-] c: sound velocity [m/s] mu: air viscosity [Pa.s]or[Ns/m^2] rhoT: tissue density [g/cm^3] lg : glottis length [cm] **mass 1**: m10 : mass in rest [g] -----: d10 : depth in rest [cm] -----: x10 : x-pos in rest [cm] -----: y10 : y-pos in rest [cm] -----: k1x : spring const x [N/m] -----: k1y : spring const y [N/m] -----: eta1x: non-lin spring const x [1/cm^2] -----: eta1y: non-lin spring const y [1/cm^2] -----: h1x : collision spring const x [N/m] -----: etah1x: non-lin coll. const x [1/cm^2] -----: zeta1x: damping ratio x [-] -----: zeta1y: damping ratio y [-]	**mass 2**: m20 : mass in rest [g] -----: d20 : depth in rest [cm] -----: x20 : x-pos in rest [cm] -----: k2x : spring const x [N/m] -----: eta2x: non-lin spring const x [1/cm^2] -----: h2x : collision spring const x [N/m] -----: etah2x: non-lin coll. const x [1/cm^2] -----: zeta2x: damping ratio x [-] **coupling**: kcx : spring const x [N/m] -----: kcy : spring const y [N/m] -----: etacx: non-lin spring const x [1/cm^2] -----: etacy: non-lin spring const y [1/cm^2] -----: zetacx: damping ratio x [-] -----: zetacy: damping ratio y [-] **lungs**: Plungs: pressure [Pa] -----: Rlungs: resistance [kg/(m^4.s)] **trachea**: length [cm] -----: area [cm^2] **contraction**: length [cm] -----: area at entrance [cm^2] -----: area at mid point [cm^2] -----: area at exit [cm^2] **mouth**: area [cm^2]



Vocal Folds Dynamics : INPUT SCREEN

Input file = D:\FRITS\Groningen\VFDYN\VFDyn-prog\VFDYN-PPT\VFDyn002b.vfi

Browse Input file | View Input files | Save Input file | (Re)read input | Print Input | Vocal Tract data | (Re)calc DC | HELP

INPUT DATA of PARAMETERS (edit/change values in table cells directly; see HELP)

1	rhoA: air density [g/cm^3]	0.00102	23	-----: x20 : x-pos in rest [cm]	0.02
2	lambda: heat conduction coeff [W/(mK)]	0.026	24	-----: k2x : spring const x [N/m]	15
3	Cp: specific heat const.press [J/(kg.K)]	1005	25	-----: eta2x: non-lin spring const x [1/cm^2]	100
4	eta: adiabatic const [-]	1.4	26	-----: h2x : collision spring const x [N/m]	180
5	c: sound velocity [m/s]	333	27	-----: etah2x: non-lin coll. const x [1/cm^2]	500
6	mu: air viscosity [Pa.s]or[Ns/m^2]	1.8E-5	28	-----: zeta2x: damping ratio x [-]	0.1
7	rhoT: tissue density [g/cm^3]	1.04	29	coupling: kcx : spring const x [N/m]	15
8	lg : glottis length [cm]	1.4	30	-----: kcy : spring const y [N/m]	15
9	mass 1: m10 : mass in rest [g]	0.09	31	-----: etacx: non-lin spring const x [1/cm^2]	100
10	-----: d10 : depth in rest [cm]	0.2	32	-----: etacy: non-lin spring const y [1/cm^2]	100
11	-----: x10 : x-pos in rest [cm]	0.02	33	-----: zetacx: damping ratio x [-]	0.7
12	-----: y10 : y-pos in rest [cm]	0	34	-----: zetacy: damping ratio y [-]	0.7
13	-----: k1x : spring const x [N/m]	60	35	lungs: Plungs: pressure [Pa]	1000
14	-----: k1y : spring const y [N/m]	100	36	-----: Rlungs: resistance [kg/(m^4.s)]	8E5
15	-----: eta1x: non-lin spring const x [1/cm^2]	500	37	trachea: length [cm]	5
16	-----: eta1y: non-lin spring const y [1/cm^2]	100	38	-----: area [cm^2]	3
17	-----: h1x : collision spring const x [N/m]	180	39	contraction: length [cm]	0.1
18	-----: etah1x: non-lin coll. const x [1/cm^2]	500	40	-----: area at entrance [cm^2]	0.5
19	-----: zeta1x: damping ratio x [-]	0.1	41	-----: area at mid point [cm^2]	0.3
20	-----: zeta1y: damping ratio y [-]	0.2	42	-----: area at exit [cm^2]	0.1
21	mass 2: m20 : mass in rest [g]	0.04	43	mouth: area [cm^2]	2
22	-----: d20 : depth in rest [cm]	0.09	44	Vocal tract Area Function nr	9

VTAF : Vocal Tract Area Function, no. 9, according to: Titze./o/

T-Circuits:	Trachea	VT-comp. 1	VT-comp. 2	VT-comp. 3	VT-comp. 4	VT-comp. 5	VT-comp. 6	VT-comp. 7
length [cm]	5.000	0.400	0.400	0.400	0.400	0.400	0.400	0.400
area [cm^2]	3.000	0.180	0.170	0.230	0.280	0.590	1.460	1.600
Ri/2	1.491E+03	8.114E+03	8.840E+03	5.617E+03	4.182E+03	1.367E+03	3.512E+02	3.062E+02
Li/2	8.500E+01	1.133E+02	1.200E+02	8.870E+01	7.286E+01	3.458E+01	1.397E+01	1.275E+01
Rp	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
Ci	3.315E-05	1.591E-07	1.503E-07	2.033E-07	2.476E-07	5.216E-07	1.291E-06	1.415E-06
Rw	3.312E+16	3.312E+16	3.312E+16	3.312E+16	3.312E+16	3.312E+16	3.312E+16	3.312E+16
Lw	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
Cw	5.528E+08	4.702E+11	5.123E+11	3.255E+11	2.424E+11	7.923E+10	2.035E+10	1.774E+10

Precalculation	DC-values
M1 (low) width [cm]	0.309
M1: area [cm^2]	0.056
M2 (up) width [cm]	0.305
M2: area [cm^2]	0.056
Flow glottis [l/s]	2.078E-01
Plungs [Pa]	1.000E+03
P0 (trachea)	8.334E+02
Ps (contraction)	8.331E+02
P11 (front mass 1)	-1.294E+02
P12 (back mass 1)	-2.296E+02
P21 (front mass 2)	-2.296E+02
P22 (back mass 2)	-2.747E+02
Pexp (expansion)	2.647E+01
P1 (circuit 1)	2.478E+01
P2 (circuit 2)	2.126E+01
P3 (circuit 3)	1.825E+01
P 1 circ < mouth	2.459E+00
P mouth	0.000E+00
R contraction	4.631E+06
R mass 1	4.821E+05
R mid-vf	0.000E+00
R mass 2	2.170E+05
R expansion	-1.449E+06
R mouth	2.447E+06
L contraction	4.752E+01
L mass 1	3.643E+02
L mass 2	1.639E+02
L mouth	3.454E+01

MODEL
- 1. Ishizaka + Flan.
- 2. Koizumi
- 3. Combined (selected)
- 4. Id+const.volume

UPPER MASS (2)
- 1. w and d var.
- 2. w const, d var. (selected)
- 3. w and d const.

LOWER MASS (1)
- 1. w and d var. (selected)
- 2. w const, d var.
- 3. w and d const.

Model code = 312

START CALC.
- from Zero's (selected)
- from DC-values

If start from zero's: rise to 5 ms

Incl. Yielding walls?

OUTPUT

Time Freq.

