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Preface – Outline

Introduction
- Motivation
- Bionic aspects
- Living paradigms
- Anatomy

→

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1. Inspiration from biology
2. Modeling
3. Scope, problem & goal
4. Mathematical model
5. Control strategies
6. Adaptors
7. Simulations
8. Experiments
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2. Functionality
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5. Modeling - Stages 1-4 - Multi-body Systems
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→

Overall conclusions

Outlook

Introduction – Motivation

Main Focus / Aim:

Tactile sensing of environmental information

Approach: Inspiration from Biology

Animal Vibrissae

Transfer Functionalities to Engineering:

BIONICS

Analytical Treatment / Simulation / Prototypes

Introduction – Bionic aspects

1. **analyzing** live biological systems, e.g. vibrissae,

2. **quantifying** the mechanical and environmental behavior: identifying and quantifying mechanosensitive responses (e.g., pressure, vibrations) and their mechanisms as adaptation,

3. **modeling** live paradigms with basic features developed before,

4. **exploiting** corresponding mathematical models in order to understand details of internal processes and,

5. **coming** to artificial prototypes (e.g., sensors in robotics), which exhibit features of the real paradigms.

Important:

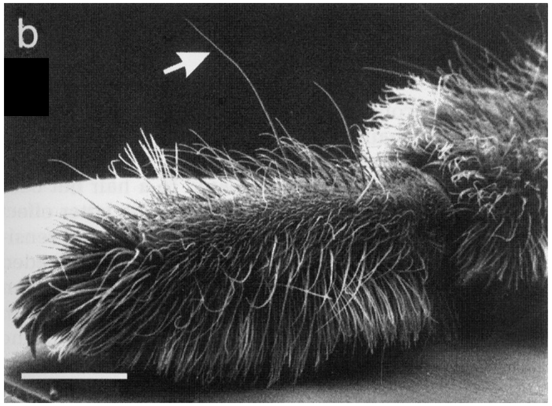
- focus is **not** on "copying" the solution from biology / animality

- **not** to construct prototypes with one-to-one properties of, e.g., a vibrissa

Introduction – Living paradigms

Different names:
vibrissa, whisker, tactile hair, sensory hair, sensillum, ...




[www]

→ variability in length, diameter, shape (curvature) and conical structure

Introduction – Living paradigms

Tactile sensing of environmental informations

- complex tactile sensory organ: sense of vibrations

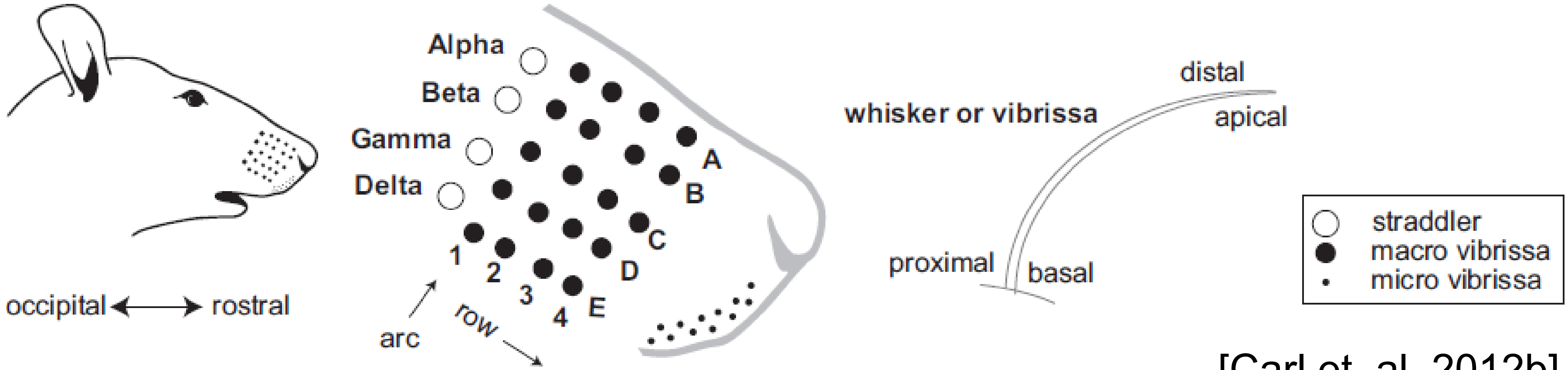
- „near field“-sense in contrast to „far field“-senses (e.g., vision)

- tactile hairs / vibrissae in the region around the snoot: *mystacial vibrissae*

- vibrissa is used as lever for force transmission

- found in nocturnal / non-visual animals (best developed in rodents e.g. rats)

Introduction – Anatomy of vibrissae



[Carl et. al. 2012b]

two components: sinus hair and own hair follicle

elastical, hollow and conically shaped

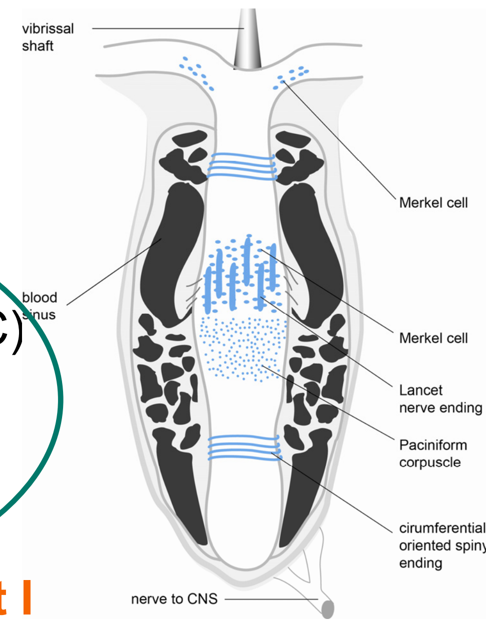
Part II

Follicle-Sinus-Complex (FSC)

blood vessels and nerves (mechanoreceptors)

→ viscoelastic support

Part I

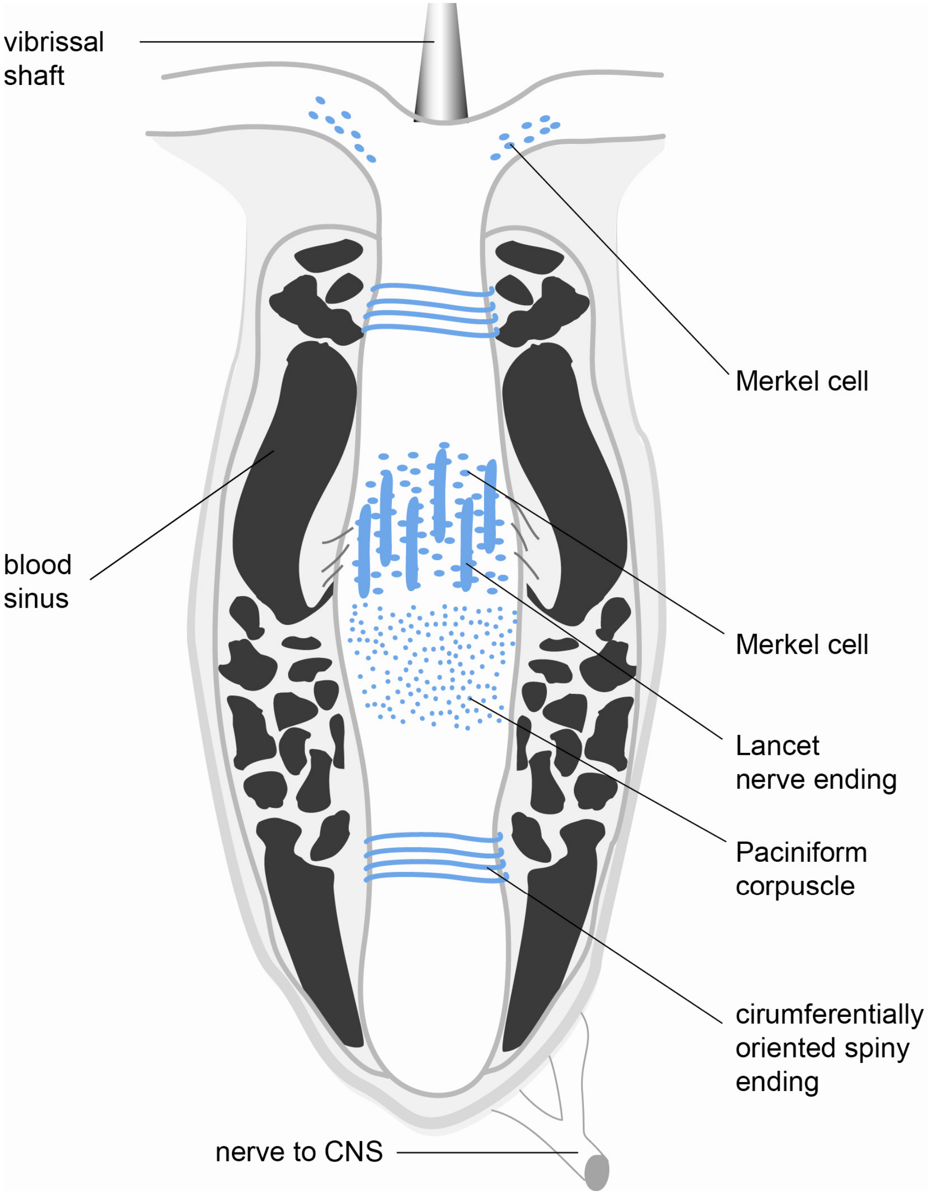


Mechanoreceptors of sensory hair systems:

- Follicle-Sinus-Complex (FSC) with blood vessels, nerves and mechanoreceptors (right side)

- Detection of vibrissa displacements by mechanoreceptors in the FSC

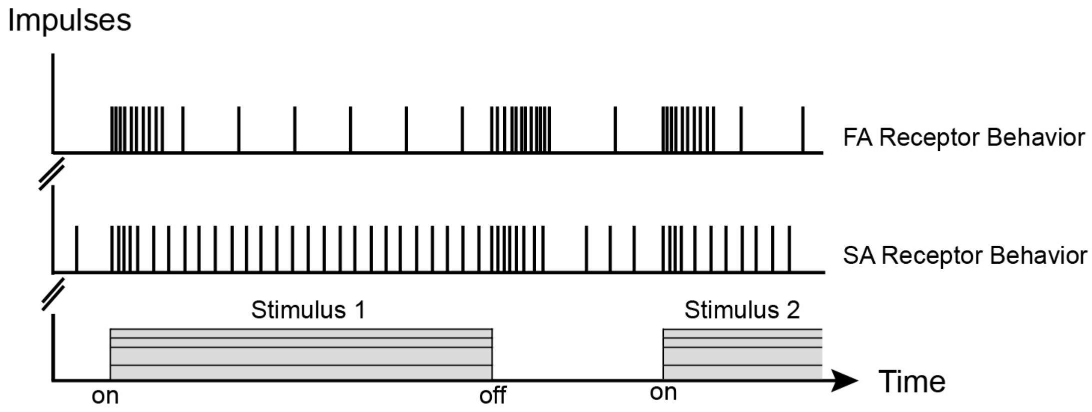
- Receptors have only one function: transduce a (mechanical) stimulus to neural impulses

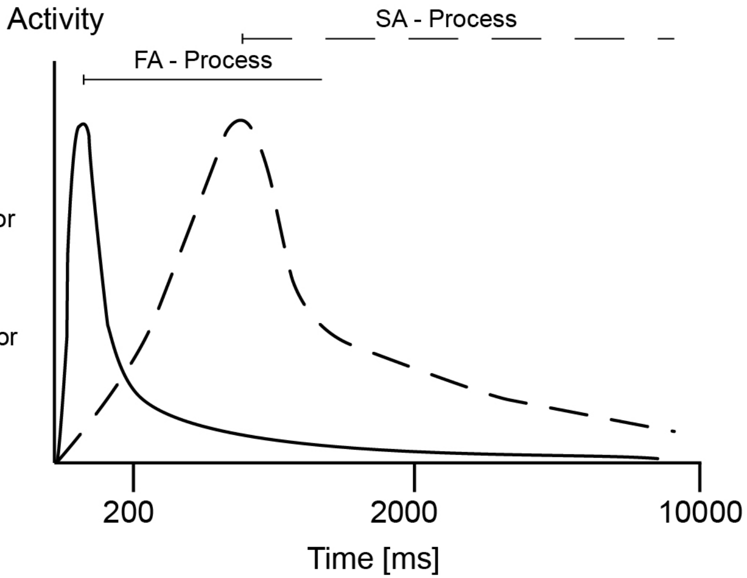


- a receptor never continues to respond to a non-changing stimulus in transducing impulses to the CNS

- the neuron's reaction is controlled:
  → is being suppressed, enhanced or left unaltered

- hence, depending on the stimulus, a receptor offers a rapid and brief response; then, this response declines if the stimulus is un-changing (stimulus is damped, is considered irrelevant once it has been perceived)





Part I: Mechanoreceptors – 1. Inspiration from biology

- sensibility of FA-receptor-cells is continuously adjusted in such a way that the whole systems tends to its rest position – despite a continued excitation

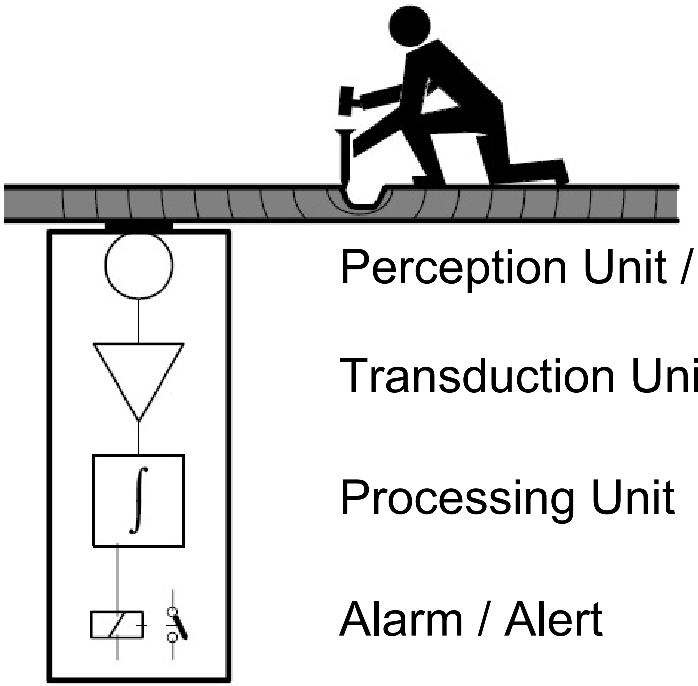
- "waiting" / sensitive for new stimulus

- due to permanently changing environment the receptor has to be in a permanent state of adaptation

- Example: think of a cat
    - exposed to wind
    - this stimulus is perceived and damped (irrelevant)
    - cat encounters obstacle, receptor should perceive this sudden deviation of the whiskers, while wind persists

    → enduring sensitivity

Part I: Mechanoreceptors – 2. Modeling



Perception Unit / Sensor

Transduction Unit

Processing Unit

Alarm / Alert

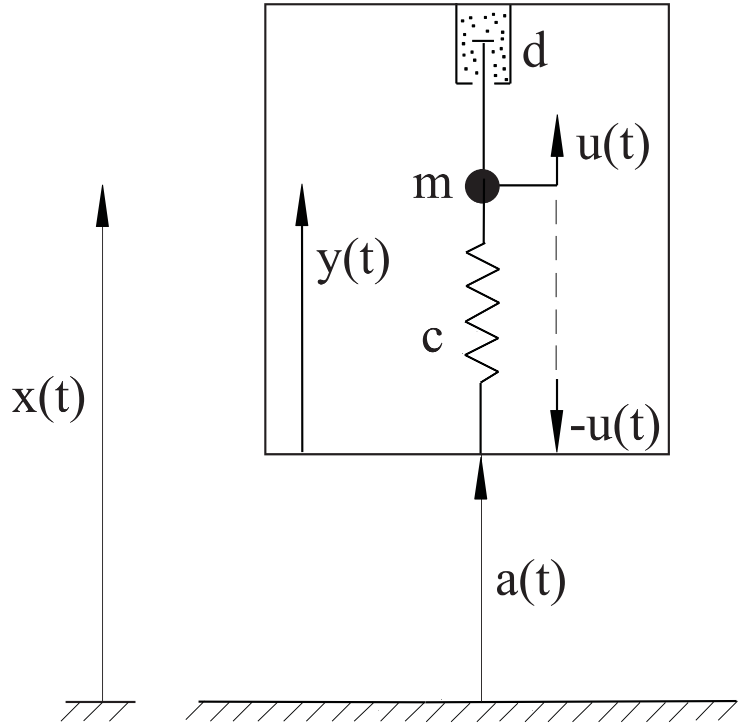
Development of new measuring and monitoring systems

- Adjustment and adaptation of its sensitiviy to the environment
- obvious: unknown surroundings

→ treatment of uncertain systems:
How to design an effective processing unit?