Time	Freq.	Signal
☑	☑	M1: x
☑	☑	M1: y
☑	☑	M1: d
☑	☑	M2: x
☑	☑	M2: y
☑	☑	M2: d
☑	☐	PL
☑	☐	Ps
☑	☐	P11
☑	☐	P12
☑	☐	P21
☑	☐	P22
☑	☐	Pexp
☑	☑	PM
☑	☑	UL
☑	☑	Ugl
☑	☑	UM

Testfile on

SHOW
- Table
- Plot (selected)

TIME DOMAIN

Time begin (ms) : 0

Time step (ms) for .....table/plot output: 400

Time step (ms) for .....calculations: 0.2

Time end (ms): 0.004

Plot window: period (ms) 20

FREQ. DOMAIN

Max.frequency (Hz): 5000

Nr. Fourier points .....(power of 2): 1024

Fourier repetition .....period (ms): 20

SIMULATION
- single (selected)
- series

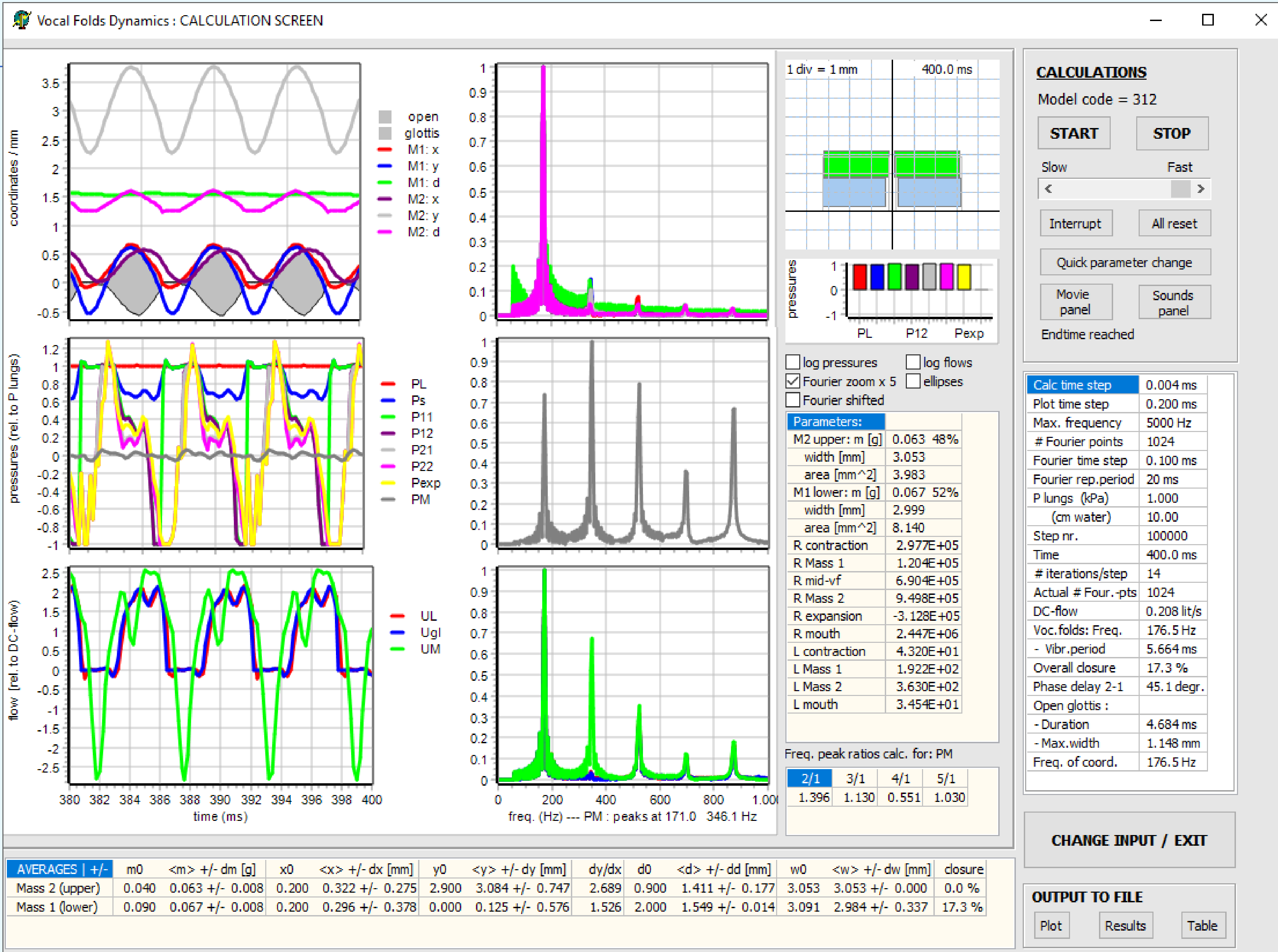
START CALC.

SAVE + EXIT

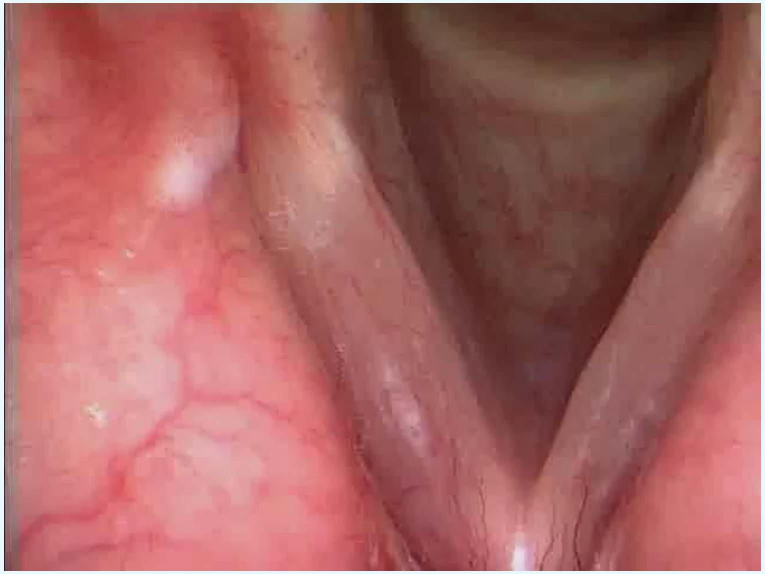
Output variables of the simulations

<table>
<tr><th>variable (o)</th><th>Variable (o)</th></tr>
<tr><td>Model code (*)
Lower mass: <<i>m</i>1> +/- <i>dm</i>1 [g]
….: <<i>x</i>1> +/- <i>dx</i>1 [mm]
….: <<i>y</i>1> +/- <i>dy</i>1
….: ratio <i>dy</i>1/<i>dx</i>1
….: <<i>d</i>1> +/- <i>dd</i>1
….: <<i>w</i>1> +/- <i>dw</i>1
Upper mass: <<i>m</i>2> +/- <i>dm</i>2 [g]
….: <<i>x</i>2> +/- <i>dx</i>2 [mm]
….: <<i>y</i>2> +/- <i>dy</i>2
….: ratio <i>dy</i>2/<i>dx</i>2
….: <<i>d</i>2> +/- <i>dd</i>2
….: <<i>w</i>2> +/- <i>dw</i>2</td><td>DC-flow [lit/s]
Mouth pressure: <<i>MP</i>> +/- <i>dMP</i> [Pa]
...: flow: <<i>MF</i>> +/-<i>dMF</i> [lit/s]
Frequencies: 1^{st} peak [Hz]
…: ratio $2^{nd}/1^{st}$, $3^{rd}/1^{st}$, $4^{th}/1^{st}$, $5^{th}/1^{st}$ peak intensity
Glottis: closure situation [%]
…: phase delay upper vs. lower mass [degr.]
…: averaged duration of open period [ms]
…: max. open width [mm]
…: max open area [mm^2]

(o) Notation: for variable <i>x</i>: <<i>x</i>> = time average;
<i>dx</i> = amplitude of vibration</td></tr>
<tr><td colspan="2">(*) Model code: “ABC” :
A = 1, 2, 3 : model: according to (1) Ishizaka-Flanagan, (2) Koizumi and
(3, present) Combined model respectively;
B = 1 : lower mass: both width w and thickness d variable; folds constrained at wall side;
2 : id.: width constant, thickness variable;
3 : id.: width and thickness constant;
C = 1, 2, 3 : upper mass, as with B (for lower mass)</td></tr>
</table>


Vocal Folds Dynamics : CALCULATION SCREEN
coordinates / mm
open
glottis
M1: x
M1: y
M1: d
M2: x
M2: y
M2: d
pressures (rel. to P lungs)
PL
Ps
P11
P12
P21
P22
Pexp
PM
flow [rel. to DC-flow)
UL
Ugl
UM
time (ms)
freq. (Hz) --- PM : peaks at 171.0 346.1 Hz
1 div = 1 mm
400.0 ms
pressures
PL
P12
Pexp
log pressures
log flows
Fourier zoom x 5
ellipses
Fourier shifted
Parameters:
M2 upper: m [g] 0.063 48%
width [mm] 3.053
area [mm^2] 3.983
M1 lower: m [g] 0.067 52%
width [mm] 2.999
area [mm^2] 8.140
R contraction 2.977E+05
R Mass 1 1.204E+05
R mid-vf 6.904E+05
R Mass 2 9.498E+05
R expansion -3.128E+05
R mouth 2.447E+06
L contraction 4.320E+01
L Mass 1 1.922E+02
L Mass 2 3.630E+02
L mouth 3.454E+01
Freq. peak ratios calc. for: PM
2/1 3/1 4/1 5/1
1.396 1.130 0.551 1.030
CALCULATIONS
Model code = 312
START
STOP
Slow
Fast
Interrupt
All reset
Quick parameter change
Movie panel
Sounds panel
Endtime reached
Calc time step 0.004 ms
Plot time step 0.200 ms
Max. frequency 5000 Hz
Fourier points 1024
Fourier time step 0.100 ms
Fourier rep.period 20 ms
P lungs (kPa) 1.000
(cm water) 10.00
Step nr. 100000
Time 400.0 ms
iterations/step 14
Actual # Four.-pts 1024
DC-flow 0.208 lit/s
Voc.folds: Freq. 176.5 Hz
- Vibr.period 5.664 ms
Overall closure 17.3 %
Phase delay 2-1 45.1 degr.
Open glottis :
- Duration 4.684 ms
- Max.width 1.148 mm
Freq. of coord. 176.5 Hz
CHANGE INPUT / EXIT
AVERAGES | +/- m0 <m> +/- dm [g] x0 <x> +/- dx [mm] y0 <y> +/- dy [mm] dy/dx d0 <d> +/- dd [mm] w0 <w> +/- dw [mm] closure
Mass 2 (upper) 0.040 0.063 +/- 0.008 0.200 0.322 +/- 0.275 2.900 3.084 +/- 0.747 2.689 0.900 1.411 +/- 0.177 3.053 3.053 +/- 0.000 0.0 %
Mass 1 (lower) 0.090 0.067 +/- 0.008 0.200 0.296 +/- 0.378 0.000 0.125 +/- 0.576 1.526 2.000 1.549 +/- 0.014 3.091 2.984 +/- 0.337 17.3 %
OUTPUT TO FILE
Plot
Results
Table

Depth Kymography
from 2D to 3D in Voice Diagnostics



VFDyn-program

Compare:
Stroboscopic
movie

Some results of the simulations:

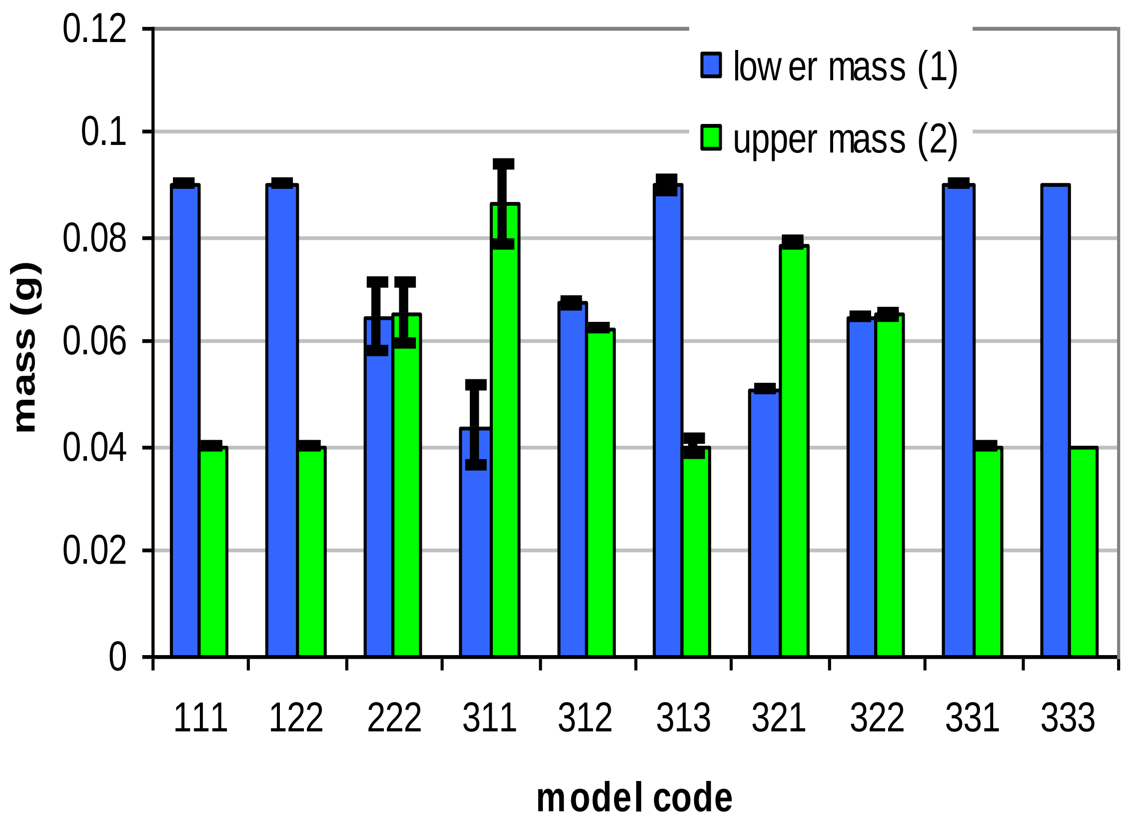
- Masses (averages, amplitudes)
- Coordinates (averages, amplitudes)
- Flows, pressures and frequencies
- Frequency peaks: intensity ratios
- Vocal Tract Area Functions
- Frequencies in mouth and glottis
- Comparison of measured and calculated values
- Slope values: (*dy/dp*) with
  y = variable (*m,x,y,f*....)
  p = parameter ($m_0.x_0$,..,*k's*,...
  ...compartment lengths etc.)

Models: (code ABC)

- A = 1: Ishizaka/Flanagan
  2: Koizumi
  3: Combined
- B: lower mass
- C: upper mass
- B,C = 1: *d* and *w* variable
  2: *d* var., *w* fixed
  3: *d* and *w* fixed

e.g. **code 313** :
A=3: "Combined model",
B=1: lower mass: *d* and *w* variable
C=3: upper mass: *d* and *w* fixed.