Receptor model:

- linear spring-mass-damper-system within a rigid frame
- forced by an unknown time-dependent displacement $a(\cdot)$
- adjustment: assuming control force $u(\cdot)$ acting on inner mass



in relative coordinate $y = x - a$ as the measured output

$$\left.\begin{aligned} \begin{pmatrix} y(t) \\ \dot{y}(t) \end{pmatrix}^{\bullet} &= \begin{bmatrix} 0 & 1 \\ -\frac{c}{m} & -\frac{d}{m} \end{bmatrix} \begin{pmatrix} y(t) \\ \dot{y}(t) \end{pmatrix} + \begin{bmatrix} 0 \\ \frac{1}{m} \end{bmatrix} u(t) + \begin{bmatrix} 0 \\ -\ddot{a}(t) \end{bmatrix} \\ y(0) = x_0 - a(0)\,, &\quad \dot{y}(0) = x_1 - \dot{a}(0)\,. \end{aligned}\right\}$$

Part I: Mechanoreceptors – 3. Scope, problem & goal

Scope:

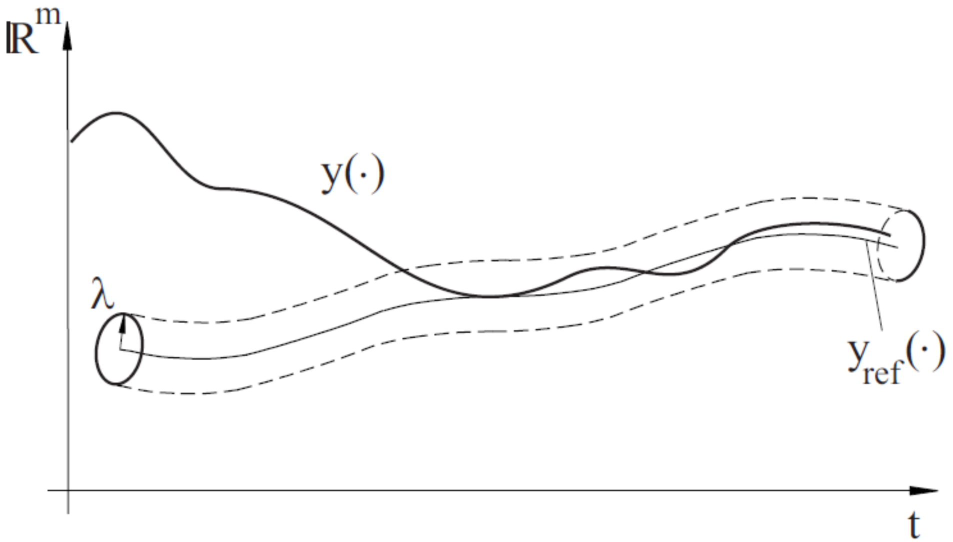
- achieve a predefined movement of the receptor mass as stabilization of the sensor system or tracking of a reference trajectory
- sole possibility: control force $u(\cdot)$
- find a suitable control strategy to reproduce the specialities of the biological system
- compensate unknown ground excitations

Problem:

- many open-loop and closed-loop controls are based on exactly known parameters
- here: highly uncertain control system (due to biological complexity)
  - unknown external perturbation
  - unknown system parameters
  - only structural properties known

What to do if the system is not known precisely?

Goal:
Design an adaptive controller, which learns from the behavior of the system, so automatically adjusts its parameters and achieves …



λ - tracking (not exact tracking)

(i) every solution of the closed-loop system is defined and bounded,

(ii) the output $y(\cdot)$ tracks the given reference signal with asymptotic accuracy λ.

Requirements:
- ability to apply controllers without knowledge about system parameters
- simple feedback / controller structure
- small level of gain parameters, level of error inside the tube
- ability to quickly adapt to parameter changes

General System Class:

$$\left.\begin{aligned} \ddot{y}(t) &= A_2\,\dot{y}(t) + f_1\big(s_1(t), y(t), z(t)\big) + G\,u(t)\,, \\ \dot{z}(t) &= A_5\,z(t) + A_0\,\dot{y}(t) + f_2\big(s_2(t), y(t)\big)\,, \\ y(t_0) &= y_0\,, \quad \dot{y}(t_0) = y_1\,, \quad z(t_0) = z_0\,, \end{aligned}\right\}$$

- $y(t)$, y_0, y_1, $u(t) \in \mathbb{R}^m$, $z(t)$, $z_0 \in \mathbb{R}^{n-2m}$;
- real valued A_2, G, A_5, A_0 of appropriate dimensions;
- $n \geq 2m$;

Properties:

- quadratic, finite-dimensional, nonlinearly perturbed, m-input $u(\cdot)$, m-output $y(\cdot)$ control system (MIMO) with strict relative degree two;
- $\mathrm{spec}(G) \subset \mathbb{C}_+$, i.e., the spectrum of the "high-frequency gain" lies in the open right-half complex plane;
- $\mathrm{spec}(A_5) \subset \mathbb{C}_-$, i.e., the unperturbed system is minimum phase (stable zero dynamics);
- functions f_1 and f_2 are continuous and linearly affine bounded;
- s_1 and s_2 may be thought of as (bounded) disturbance terms;

Part I: Mechanoreceptors – 4. Mathematical model

Special System Subclass:

$$\left.\begin{aligned} \ddot{y}(t) &= A_2\,\dot{y}(t) + f_1\big(s_1(t), y(t), z(t)\big) + G\,u(t)\,, \\ \dot{z}(t) &= A_5\,z(t) + f_2\big(s_2(t), y(t)\big)\,, \\ y(t_0) &= y_0\,, \quad \dot{y}(t_0) = y_1\,, \quad z(t_0) = z_0\,, \end{aligned}\right\}$$

- $y(t)$, y_0, y_1, $u(t) \in \mathbb{R}$, $z(t)$, $z_0 \in \mathbb{R}^{n-2}$;
- real valued A_2, G, A_5 of appropriate dimensions;
- $n \geq 2$;

restriction

Properties:

- quadratic, finite-dimensional, nonlinearly perturbed, SISO-control system with strict relative degree two;
- $G > 0$, i.e., positive input gain;
- $\mathrm{spec}(A_5) \subset \mathbb{C}_-$, i.e., the unperturbed system is minimum phase (stable zero dynamics);
- functions f_1 and f_2 are continuous and linearly affine bounded;
- s_1 and s_2 may be thought of as (bounded) disturbance terms;
- $A_2 < 0$, i.e., stable zero-center;

Modified from literature, high-gain controllers:

Controller 1: (using the derivative of the output)

$$e(t) := y(t) - y_{\mathrm{ref}}(t)\,,$$
$$u(t) = -\Big(k(t)e(t) + \tfrac{d}{dt}\big(k(t)e(t)\big)\Big)\,,$$
$$\dot{k}(t) = \gamma\Big(\max\big\{0, \|e(t)\| - \lambda\big\}\Big)^2, \quad k(0) = k_0 \in \mathbb{R}$$

Works for general class, proven 2006

Controller 2: (includes a dynamic compensator, no derivative measurement)

$$e(t) := y(t) - y_{\mathrm{ref}}(t)\,,$$
$$u(t) = -k(t)\,\theta(t) - \tfrac{d}{dt}\big(k(t)\,\theta(t)\big)\,,$$
$$\dot{\theta}(t) = -k(t)^2\,\theta(t) + k(t)^2\,e(t)\,, \quad \theta(0) = \theta_0 \in \mathbb{R}^m$$
$$\dot{k}(t) = \gamma\,\max\big\{0\,, \|\,e(t)\| - \lambda\big\}^2, \quad k(0) = k_0 \in \mathbb{R}$$

Works for general class, proven 2011

Controller 3: (controller of order 1, P-structure)

$$e(t) := y(t) - y_{\mathrm{ref}}(t)\,,$$
$$u(t) = -k(t)\,e(t)\,,$$
$$\dot{k}(t) = \gamma\,\max\big\{0, |e(t)| - \lambda\big\}^2, \quad k(0) = k_0 \in \mathbb{R}_+$$

Works only for special subclass, proven 2013, not extendable to MIMO

Let $\lambda > 0$, $y_{\text{ref}}(\cdot) \in \mathcal{R}$, $s_1(\cdot) \in \mathcal{L}^\infty(\mathbb{R}_{\geq 0}; \mathbb{R}^{q_1})$ and $s_2(\cdot) \in \mathcal{L}^\infty(\mathbb{R}_{\geq 0}; \mathbb{R}^{q_2})$. Then the presented adaptive λ-trackers applied to every system of the general system class yields for any initial data $(y_0, y_1, z_0, \theta_0, k_0) \in \mathbb{R}^m \times \mathbb{R}^m \times \mathbb{R}^{n-2m} \times \mathbb{R}^m \times \mathbb{R}_{>0}$

$$\left.\begin{aligned}
\dot{y}(t) &= \zeta(t), & y(0) &= y_0,\\
\dot{\zeta}(t) &= A_2\,\zeta(t) + f_1\big(s_1(t), y(t), z(t)\big) & &\\
&\quad -G\Big[k(t)\,\theta(t) + k(t)^3\,[y(t) - y_{\text{ref}}(t)] & &\\
&\quad + \max\Big\{0, \big\|y(t) - y_{\text{ref}}(t)\big\| - \lambda\Big\}^2 \theta(t) - k(t)^3\,\theta(t)\Big], & \zeta(0) &= y_1,\\
\dot{z}(t) &= A_5\,z(t) + A_0\,\zeta(t) + f_2\big(s_2(t), y(t)\big), & z(0) &= z_0,\\
\dot{\theta}(t) &= -k(t)^2\,\theta(t) + k(t)^2\,[y(t) - y_{\text{ref}}(t)], & \theta(0) &= \theta_0,\\
\dot{k}(t) &= \max\Big\{0, \big\|y(t) - y_{\text{ref}}(t)\big\| - \lambda\Big\}^2, & k(0) &= k_0,
\end{aligned}\right\}$$

which has a maximal solution $(y, \zeta, z, \theta, k) : [0, t') \to \mathbb{R}^m \times \mathbb{R}^m \times \mathbb{R}^{n-2m} \times \mathbb{R}^m \times \mathbb{R}_{>0}$ with:

(i) $t' = \infty$, i.e. there does not exist a finite escape time;

(ii) $\lim_{t\to\infty} k(t)$ exists and is finite;

(iii) the solution, $\dot{\zeta}(\cdot)$, $\dot{z}(\cdot)$, $\dot{\theta}(\cdot)$ and $u(\cdot)$ are bounded;

(iv) $\limsup_{t\to\infty} \big\|y(t) - y_{\text{ref}}(t)\big\| \leq \lambda$;

(v) $\limsup_{t\to\infty} \big\|\theta(t)\big\| \leq \lambda$.

Problems

- stabilization and tracking are guaranteed / proven

- slow convergence of controller gain: introducing new parameter γ

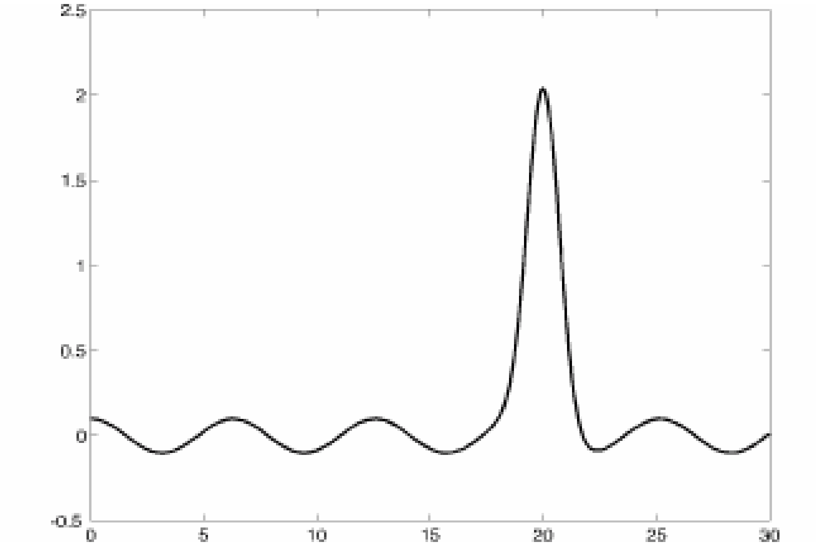
$$\dot{k}(t) = \gamma\Big(\max\big\{0, \|e(t)\| - \lambda\big\}\Big)^2, \quad k(0) = k_0 \in \mathbb{R}$$

- this parameter strongly determines the growth of the gain parameter (sufficiently large enough)

- Example:

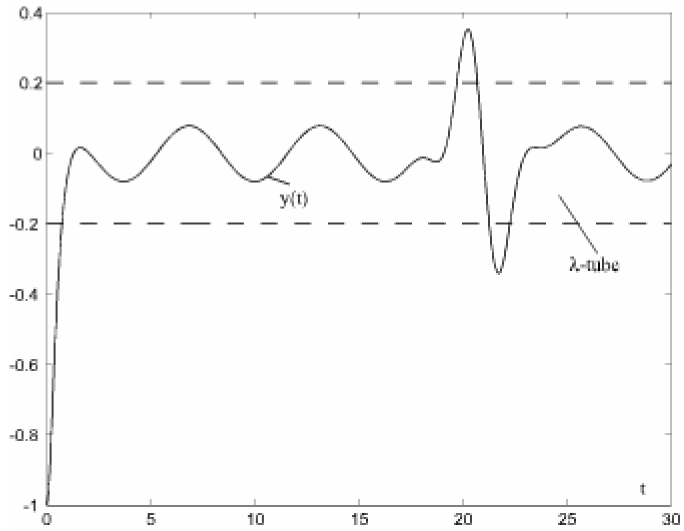
soliton excitation peak at t=20.5:

$$t \mapsto a(t) = \left(1 + 3\,e^{-0.5(t-20.5)^2}\right)\cos(t)$$



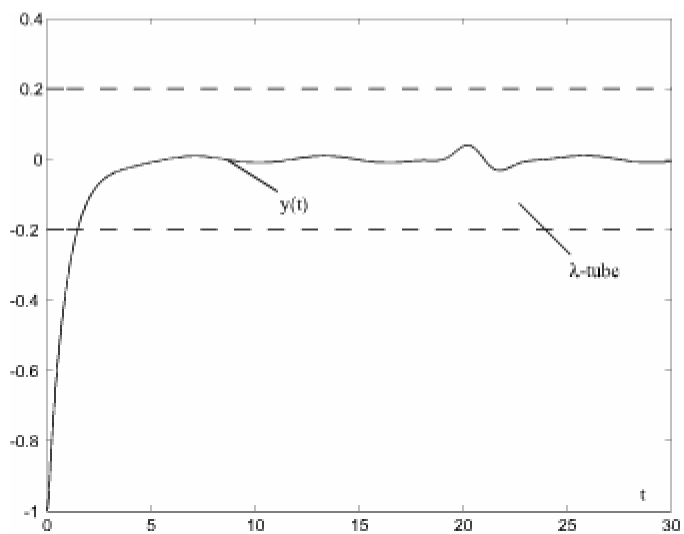
Part I: Mechanoreceptors – 6. Adaptors

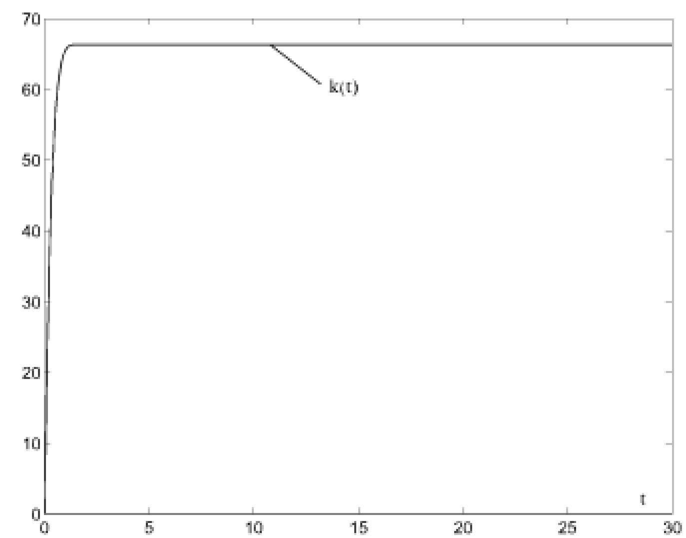
$\gamma = 10:$



- high gain values, still stays constant although control objective is achieved
- arrive also at high feedback values
- furthermore: system is now not really sensitive to notice other impulses (see t=20.5)

$\gamma = 300:$





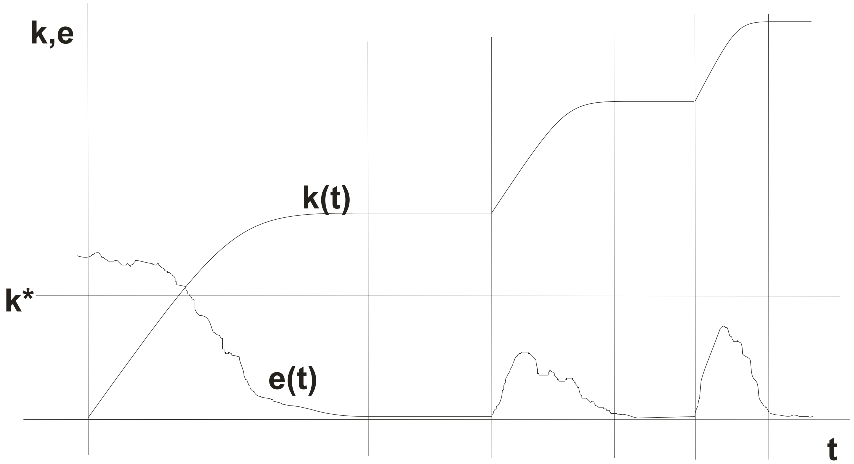
Part I: Mechanoreceptors – 6. Adaptors

- closed-loop system is getting insensitive for changes of the stimulus

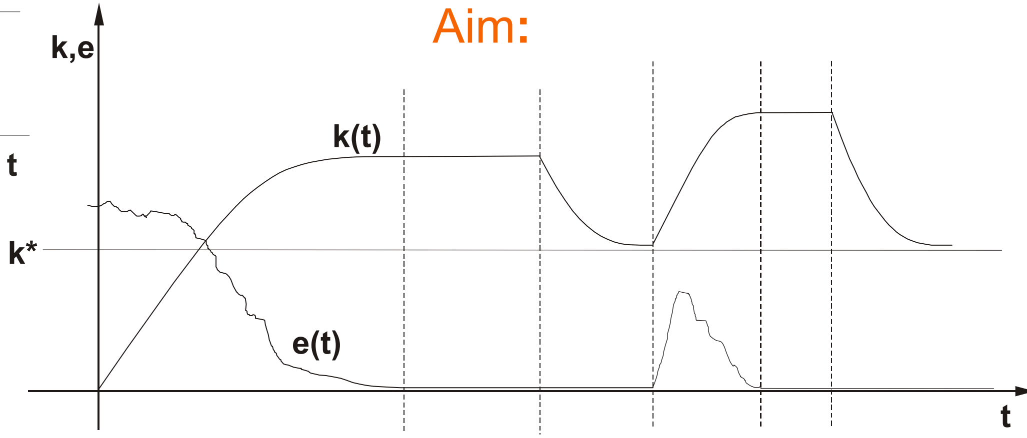
- caused by only monotonic increase of the gain parameter (classical adaptor)

$$\dot{k}(t) = \gamma \left(\max\left\{0, \|e(t)\| - \lambda\right\}\right)^2$$

- also do almost all controllers existing in the literature



Aim:



Also: What about limited resources in applications?

Attempt 1: so-called „sigma-modification“ (in the literature):

$$\dot{k}(t) = -\sigma\, k(t) + \gamma \left(\max \left\{ 0, \|e(t)\| - \lambda \right\} \right)^2 , \quad \lambda > 0\,, \sigma > 0\,, \gamma \gg 1$$

- this adaptor achieves damping and increase of the gain k simultaneously when e is outside the tube
- this law (often) leads to chaotic behavior of the system

Attempt 2: first simple modification:

$$\dot{k}(t) = \begin{cases} \gamma \left(\|e(t)\| - \lambda \right)^2, & \|e(t)\| \geq \lambda\,, \\ -\sigma\, k(t), & \|e(t)\| < \lambda, \end{cases} \quad \lambda > 0\,, \sigma > 0\,, \gamma \gg 1$$

- also showing alternating increase and exponential decrease of k

- Problem:
  It could happen that e rapidly traverses the tube. Then it would be inadequate to immediately decrease k after e entered the tube.

Part I: Mechanoreceptors – 6. Adaptors

Attempt 3: Distinguishing three cases:

1. increasing k while e is outside the tube,
2. constant k after e entered the tube - no longer than a pre-specified duration t_d of stay,
3. decreasing k after this duration has been exceeded:

$$\dot{k}(t) = \begin{cases} \gamma\left(\|e(t)\| - \lambda\right)^2, & \|e(t)\| \geq \lambda\,, \\ 0, & \left(\|e(t)\| < \lambda\right) \wedge (t - t_E < t_d)\,, \\ -\sigma\, k(t), & \left(\|e(t)\| < \lambda\right) \wedge (t - t_E \geq t_d), \end{cases}$$

$$\lambda > 0\,, \sigma > 0\,, \gamma \gg 1\,, t_d > 0\,, t_E \text{ internal}$$

Attempt 4: In order to make the attraction of the tube stronger using different exponents for large/small distance from the tube:

$$\dot{k}(t) = \begin{cases} \gamma\left(\|e(t)\| - \lambda\right)^2, & \|e(t)\| \geq \lambda + 1\,, \\ \gamma\left(\|e(t)\| - \lambda\right)^{0.5}, & \lambda + 1 > \|e(t)\| \geq \lambda\,, \\ 0, & \left(\|e(t)\| < \lambda\right) \wedge (t - t_E < t_d)\,, \\ -\sigma\, k(t), & \left(\|e(t)\| < \lambda\right) \wedge (t - t_E \geq t_d), \end{cases}$$

Attempt 5: One way to guarantee that e will not leave the tube after entering the tube and k is going to be decreased, is tracking of a smaller value than the desired one, for example $\varepsilon = 0.7$:

$$\dot{k}(t) = \begin{cases} \gamma\left(\|e(t)\| - \varepsilon\,\lambda\right)^2, & \|e(t)\| \geq \varepsilon\,\lambda + 1\,, \\ \gamma\left(\|e(t)\| - \varepsilon\lambda\right)^{\frac{1}{2}}, & \varepsilon\lambda + 1 > \|e(t)\| \geq \varepsilon\lambda\,, \\ 0, & \left(\|e(t)\| < \varepsilon\,\lambda\right) \wedge (t - t_E < t_d)\,, \\ -\sigma\,k(t), & \left(\|e(t)\| < \varepsilon\,\lambda\right) \wedge (t - t_E \geq t_d), \end{cases}$$

- turns out as the to-be-favoured one

- „ ε– safe λ– tracking“

Part I: Mechanoreceptors – 7. Simulations

- adaptive nature: arbitrary choice of the system parameters

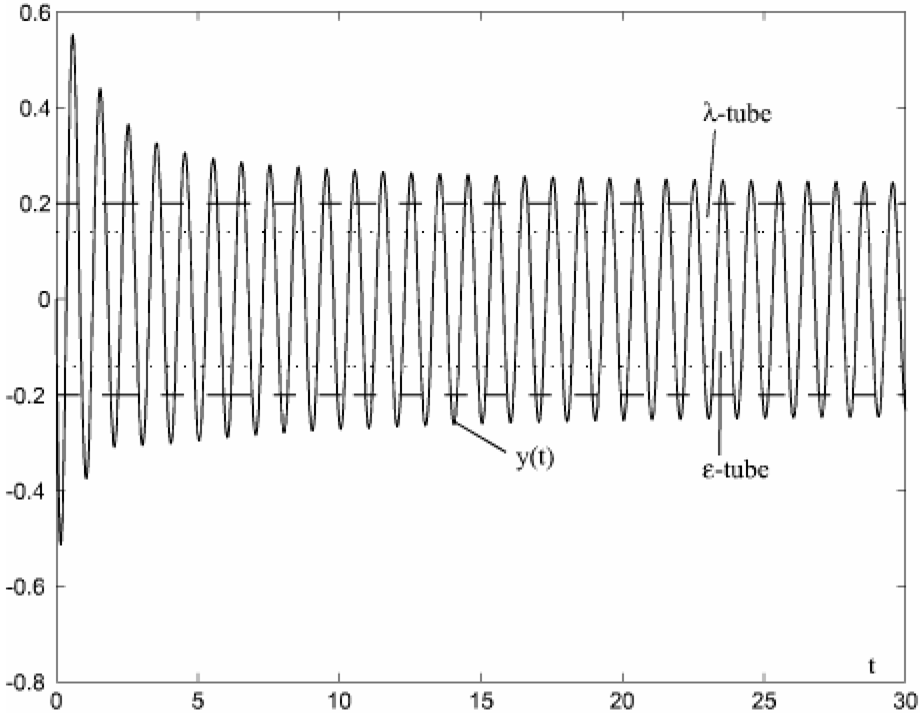
- obvious (for numerical simulation) to choose system data fixed and known, but controllers adjust their gain parameter to each set of system data

- parameters: arbitrarily chosen, not measured, not identified from biological paradigm

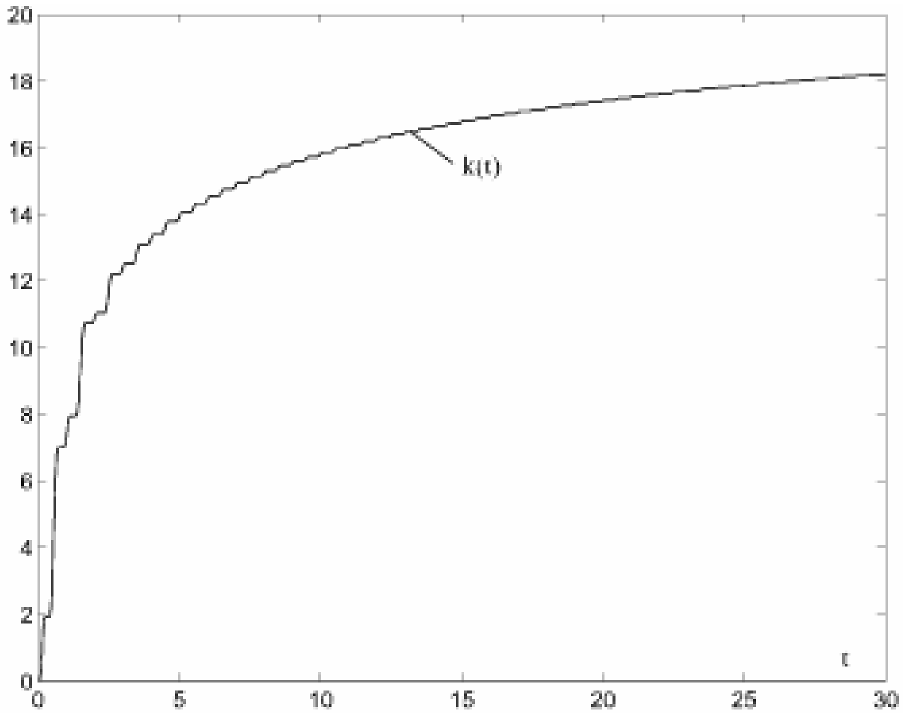
- sensor system: sensor mass $m = 1$, damping coefficient $d = 5$, spring stiffness $c = 10$;
- initial values $\big(y(0), \dot{y}(0)\big) = \big(-a(0), -\dot{a}(0)\big)$
- reference signal $t \mapsto y_{\mathrm{ref}}(t) = 0$ (rest position)
- ground excitation $t \mapsto a(t) = \sin(2\,\pi\,t)$
- ε-safe λ-tracker: initial gain value $k_0 = 1$, tracking tolerance $\lambda = 0.2$, decrease rate $\sigma = 1$, time of duration in tube $t_d = 3$, gain convergence parameter $\gamma = 50$, safe $\varepsilon = 0.7$

λ-tracker / classical adaptor

Output, tubes vs. t



Gain parameter vs. t



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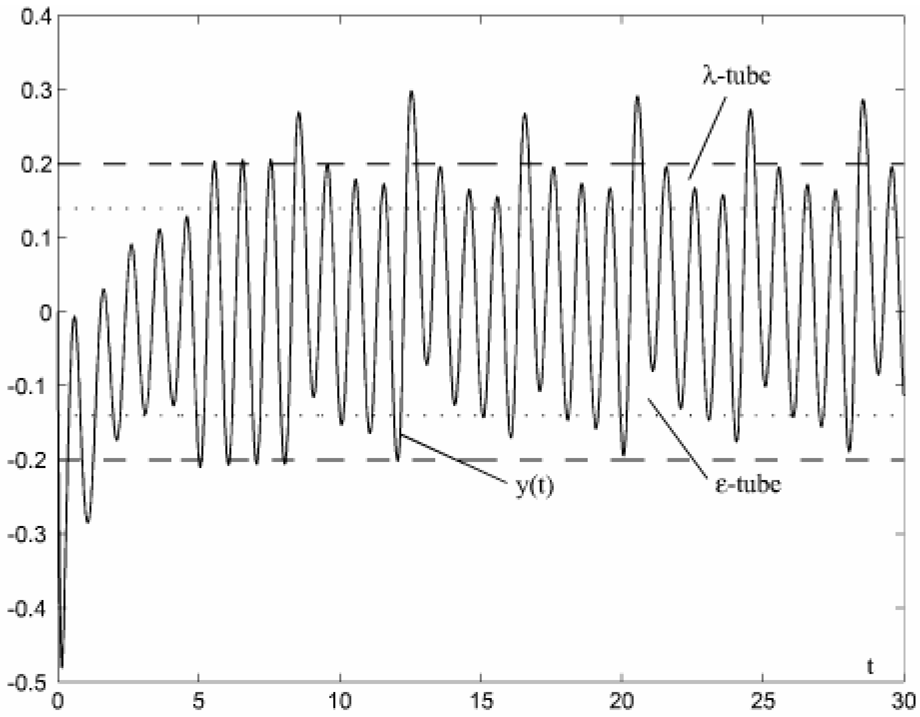
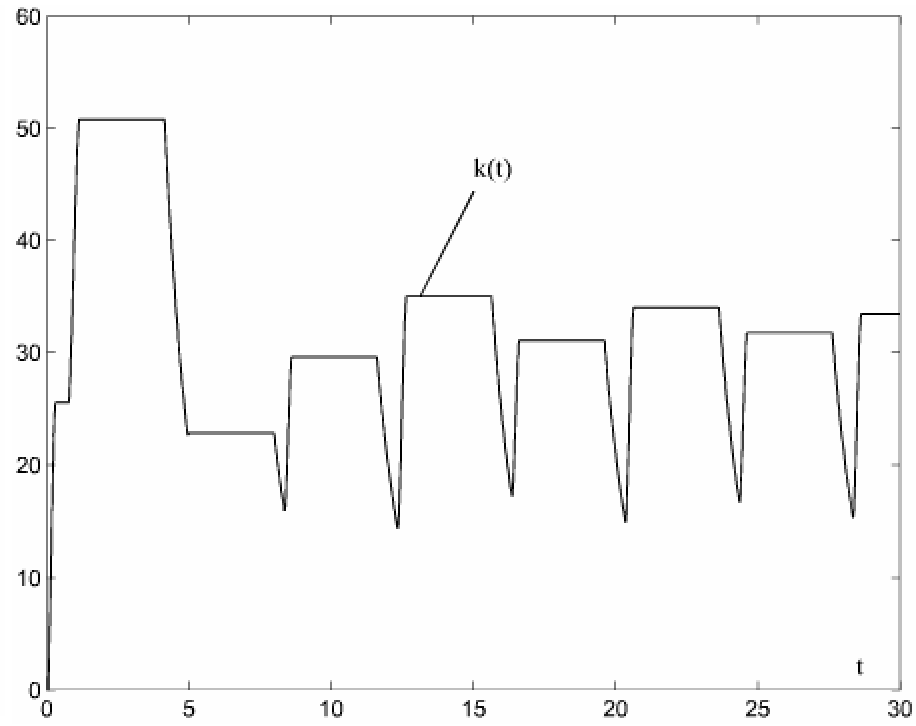
λ-tracker / Adaptor with two exponents