Masses (averages, amplitudes) in various models



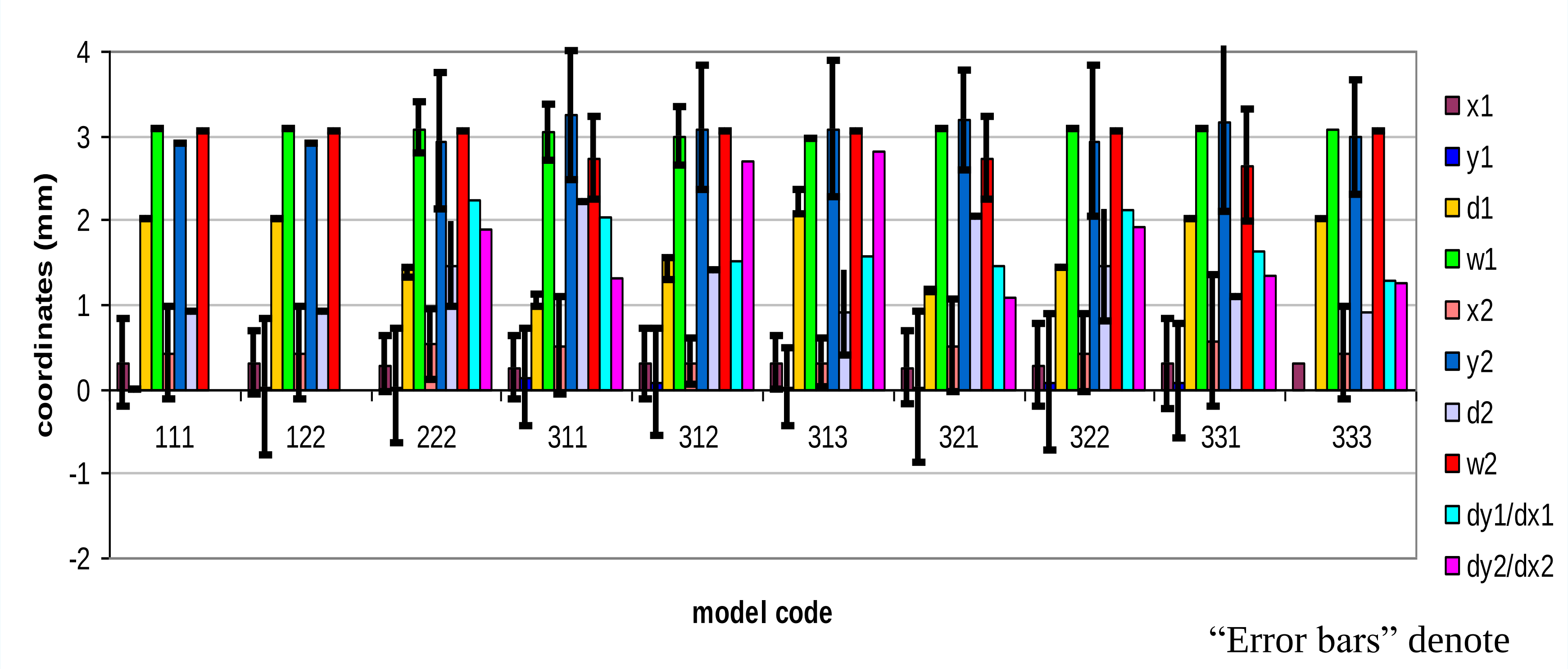
Models: (ABC)

A = 1: Ishizaka/Flanagan
2: Koizumi
3: Combined
B: lower mass
C: upper mass
B,C = 1: *d* and *w* variable
2: *d* var., *w* fixed
3: *d* and *w* fixed

"Error bars" denote amplitudes of oscillations

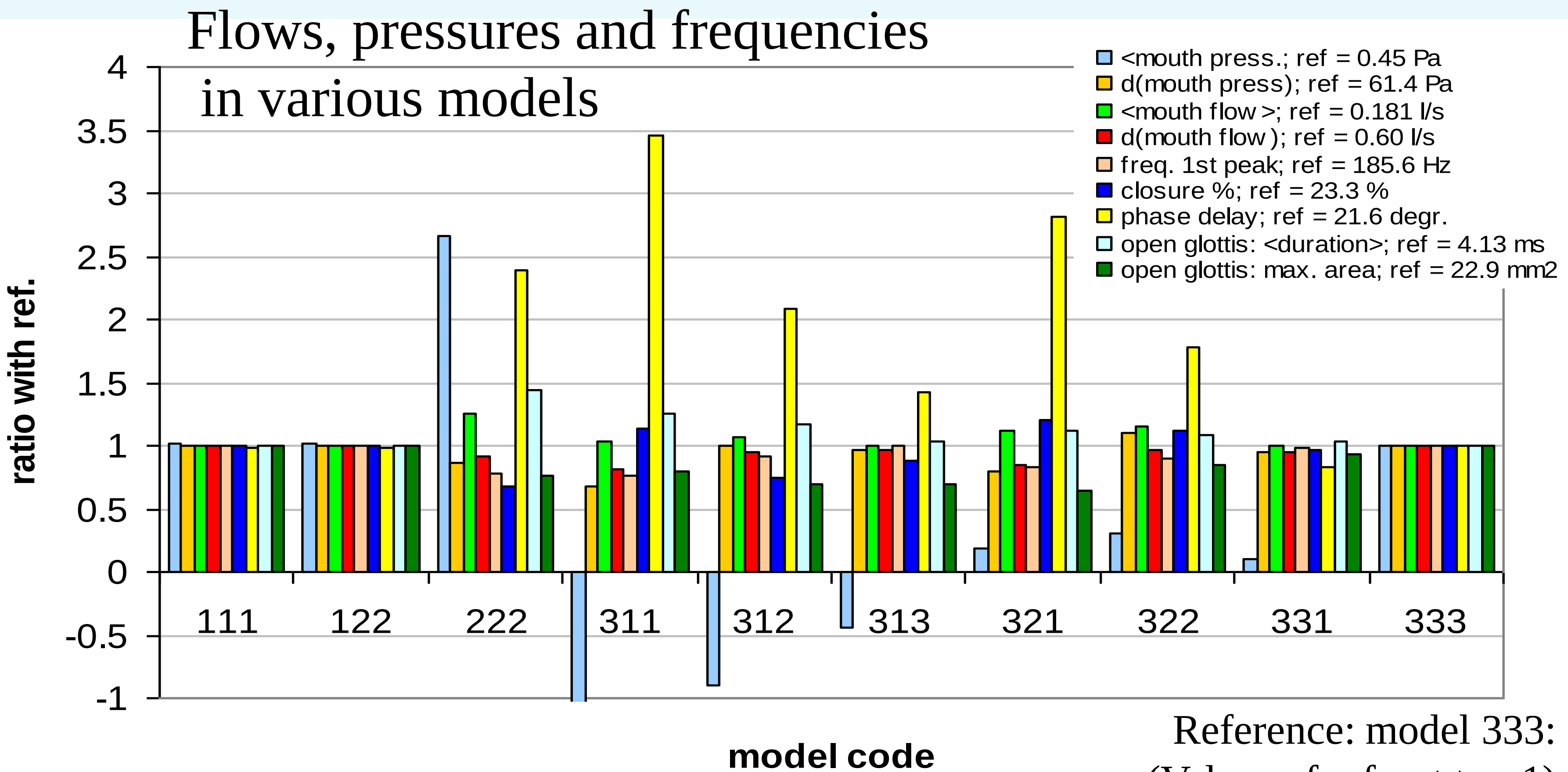
e.g. code 313 : A=3: "Combined model",
B=1: lower mass: *d* and *w* variable
C=3: upper mass: *d* and *w* fixed.