Output, tubes vs. t

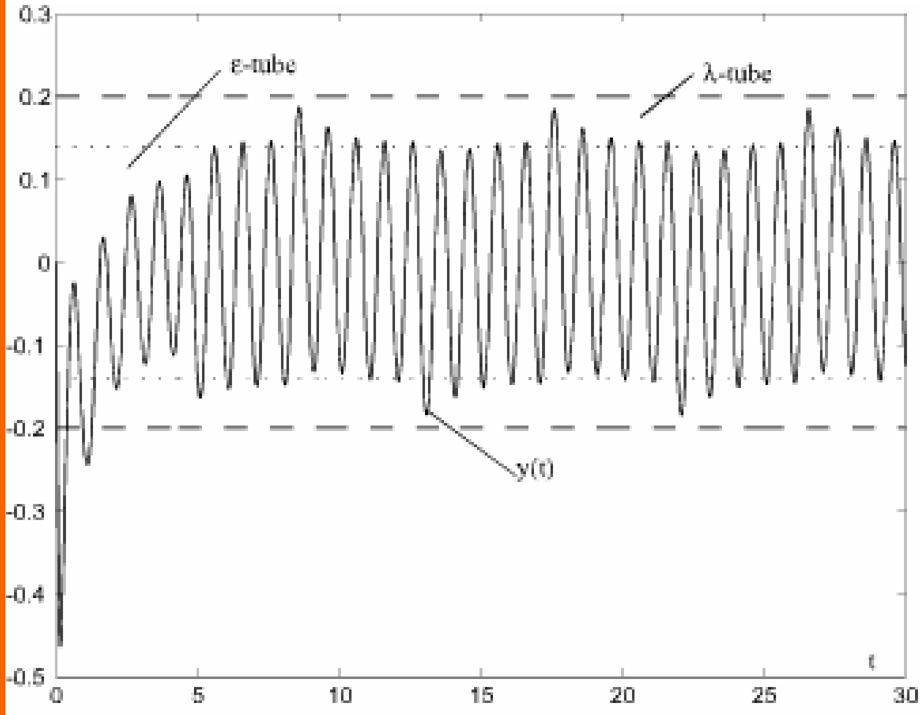


Gain parameter vs. t

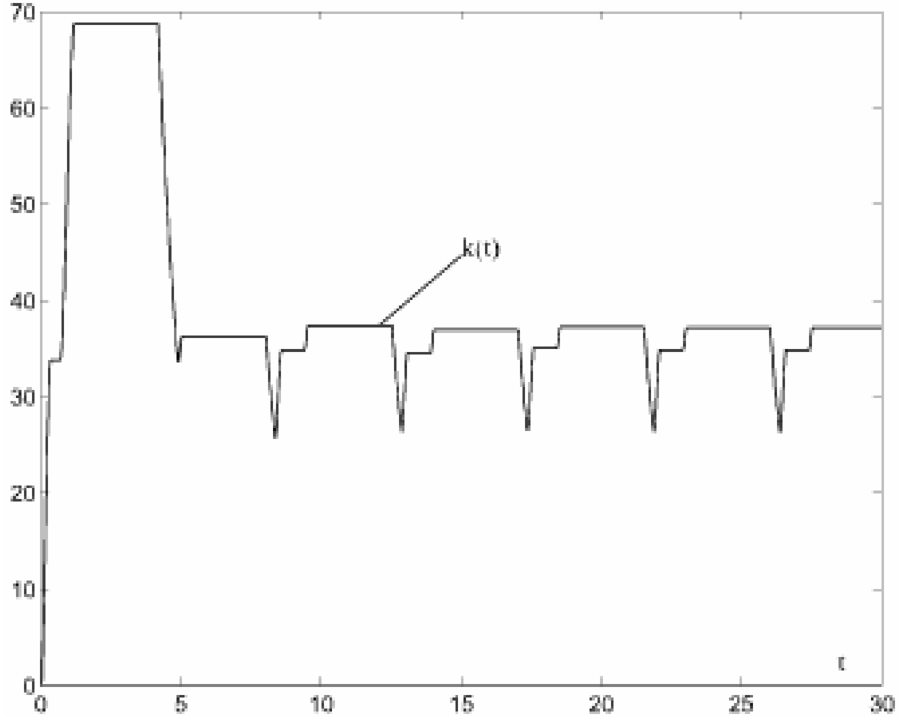


ε-safe λ-tracker

Output, tubes vs. t



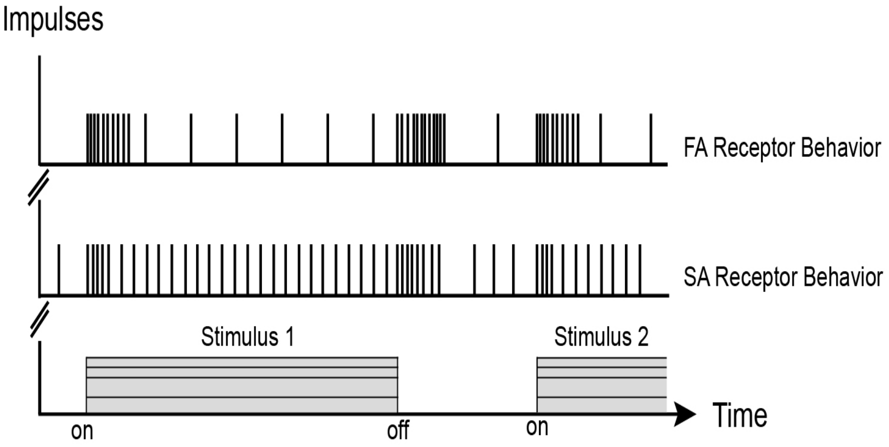
Gain parameter vs. t



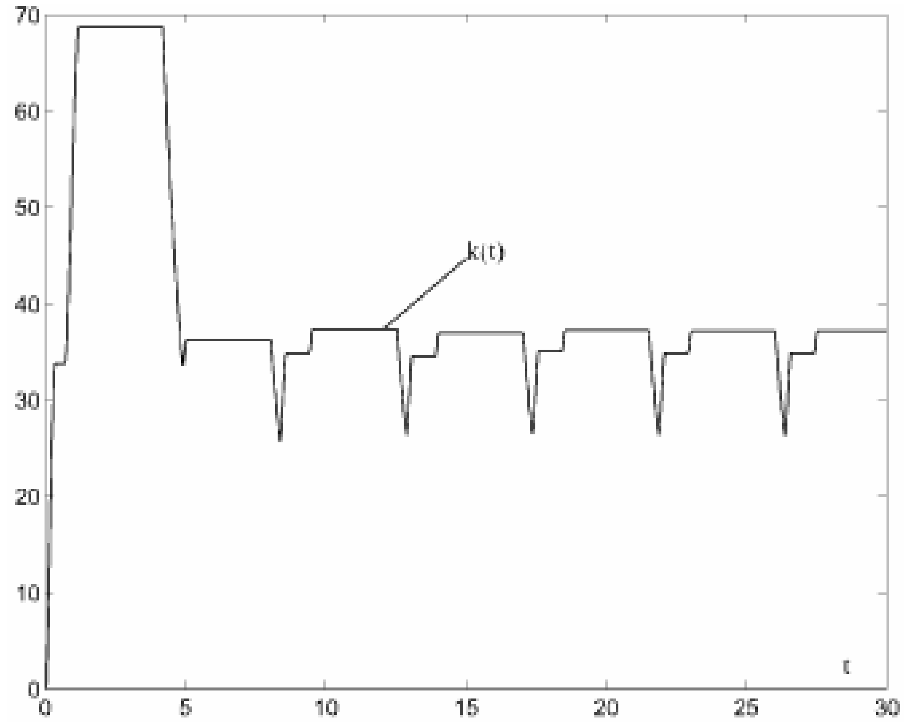
- no apparantly leaving of the λ-tube as before
- steep increase of $k(\cdot)$ is due to „switching on“ the controller

Part I: Mechanoreceptors – 7. Simulations

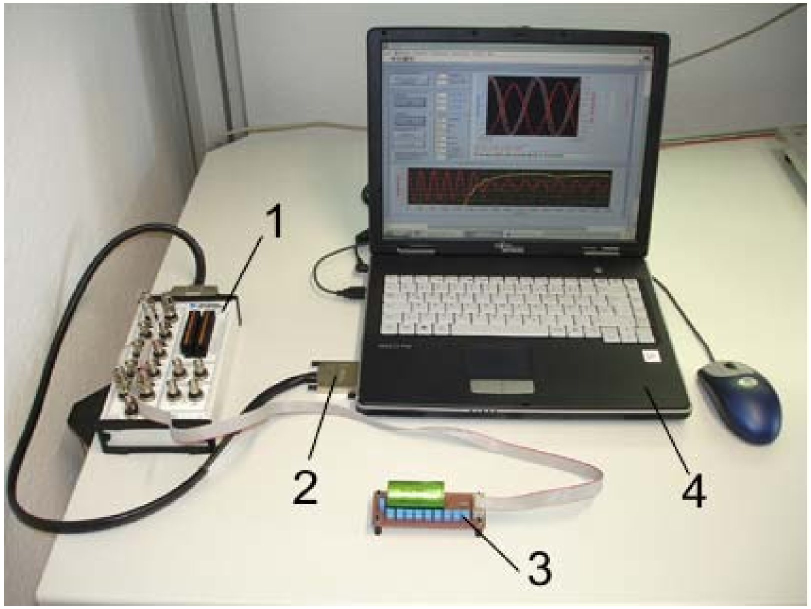
ε-safe λ-tracker

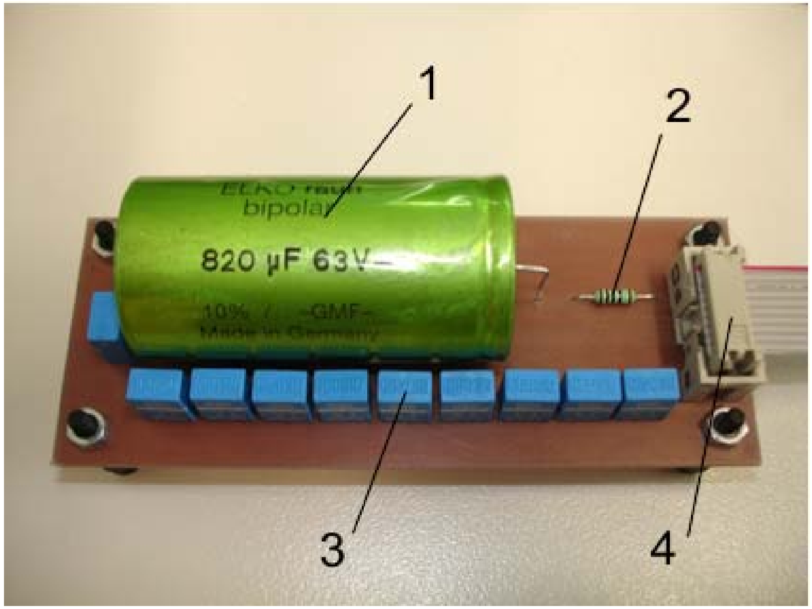


Gain parameter vs. t



Gain parameter reflects the behavior of the biological paradigm demonstrator in form of an electrical oscillating circuit





Test rig:
1 - I/O-system (BNC-2110),
2 - DAQ-6036-PCMCIA-card,
3 - demonstrator,
4 - PC with LabView

Circuit:
1 - capacitor $(C = 800\,\mu F)$,
2 - resistor $(R = 100\,\Omega)$,
3 - one inductor
(overall inductance $L_{ges} = 640\,mH$),
4 - communication to PC

Equations of motion:

$$L\,\ddot{q}(t) + R\,\dot{q}(t) + \frac{1}{C}\,q(t) = U(t) + u(t)\,.$$

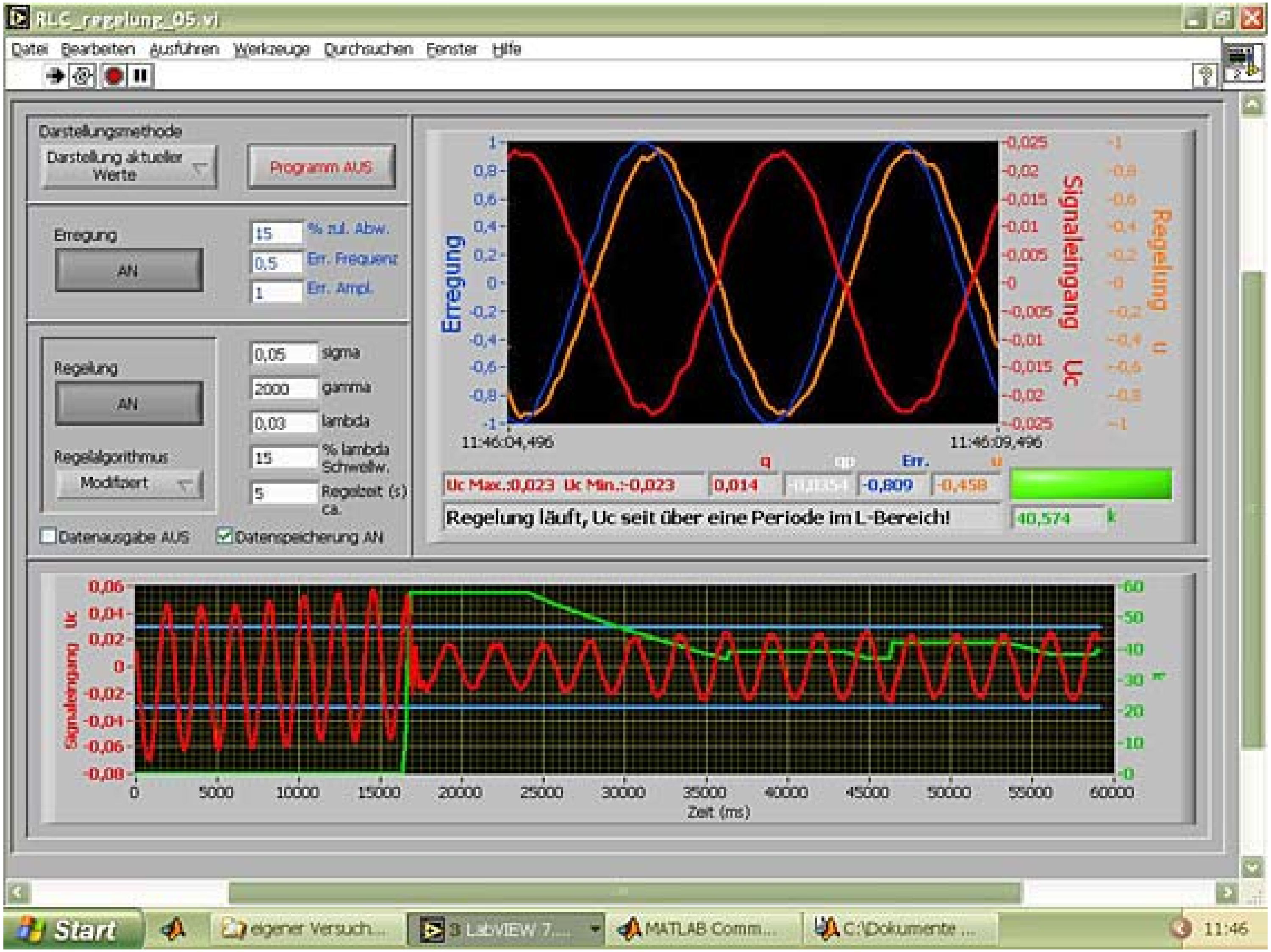
Goal: adaptively compensating changes of $U(\cdot)$ by means of control input $u(\cdot)$

Control input: $u := U_C$ (directly control the capacity voltage,
depends linearly on measured output charge $q(\cdot)$)

Parameters:

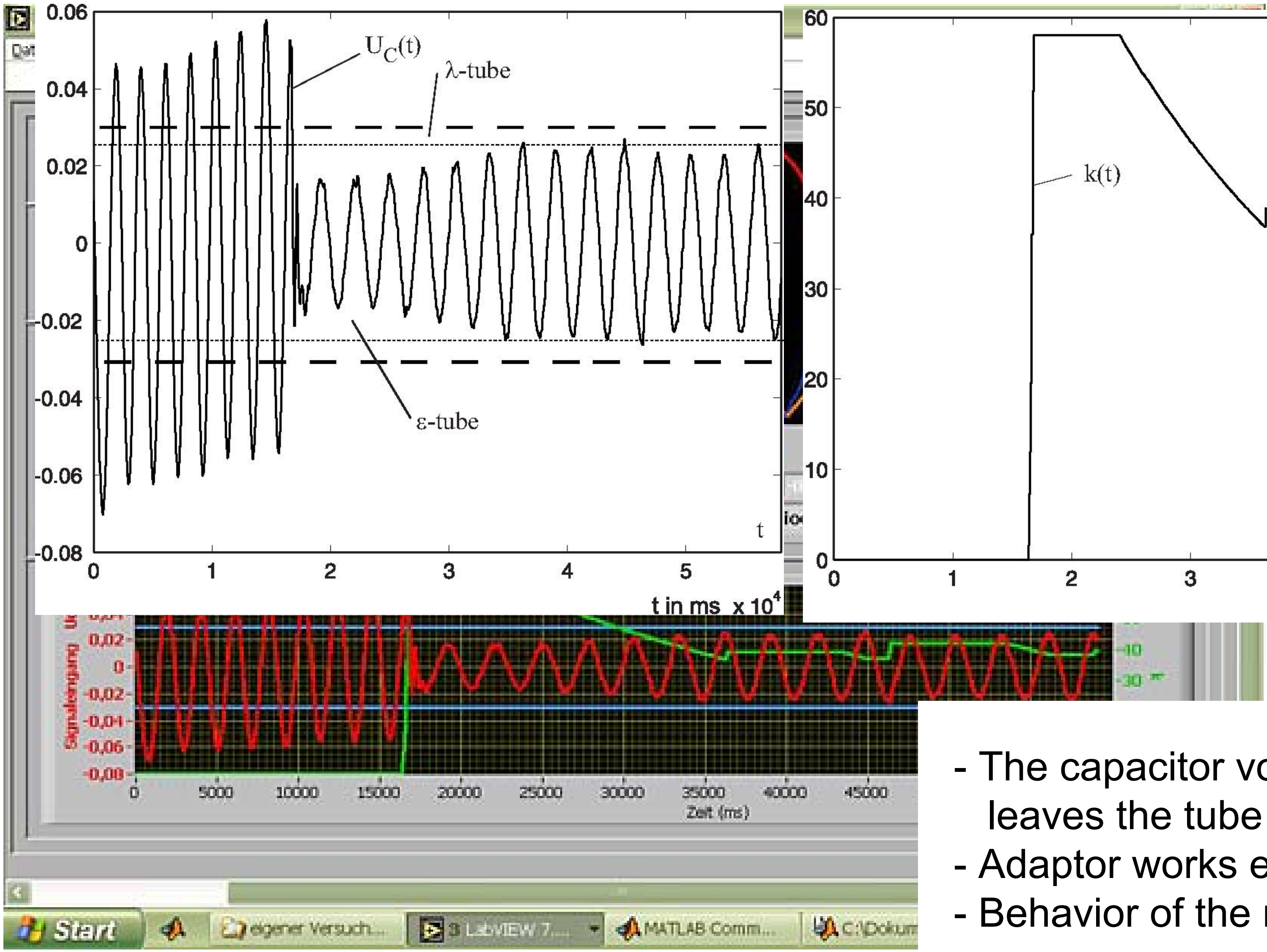
- reference signal $t \mapsto q_{\text{ref}}(t) = 0$
- excitation $t \mapsto U(t) = U_0\,\sin(\omega\,t)$ with amplitude $U_0 = 5\,V$ and frequency $f = 0.5\,Hz$
- ε-safe λ-tracker: initial gain value $k_0 = 1$, tracking tolerance $\lambda = 0.03\,V$, decrease rate $\sigma = 0.05$, time of duration in tube $t_d = 1s$, gain convergence parameter $\gamma = 100$, safe $\varepsilon = 0.7$ (much smaller tolerance)

Part I: Mechanoreceptors – 8. Experiments



Control panel in LabView

Part I: Mechanoreceptors – 8. Experiments



- The capacitor voltage never leaves the tube
- Adaptor works effectively
- Behavior of the receptor cell

Control panel in LabView

Part I: Mechanoreceptors – 9. Conclusions

- Development of new control strategies and sensor models

- Motivated by a sensory hair receptor: permanent state of adaptation

- Behavior mimicked by an artificial sensor system via adaptive control

- Supposed high degree of unknown system parameters

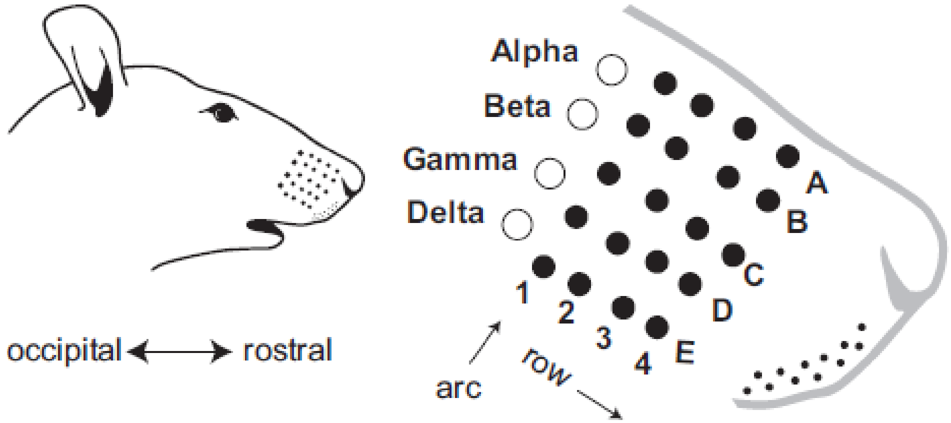
- Adaptive control design to dominate an uncertain system with improved gain parameter models with minimal knowledge of system parameters

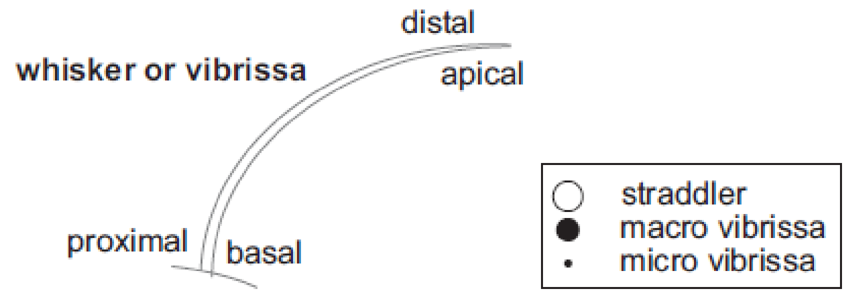
- Simple control design: rely only on structural properties, do not invoke any estimation or identification mechanism, do not depend on output derivative

- Numerical simulations and experiments have shown that the proposed controller exhibit both sensibility and adaptivity.

- The receptor model rapidly suppresses the persisting stimuli and shows good reactions to sudden changes in the stimulus.

Part II: Vibrissae – 1. Introduction (Anatomy)





[Carl et. al. 2012b]

two components: sinus hair and own hair follicle

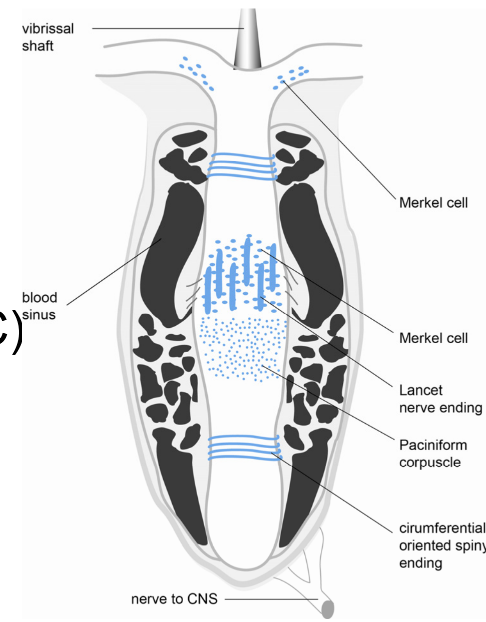
elastical, hollow and conically shaped

Part II

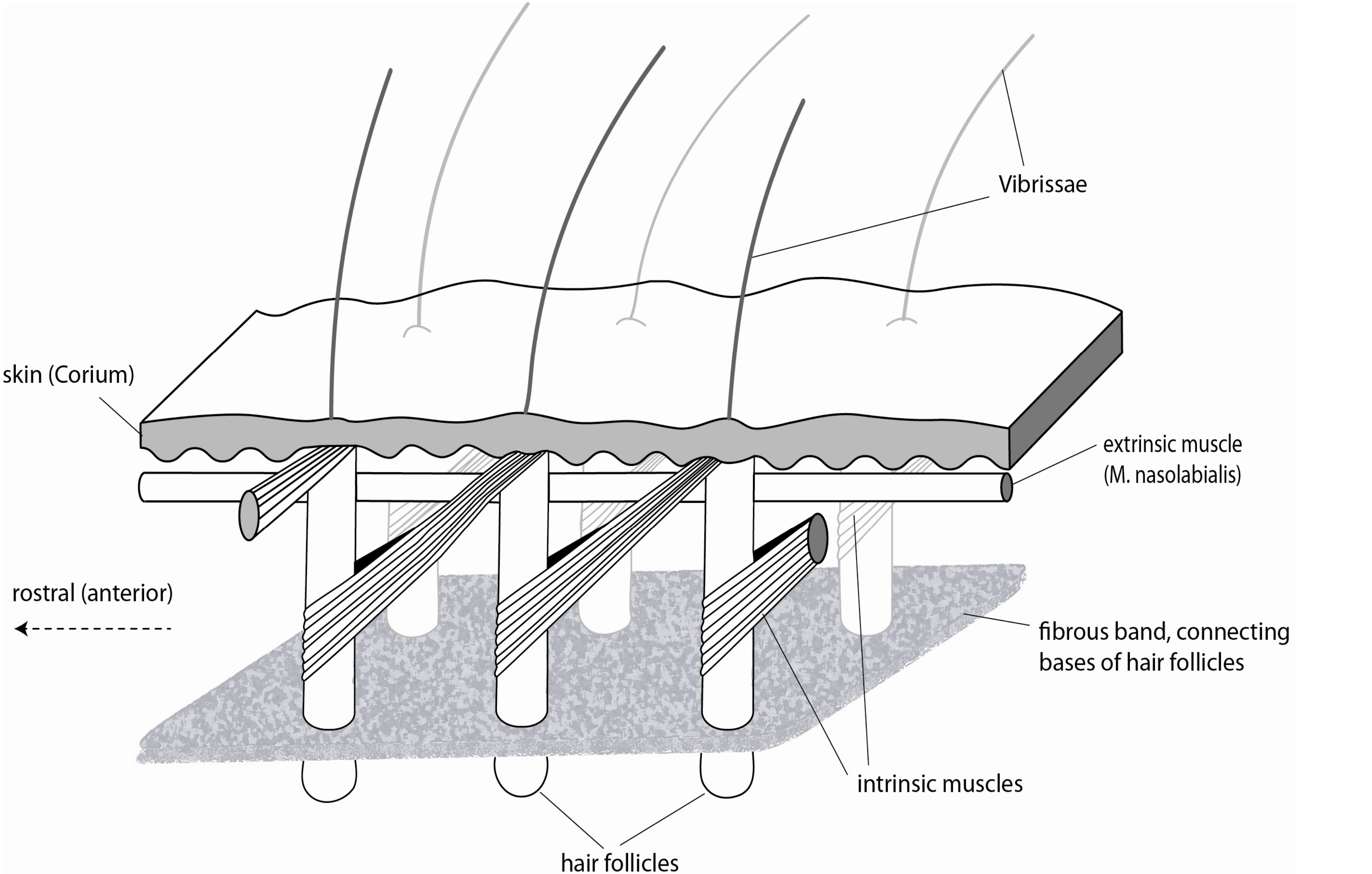
Follicle-Sinus-Complex (FSC)

blood vessels and nerves (mechanoreceptors)

→ viscoelastic support

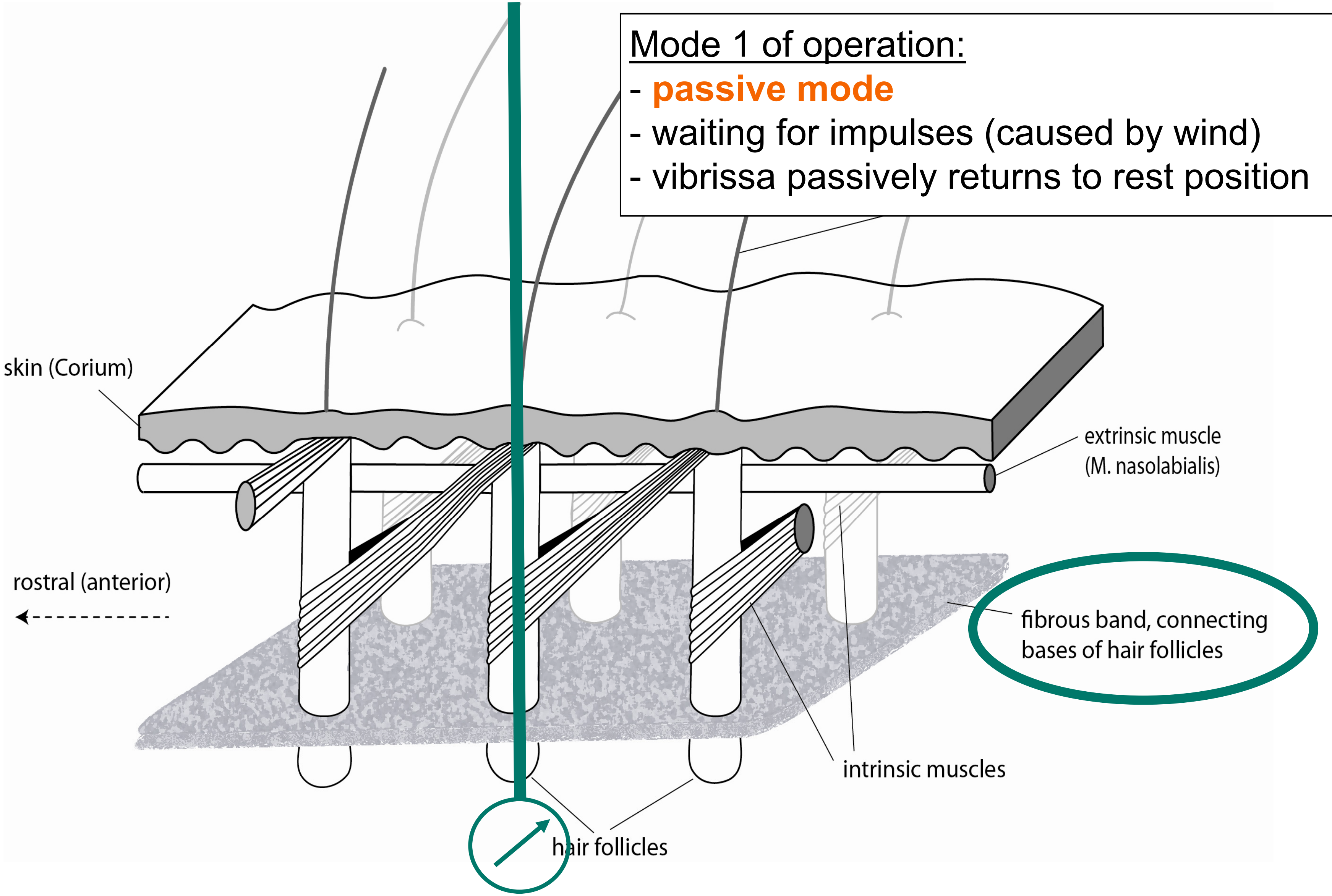


Part II: Vibrissae – 1. Introduction (Anatomy)



[D. Voges, TUI, 2012]