Coordinates (averages, amplitudes) in various models



"Error bars" denote oscillation amplitudes

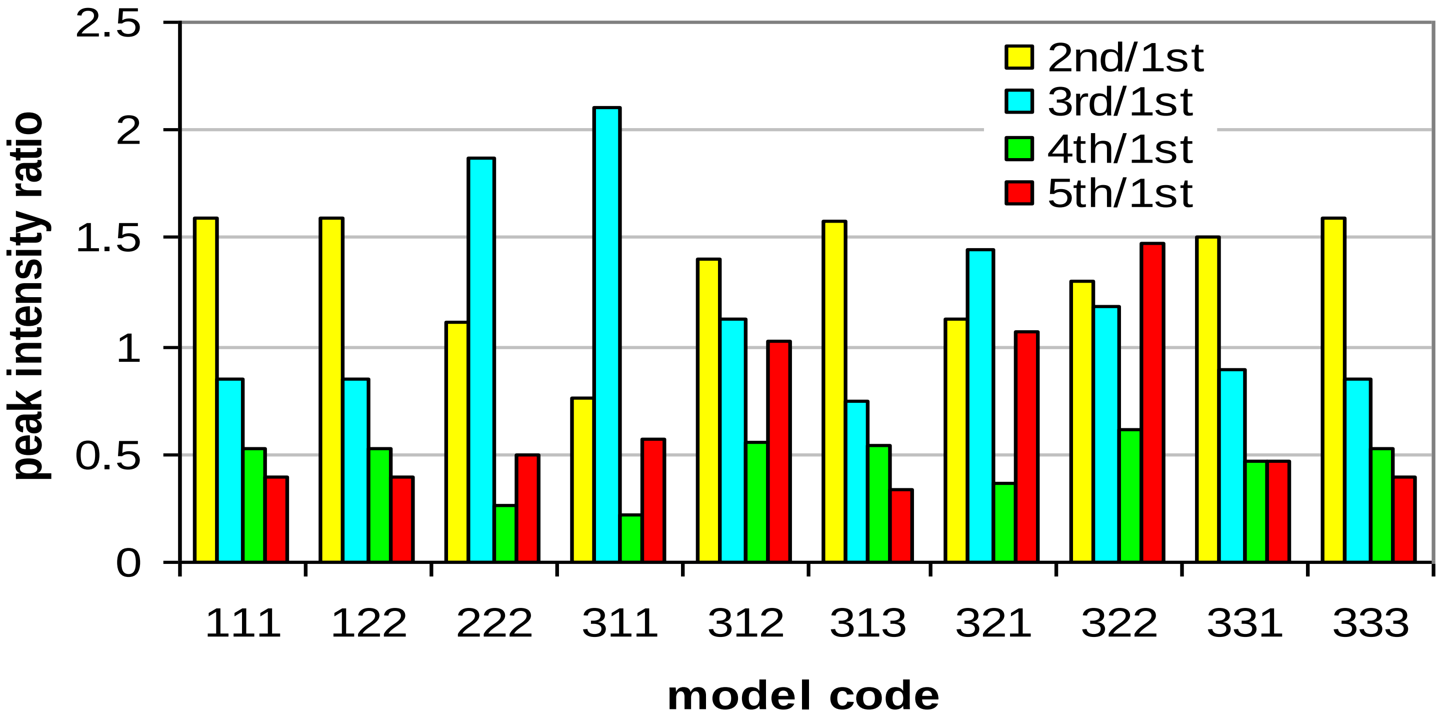
Models: (ABC)
A = 1: Ishizaka/Flanagan, 2: Koizumi, 3: Combined
B: lower mass; C: upper mass
B,C = 1: *d* and *w* var.; 2: *d* var., *w* fixed; 3: *d* and *w* fixed



Reference: model 333:
(Values of ref. set to =1)

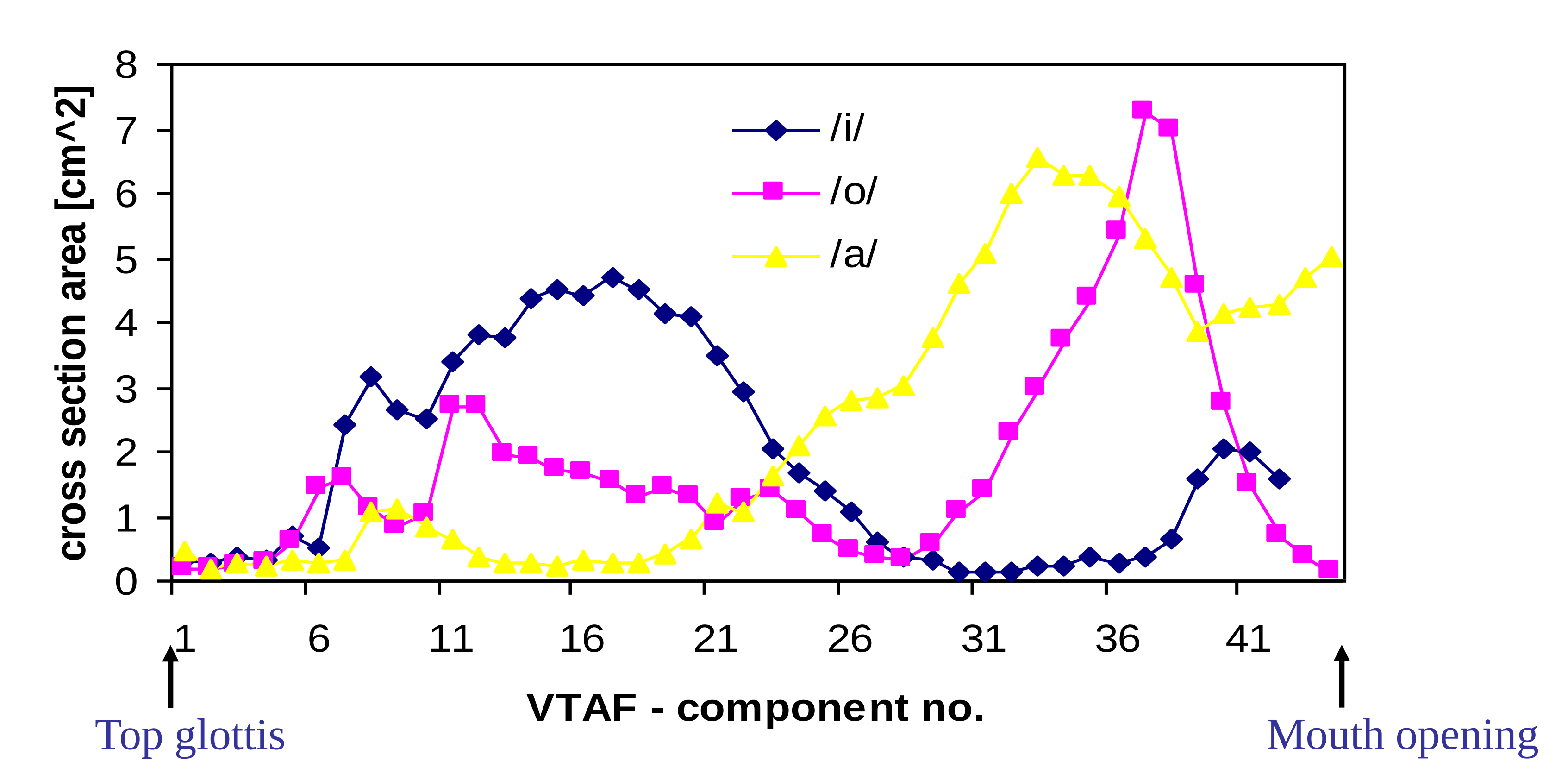
Models: (ABC)
A = 1: Ishizaka/Flanagan, 2: Koizumi, 3: Combined
B: lower mass; C: upper mass
B,C = 1: *d* and *w* var.; 2: *d* var., *w* fixed; 3: *d* and *w* fixed

Frequency peaks: intensity ratios in various models



Models: (ABC)
A = 1: Ishizaka/Flanagan, 2: Koizumi, 3: Combined
B: lower mass; C: upper mass
B,C = 1: *d* and *w* var.; 2: *d* var., *w* fixed; 3: *d* and *w* fixed

Effects of different Vocal Tract Area Functions (VTAF's).