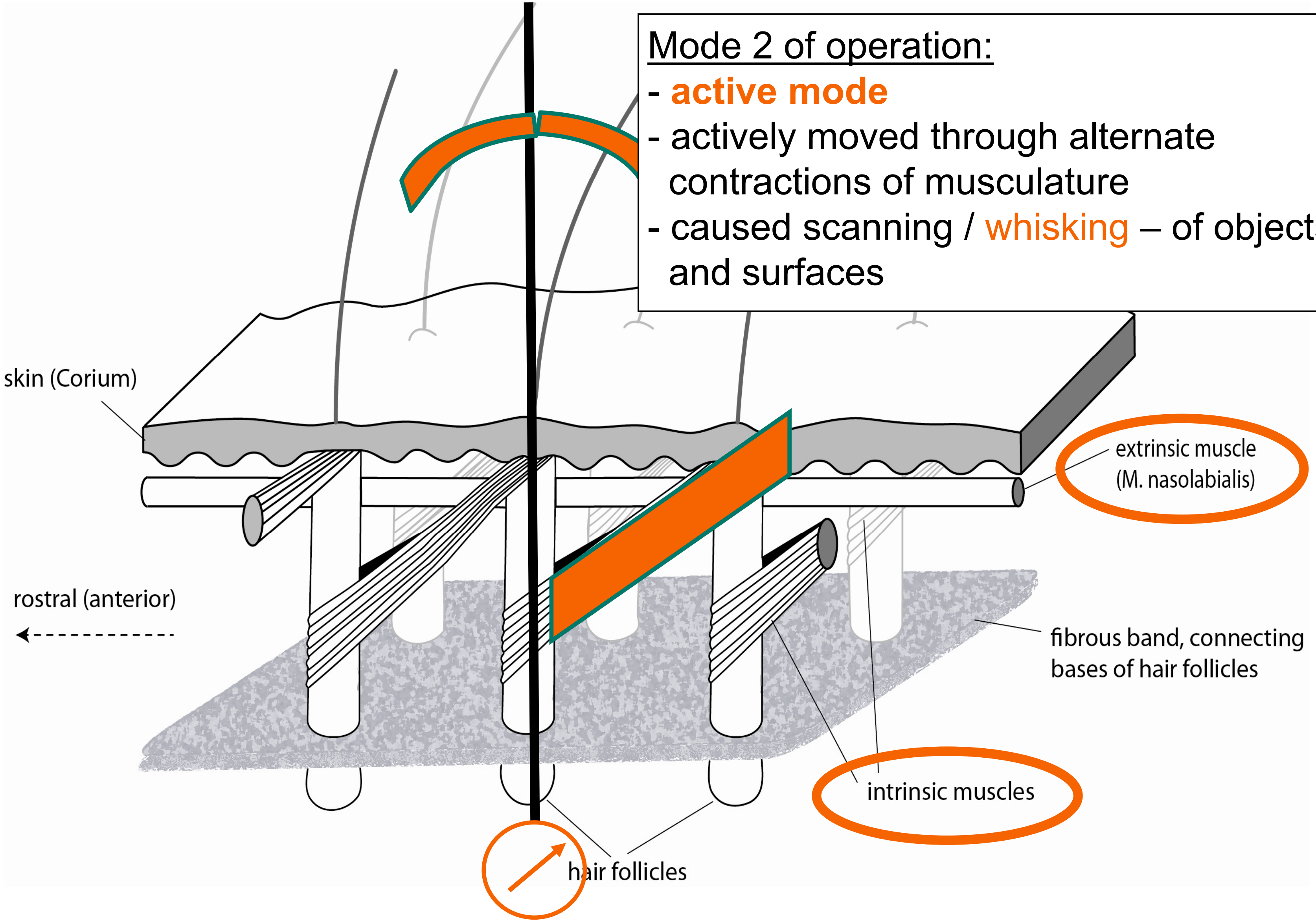
Part II: Vibrissae – 2. Functionality



Mode 1 of operation:

- **passive mode**
- waiting for impulses (caused by wind)
- vibrissa passively returns to rest position

Part II: Vibrissae – 2. Functionality



Mode 2 of operation:

- **active mode**
- actively moved through alternate contractions of musculature
- caused scanning / whisking – of objects and surfaces

Part II: Vibrissae – 2. Functionality / control strategies

Offering the ability to adapt its sensitivity to its environment:

- detection of vibrissa displacements by mechanoreceptors in the FSC

- a feedback loop (closed-loop control system) enables the rodents to immediately react to an object contact: they slow down the vibrissae

- depending on the mode (passive or active) and the expectations, the neuron's reaction is controlled: is being suppressed, enhanced or left unaltered

- the rodents can *probably* modify the stiffness of the vibrissa support by varying the pressure in the blood-sinus

- active whisking pattern
  a) exploratory whisking: large amplitudes, low frequency (5-15Hz)
  b) foveal whisking: small amplitudes, high frequency (15-25Hz)

<u>still unclear:</u>

How the animals convert these multiple contacts with single objects into coherent information about their surroundings?

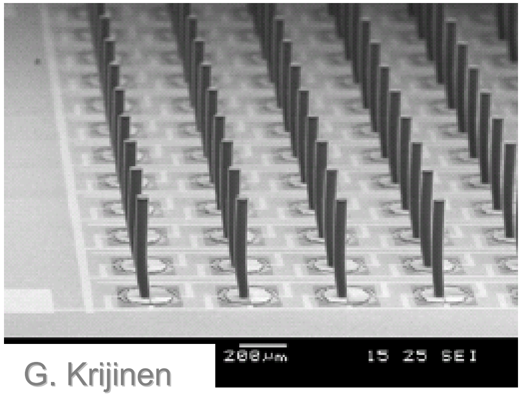
<u>But:</u>
highly interesting sensory system (autonomous robotics, reliable information in dark, smoky or noisy environments)

Part II: Vibrissae – 3. Application

Paradigms of tactile sensors for perceptions in applications:

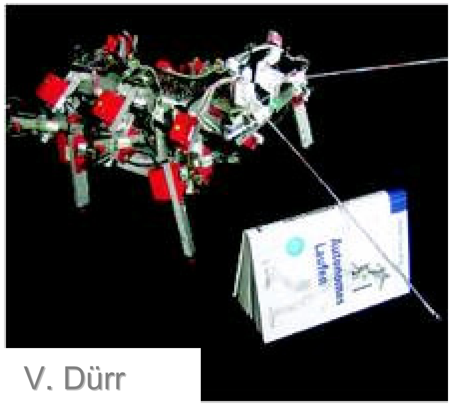
- quality assurance (e.g., coordinate measuring machines)
- measurements of flow rates
- detection of packaged goods on conveyor belts

Microsystem Technology

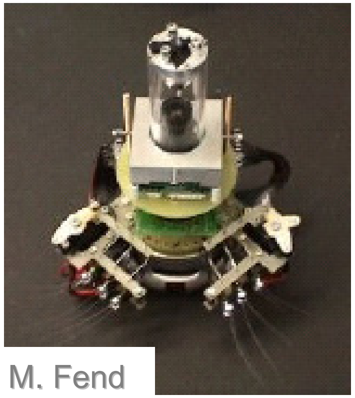


detection of flow rates

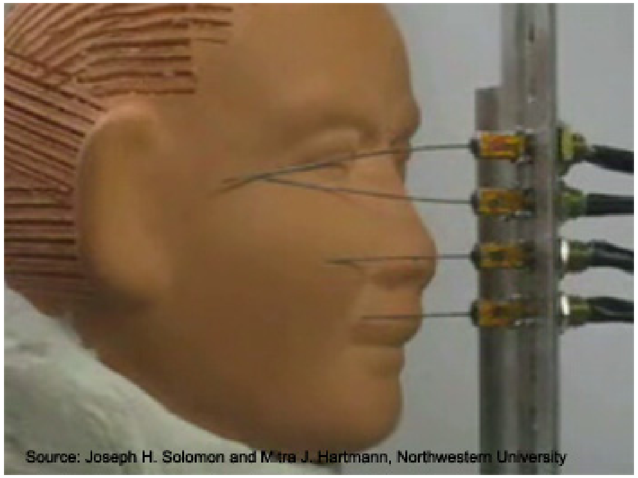
Robotics



object localization

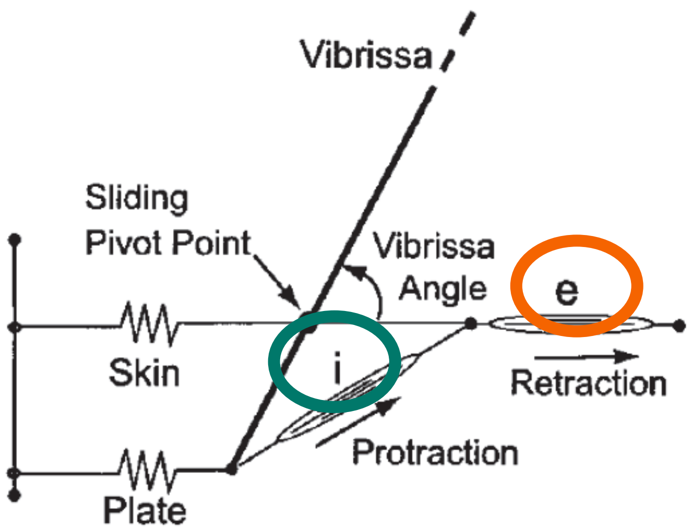


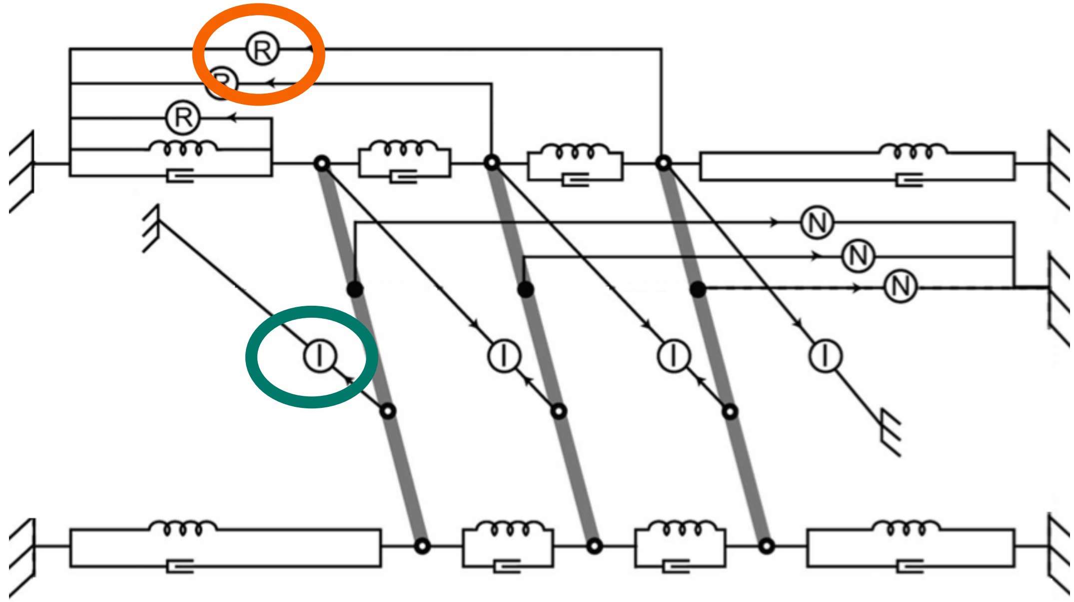
detection of texture



detection of surfaces

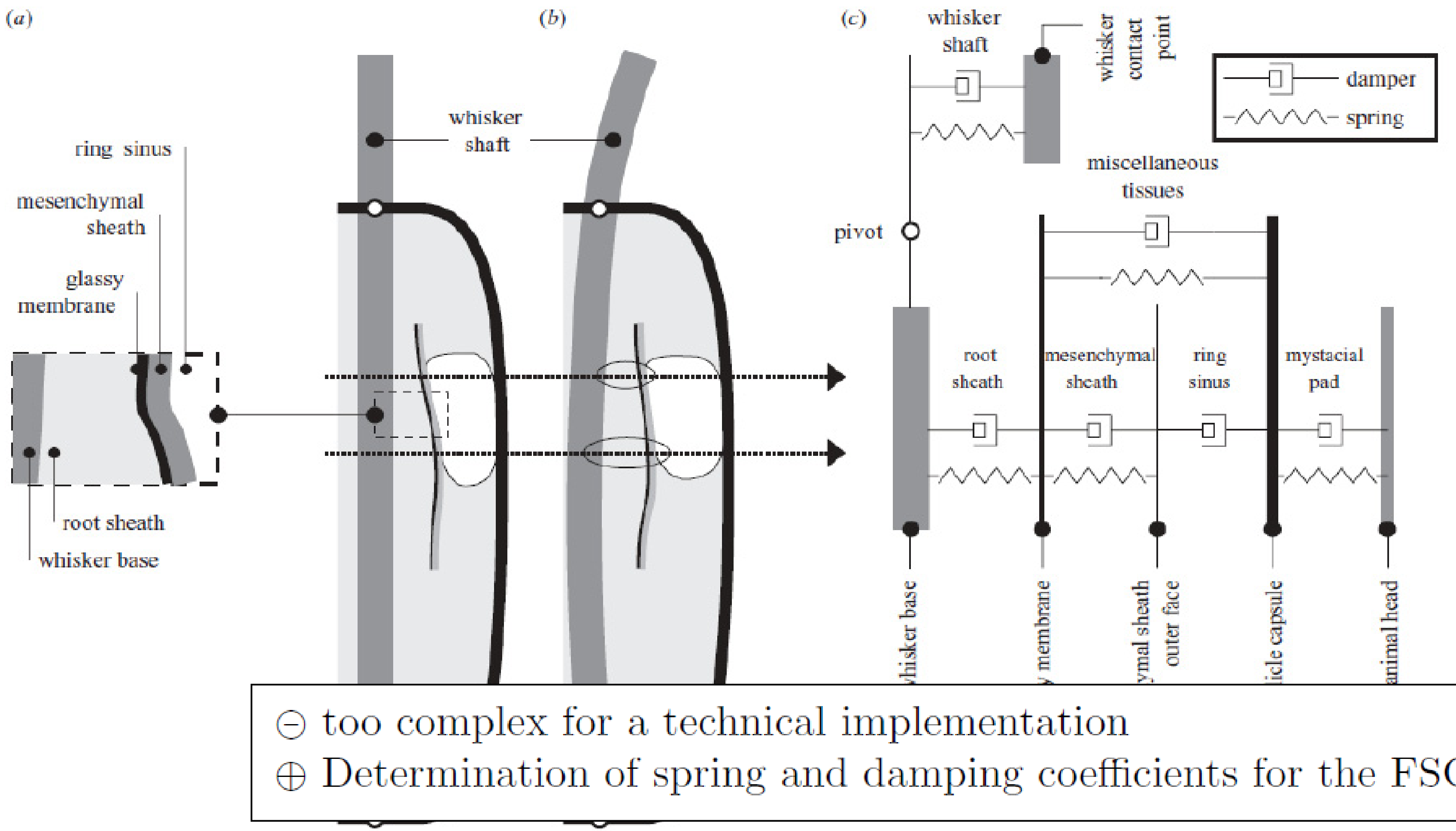
Rigid body model of a vibrissa / vibrissa row with musculature
in **[Berg, Kleinfeld 2003]** and **[Hill et. al. 2008]**





- ⊕ Implementation of the intrinsic and extrinsic musculature
- ⊕ Simulating the viscoelastic properties of the skin
  - ↪ Determination of spring and damping coefficients for the skin
- ⊖ Neglecting the viscoelastic properties of the FSC
- ⊖ Connection between the follicles
  - ↪ leads to complex control strategy and high control effort

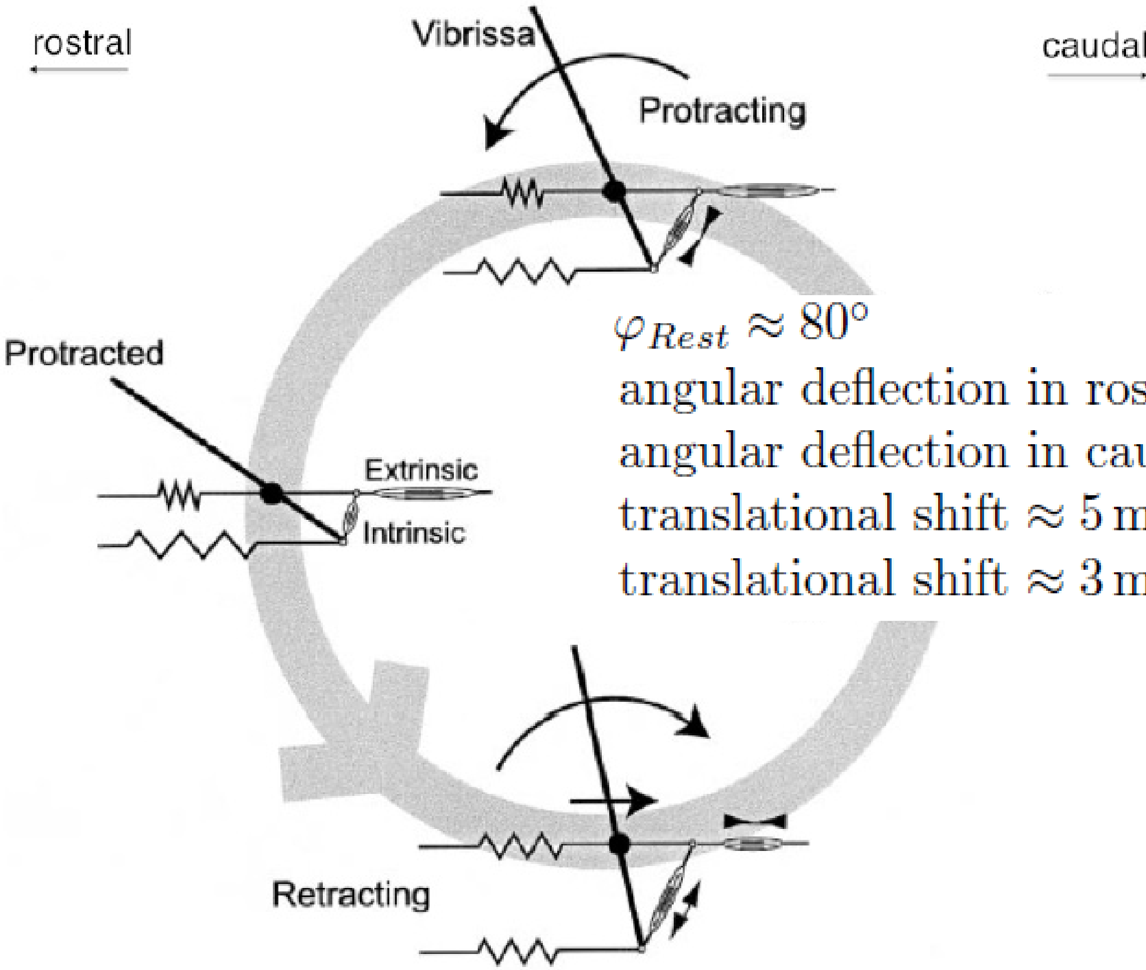
Rigid body model of the vibrissa / Simulating the compliance of the FSC in [Mitchinson et. al. 2004], [Mitchinson et. al. 2007]



⊖ too complex for a technical implementation
⊕ Determination of spring and damping coefficients for the FSC

Part II: Vibrissae – 4. State of Art – Rigid body models

Rigid body model of a vibrissa for determination of the range of movement of the vibrissa in [**Berg, Kleinfeld 2003**]



$\varphi_{Rest} \approx 80^\circ$

angular deflection in rostral direction $\varphi_{rest} + 65^\circ$

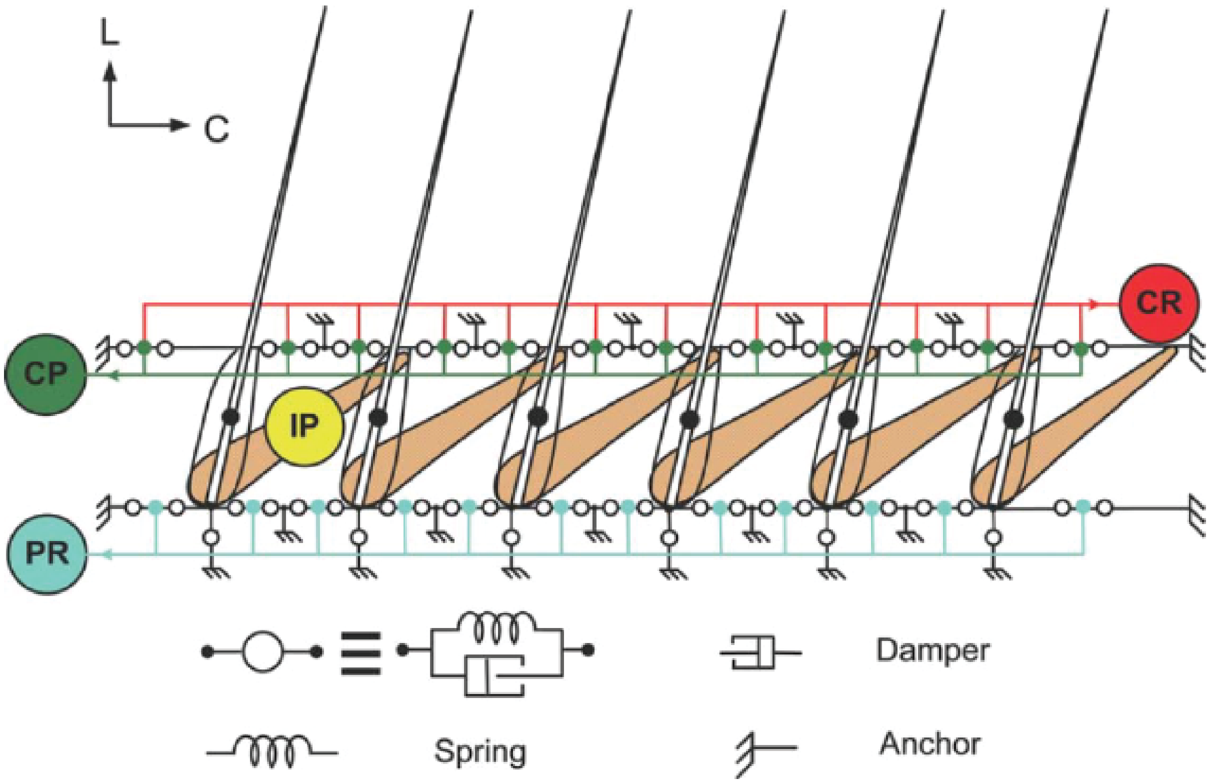
angular deflection in caudal direction $\varphi_{rest} - 35^\circ$

translational shift $\approx 5\,\mathrm{mm}$ in caudal-rostral direction

translational shift $\approx 3\,\mathrm{mm}$ in dorsal-ventral direction

Biomechanical model representing one vibrissal row
in **[Haidarliu et al. 2010]** and **[Haidarliu et al. 2011]**

Goal: modeling the muscle-tissue-system in the mystacial pad

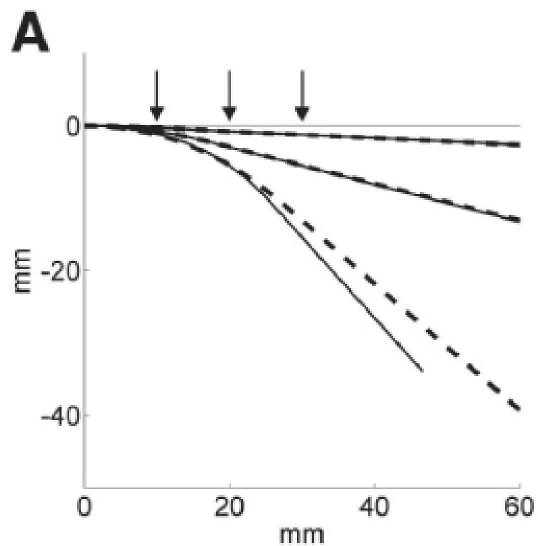


just for illustration, model is too complex to investigate control algorithm, no focus

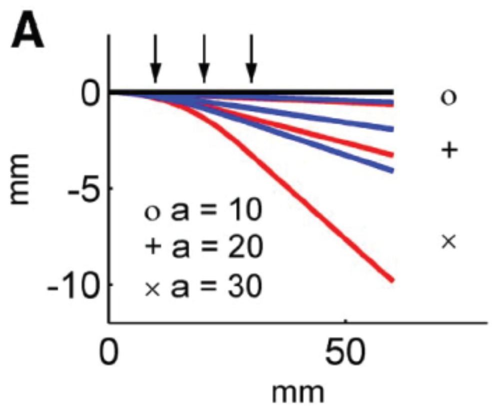
Analyzing the bending behavior of natural vibrissae using beams in [Birdwell et. al. 2007]

Non-linear $\kappa = \frac{v''(x)}{[1+v'(x)^2]^{\frac{3}{2}}} = \frac{M(x)}{E \cdot I_z}$

Linearized $\kappa = v''(x) = \frac{M(x)}{E \cdot I_z}$



non-linear (solid)
vs.
linearized (dashed)



cylindrical (blue)
vs.
conical (red)

- ⊕ suitable to analyze the bending behavior
- ⊖ Linearized model: only valid for small deflections
- ⊕ Consideration of the conical shape of the vibrissa
- ⊖ Neglecting the support's compliance
- ⊕ Finding: Shape of the beam influences the bending behavior
  ↪ not negligible

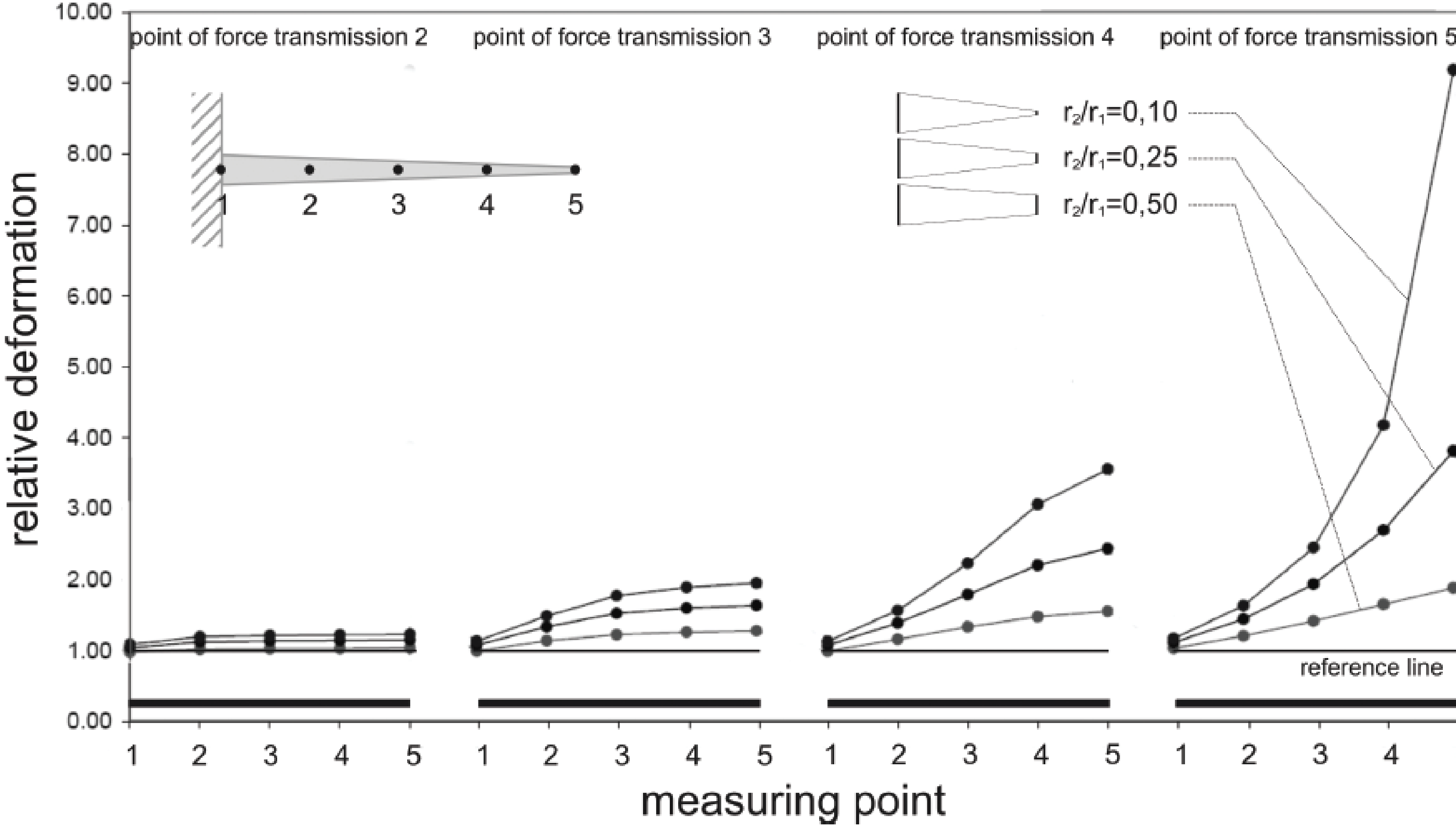
Determination of various vibrissa parameters using the bending behavior in [Birdwell et. al. 2007]

heuristically determined parameters of various vibrissae:

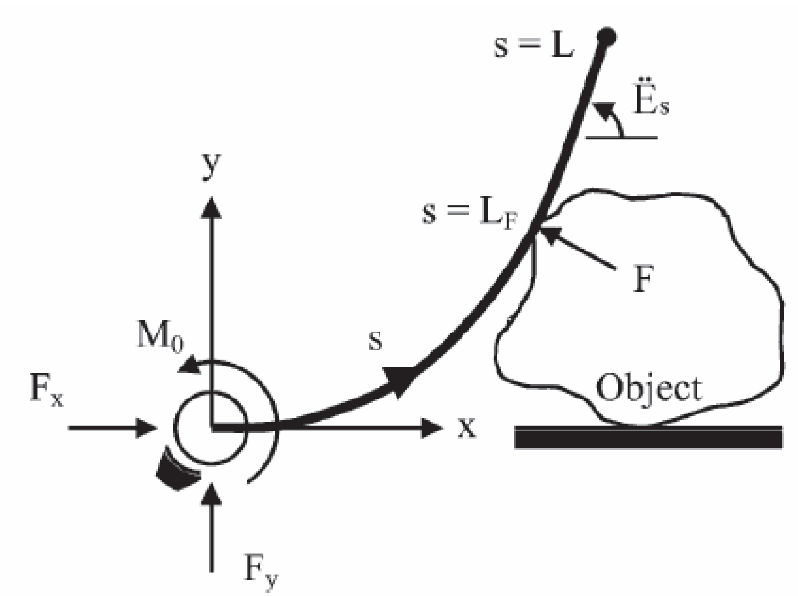
- simulated bending behavior of beams
- photos of deformed vibrissa
- varying Young's modulus if graphs do not match

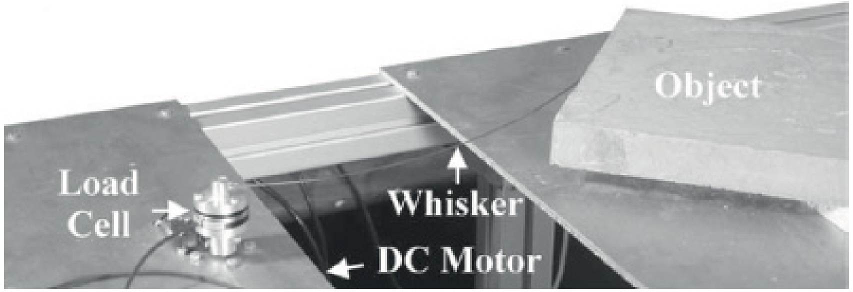
Vibrissa	Arc length in mm	Base diameter in μm	E modulus in GPa
β	66.2	225	1.40
γ	60.3	199	3.75
A1	51.7	160	2.75
E2	48.1	232	1.90
B2	41.1	169	2.30
E3	33.3	189	3.90
C3	21.5	119	6.25