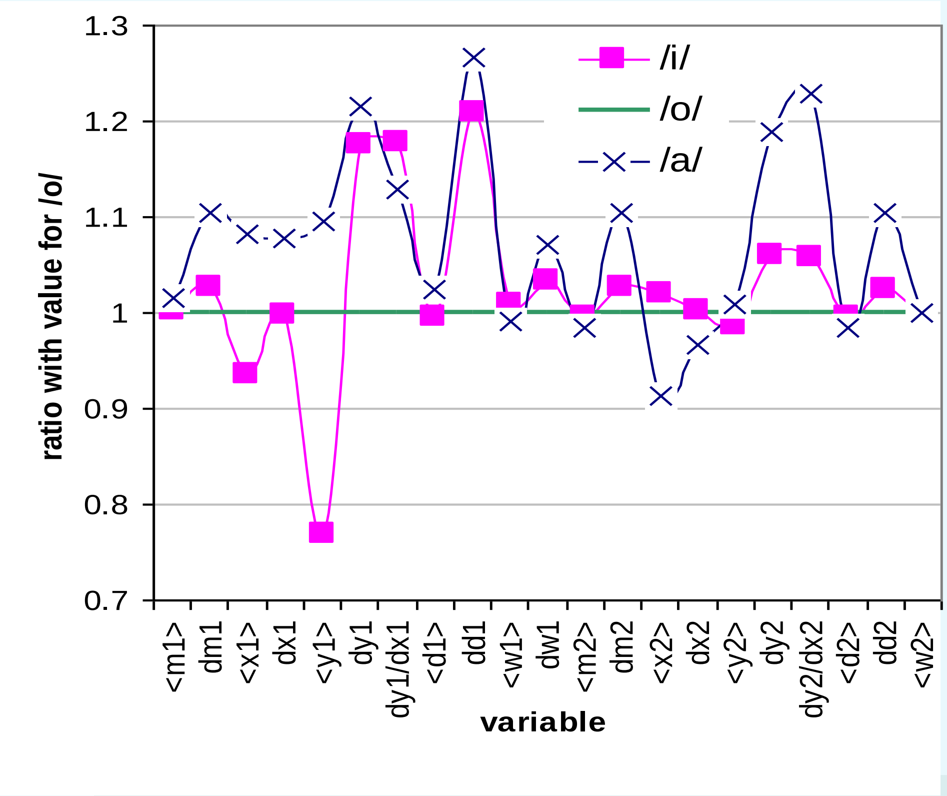


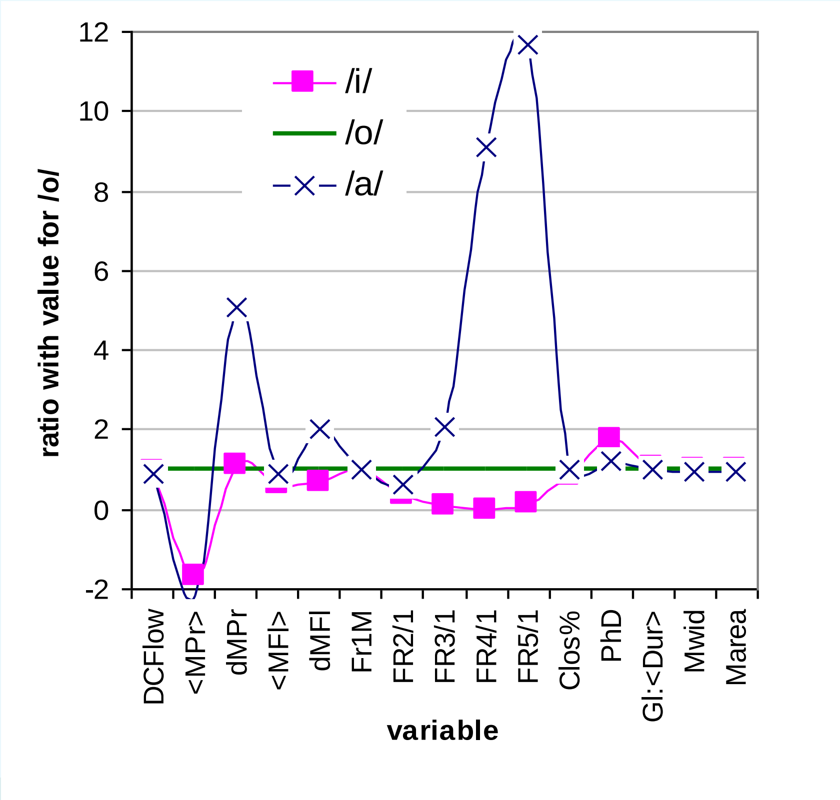
Vocal Tract Area Functions according to Story & Titze.

Component length: 0.40 cm.

Depth Kymography from 2D to 3D in Voice Diagnostics

Effects of different Vocal Tract Area Functions (VTAF's).





Model 312.

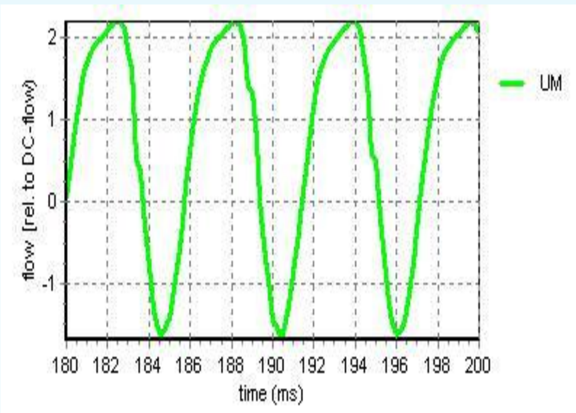
The variable values are relative to the values of VTAF = /o:/ (green line).

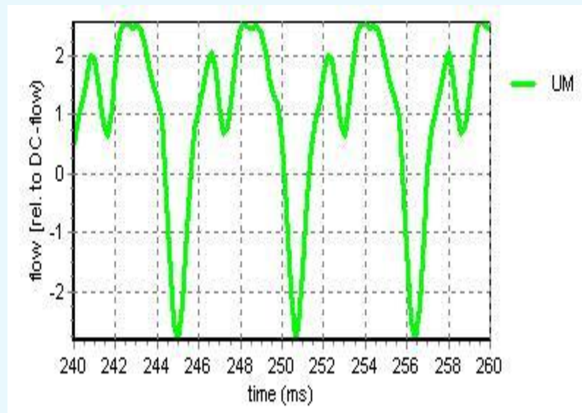
/a:/ has stronger overtones than /i:/ and /o:/.

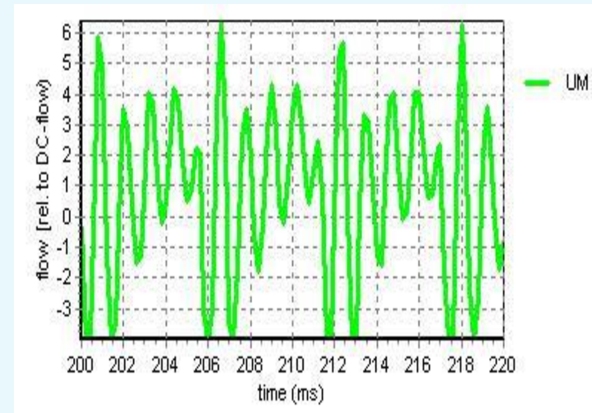
Effects of different Vocal Tract Area Functions (VTAF's).

Vowels /i:/, /o:/, /a:/ (for components: ref. Story & Titze).

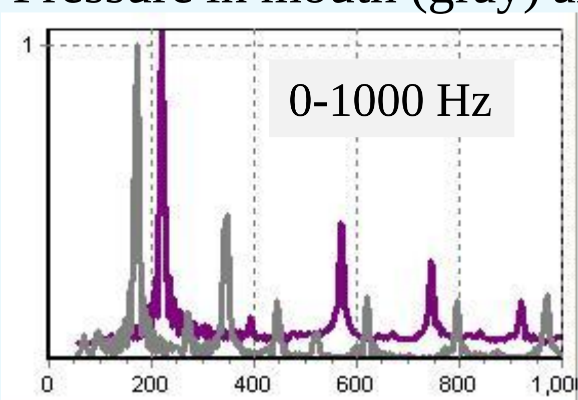
Flow in mouth (time) **/i:/** **/o:/** **/a:/**

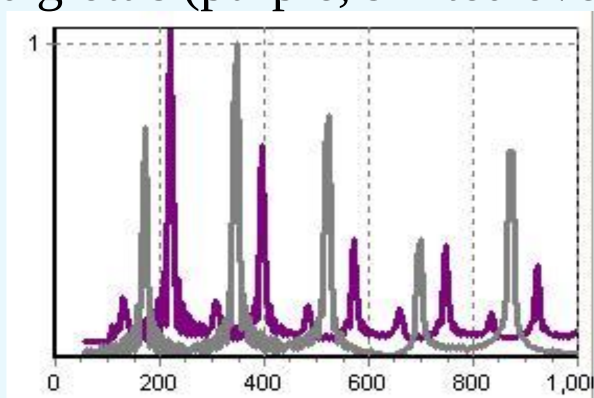


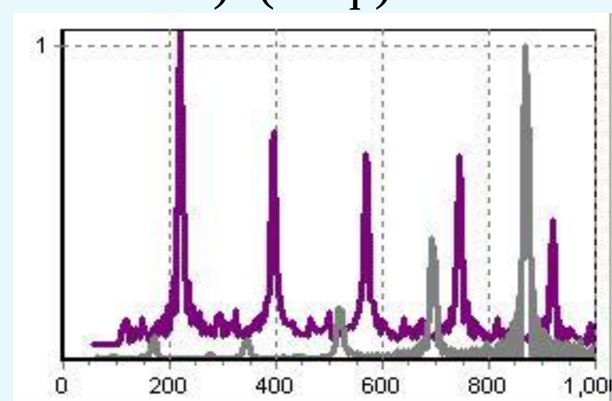




Pressure in mouth (gray) and glottis (purple; shifted over 1/20 scale) (freq.)





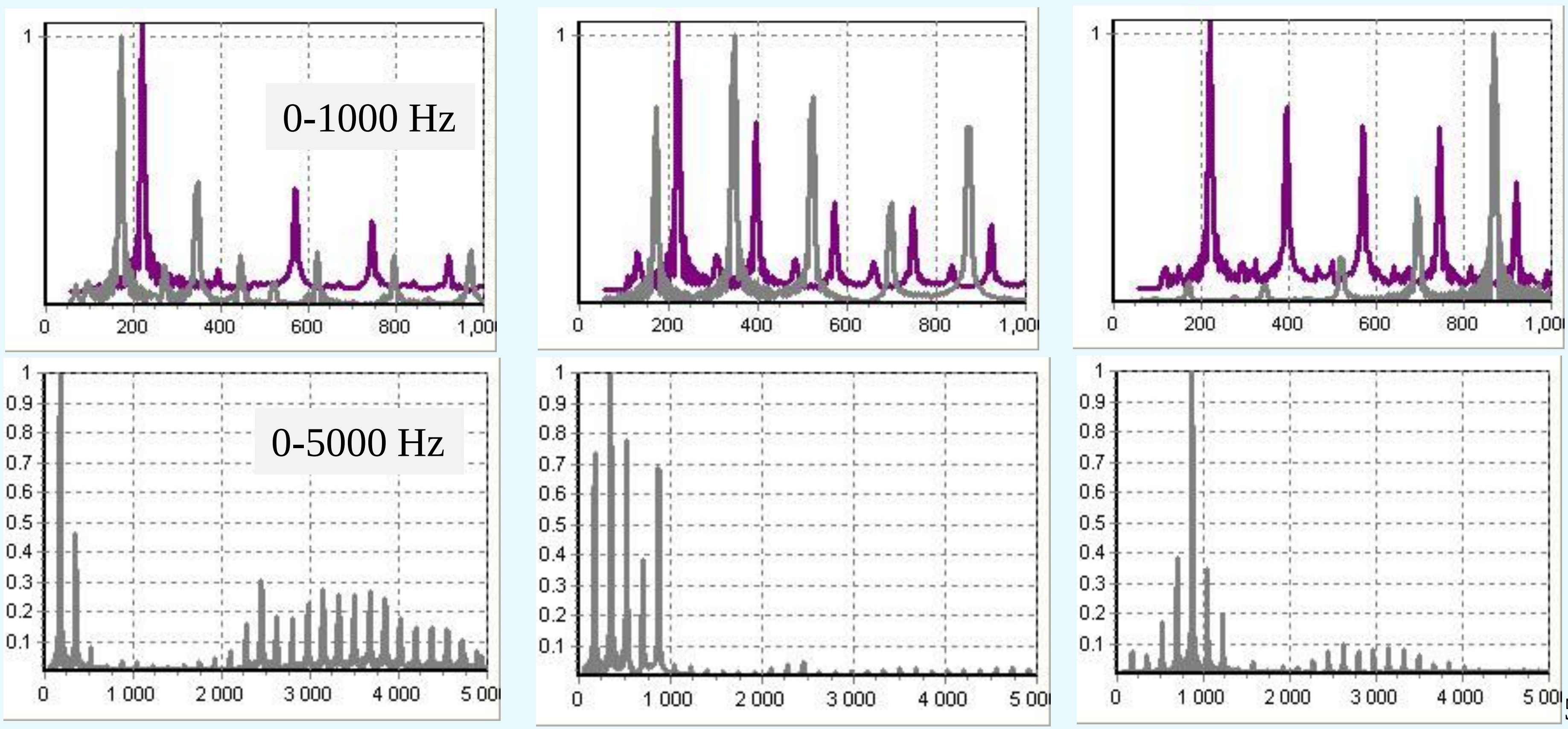


Effects of different Vocal Tract Area Functions (VTAF's).

Vowels /i:/, /o:/, /a:/ (for components: ref. Story & Titze).

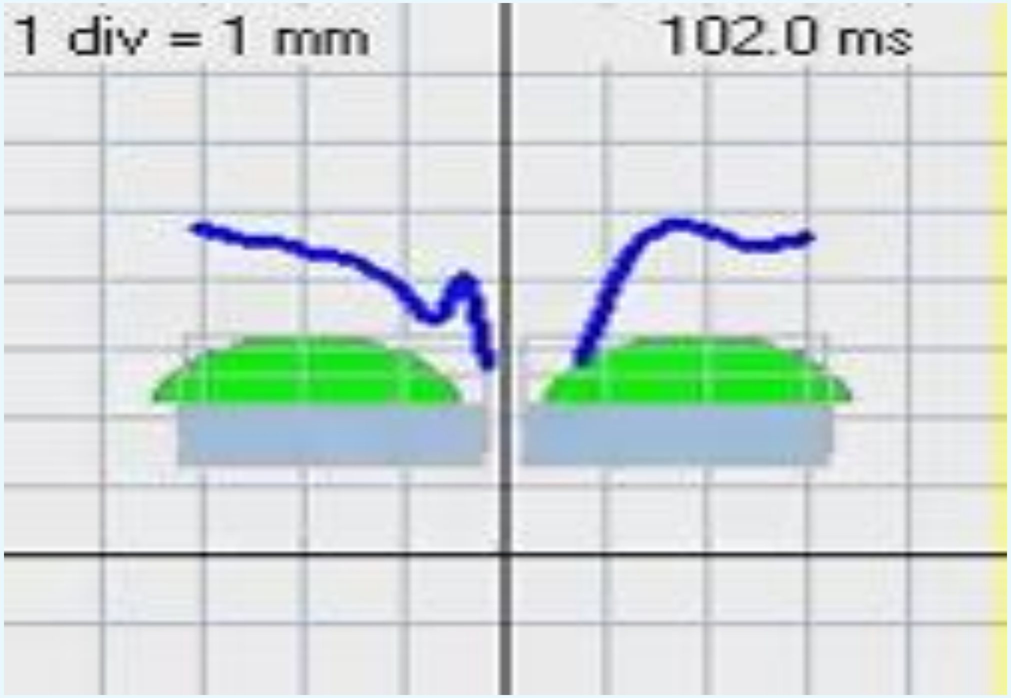
Frequencies in mouth (gray) and glottis (purple; shifted over 1/20 scale)

/i:/ /o:/ /a:/



Contents:

Comparison of measurements and simulations

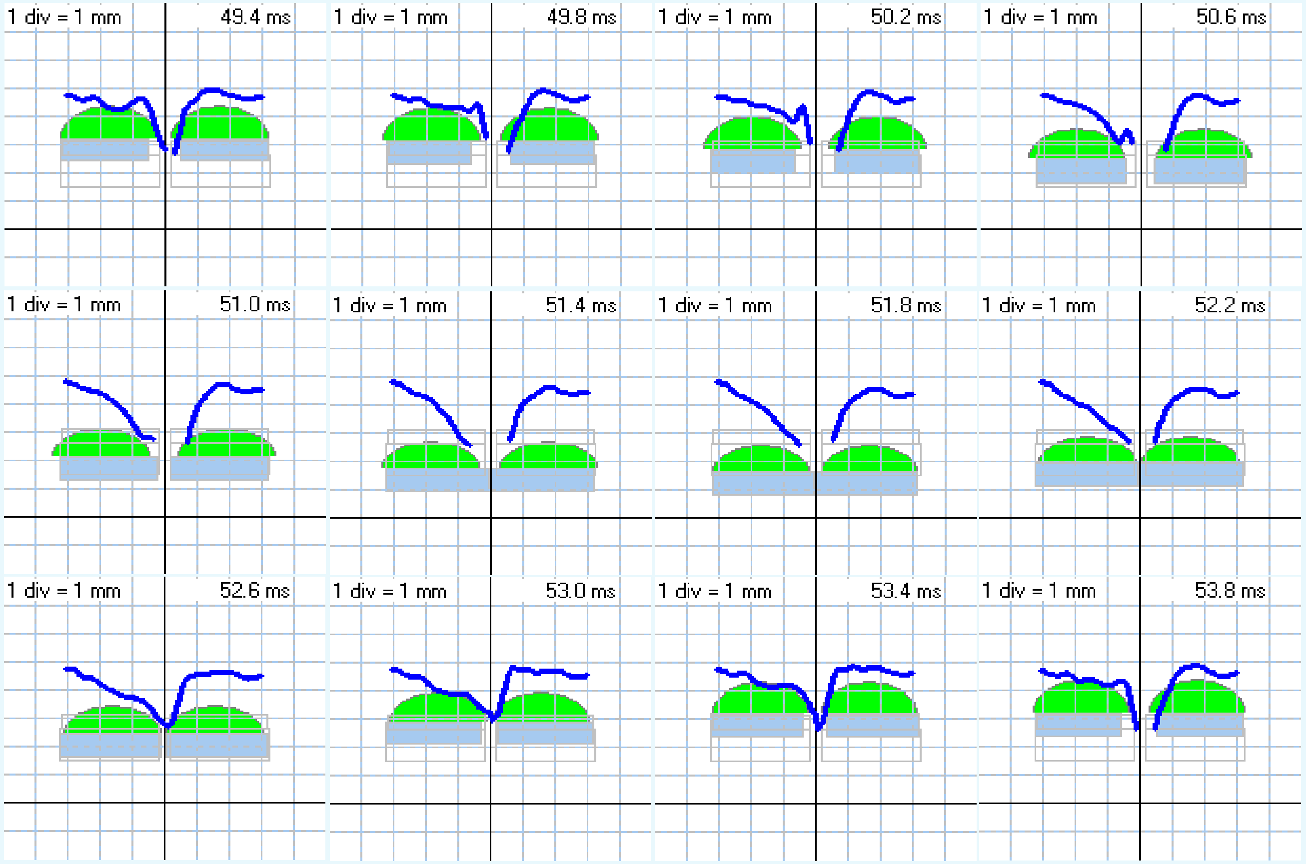


Successive vertical cross sections of the simulations.
Curve: overlay from the corresponding Depth-Kymographic measurement.

Simulation parameter settings adjusted to match measured positions and frequency.

Depth Kymography from 2D to 3D in Voice Diagnostics

Comparison of measurements and simulations **during one vibration cycle**



Successive vertical cross sections of the simulations.

Curve: overlay from the corresponding depth-Kymographic measurement.

Contents:

Conclusions:

1. Laryngoscope for Depth-Kymography:
   - Design and development are ready
   - Successful tests with human subjects

2. The program seems to be capable of simulating the vocal fold dynamics:
   - In horizontal and vertical directions
   - With mass exchange between solid mass (lower) and mucosal mass (upper)

3. Additional result:
   - Direct comparison between simulations and measurements.

More details and the program can be downloaded from
www.demul.net/frits

Publications :

1. New Laryngoscope for quantitative high-speed imaging of human vocal folds vibration in the horizontal and vertical direction
Nibu A. George, Frits F.M. de Mul, Qingjun Qiu, Gerhard Rakhorst and Harm K. Schutte, Journ.Biomed.Optics, 13(6), 064024 (2008)

2. Depth Kymography: high-speed calibrated 3D imaging of human vocal fold vibration dynamics
Nibu A. George, Frits F.M. de Mul, Qingjun Qiu, Gerhard Rakhorst and Harm K. Schutte, Phys.Med.Biol. 53 (2008) 2667-2675

3. Depth Kymograhpy of Vocal Fold Vibrations: part II. Simulations and direct comparisons with 3D profile measurements
Frits F.M. de Mul, Nibu A. George, Qingjun Qiu, Gerhard Rakhorst and Harm K. Schutte, Phys.Med.Biol. 54 (2009) 3955-3977.

The end