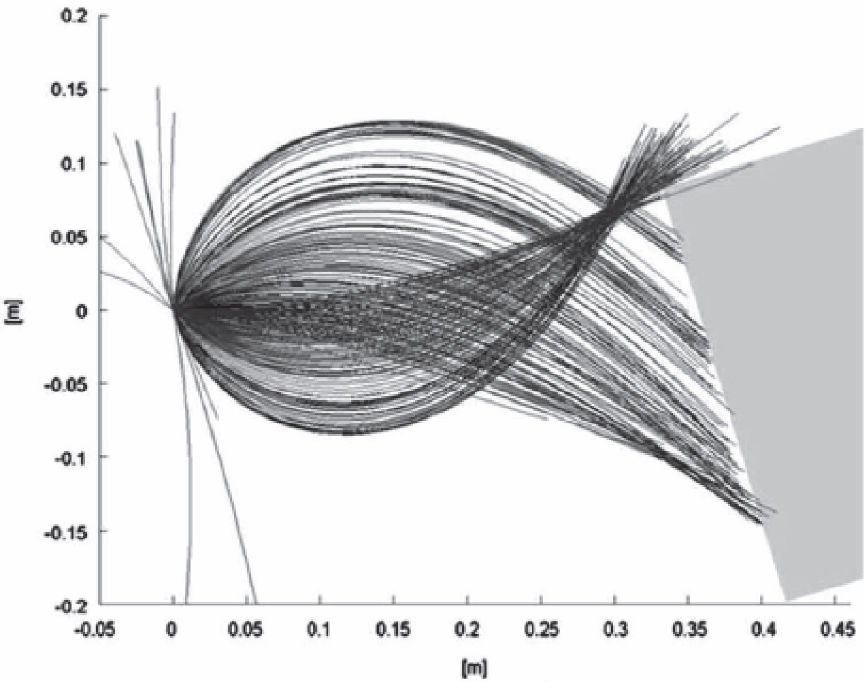
Investigating the influence of the vibrissa's shape to the bending behavior in [Carl 2009] and [Carl et. al. 2012a]



Model for active sensing in **[Scholz, Rahn 2004]**







$$\frac{dx}{ds} = \cos(\theta) \quad \frac{dy}{ds} = \sin(\theta)$$

$$E\,I_z\,\frac{d\theta}{ds} = M_s$$

$$M_s = \begin{cases} M_0 - F_y\,x + F_x\,y\,, & s \leqslant L_F\,, \\ 0\,, & s > L_F\,, \end{cases}$$

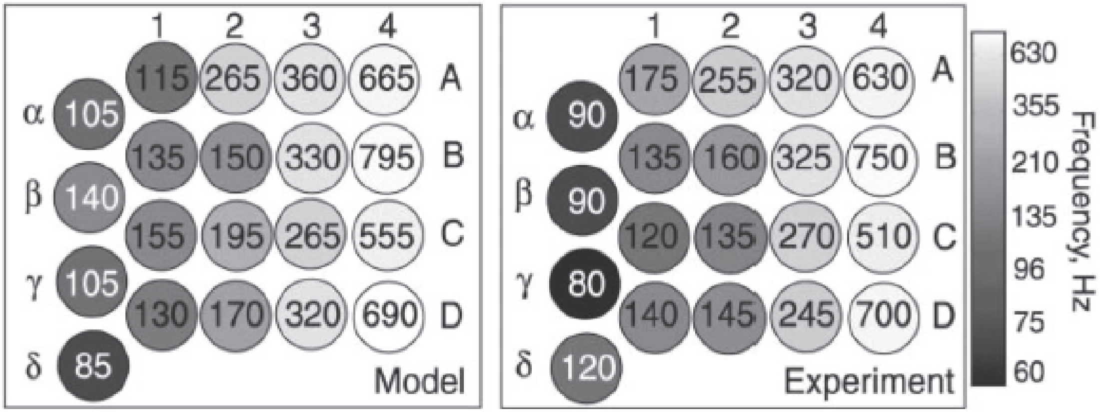
Neglecting support‘s compliance

Model to determine the influence of the support on the eigenfrequencies in [Neimark et. al. 2003] and [Andermann et. al. 2004]

- infra-red measurements of the first eigenfrequency (EF) of various natural vibrissae

→ connection between first EF and length of vibrissa (length increase, EF decrease)
→ hence systematical arrangement
topologically distributed sensitivity in the vibrissa array

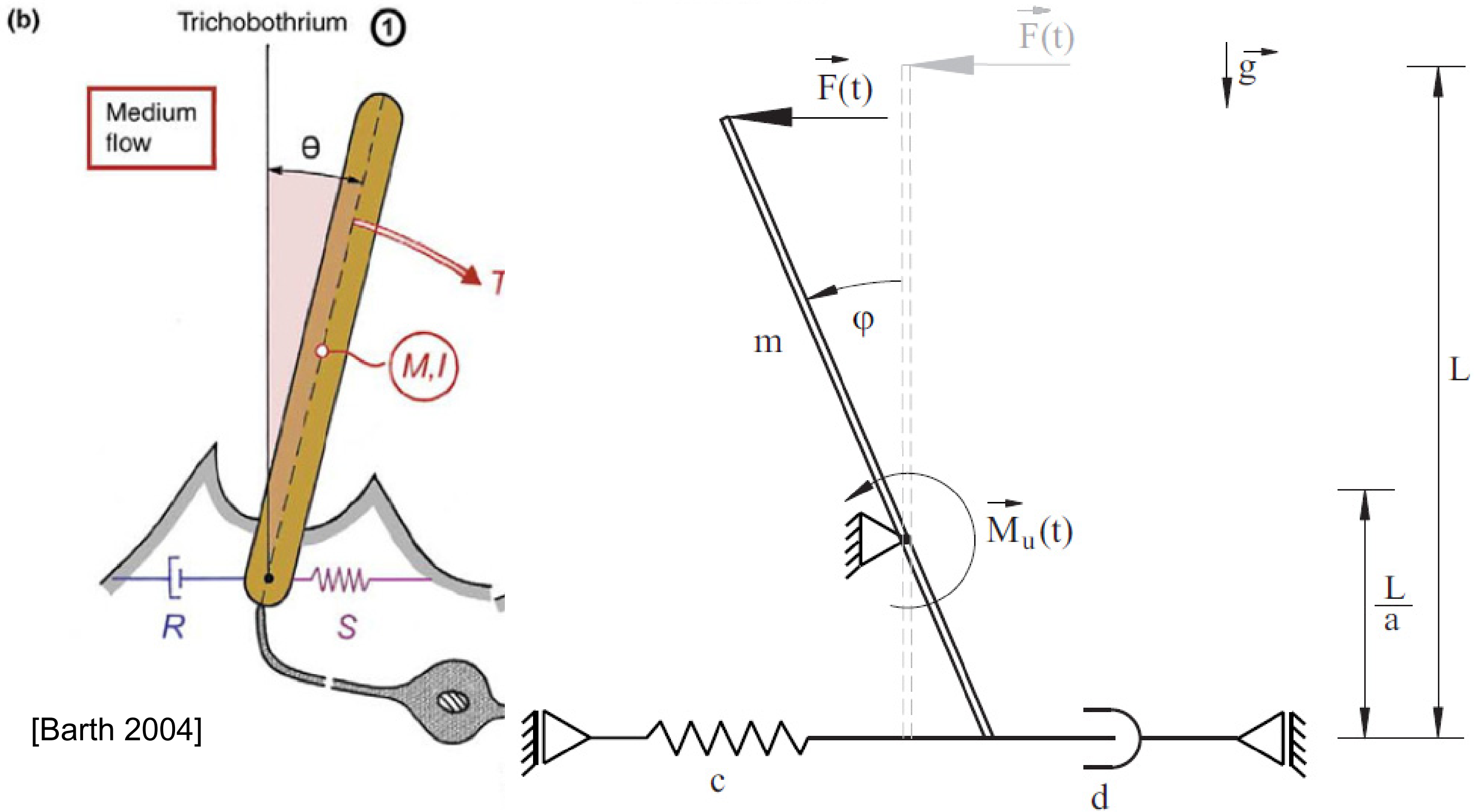
- mechanical model of a thin, conical beam and present dynamical investigations (massive influence of the support on the EF → obvious)



focus on supports which do not match the real objects sufficiently

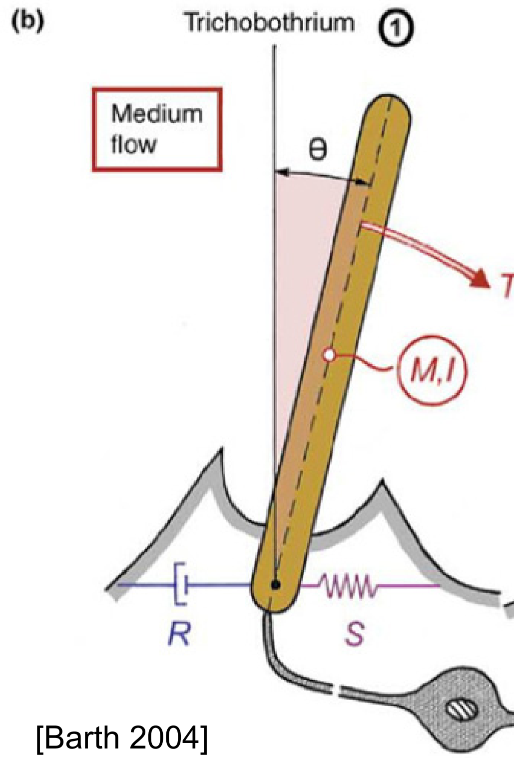
- but: determination only of the first EF of the vibrissae

Single vibrissa system with DoF=1

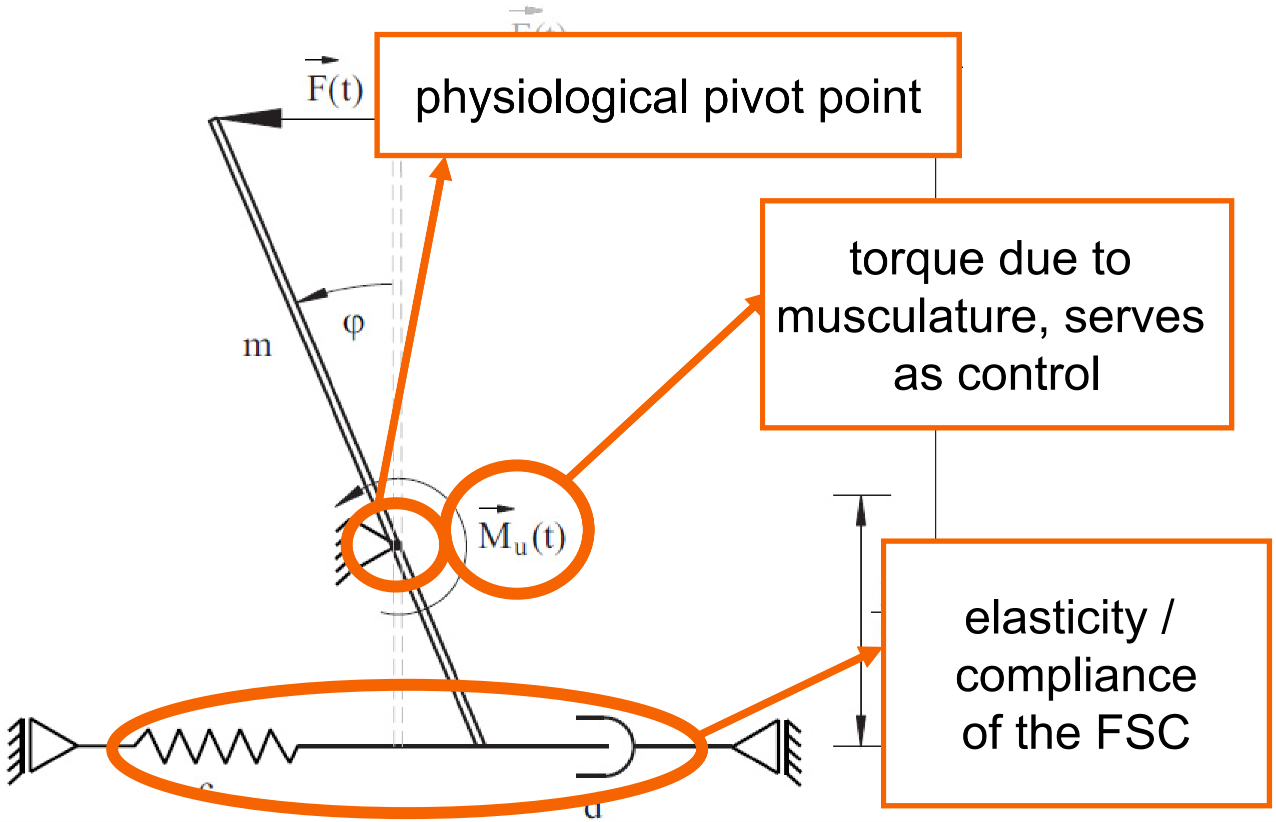


$$\ddot{\varphi}(t) = \frac{1}{J_{0z}} \left[\left(L - \frac{L}{a} \right) F(t) \cos(\varphi(t)) - c\, \frac{L^2}{a^2} \cos(\varphi(t)) \sin(\varphi(t)) - d\, \frac{L^2}{a^2} \cos^2(\varphi(t))\, \dot{\varphi}(t) + \left(\frac{L}{2} - \frac{L}{a} \right) mg \sin(\varphi(t)) + M_u(t) \right]$$

Single vibrissa system with DoF=1



[Barth 2004]



$$\ddot{\varphi}(t) = \frac{1}{J_{0z}}\left[\left(L - \frac{L}{a}\right) F(t)\cos(\varphi(t)) - c\,\frac{L^2}{a^2}\cos(\varphi(t))\,\sin(\varphi(t)) - d\,\frac{L^2}{a^2}\cos^2(\varphi(t))\,\dot{\varphi}(t) + \left(\frac{L}{2} - \frac{L}{a}\right) mg\,\sin(\varphi(t)) + M_u(t)\right]$$

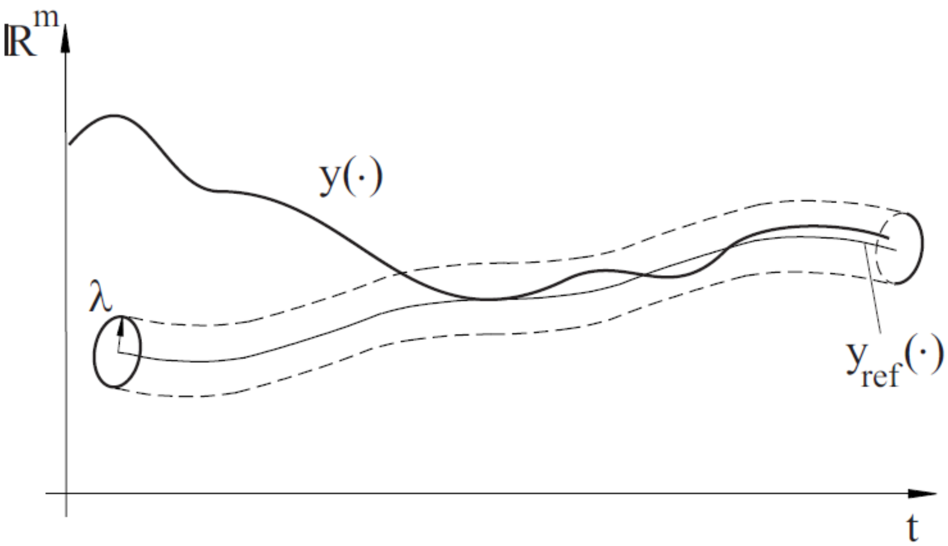
Goal:
Control the vibrissa system in a chosen mode of operation: passive or active

Problem:
- many open-loop and closed-loop controls are based on exactly known parameters
- here: suppose uncertain system (due to biological complexity)
  - unknown system parameters
  - only structural properties known

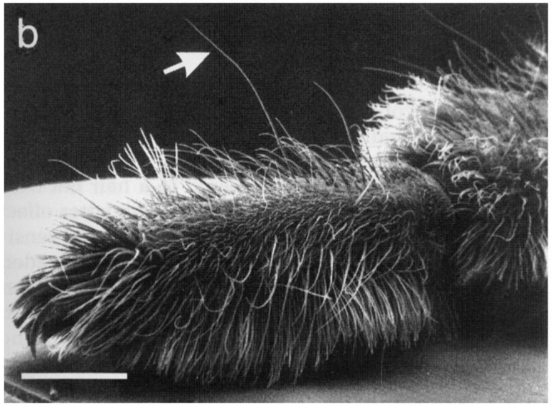
What to do if the system is not known precisely?

Solution:
Design an adaptive controller, which learns from the behavior of the system, so automatically adjusts its parameters and achieves

λ-tracking



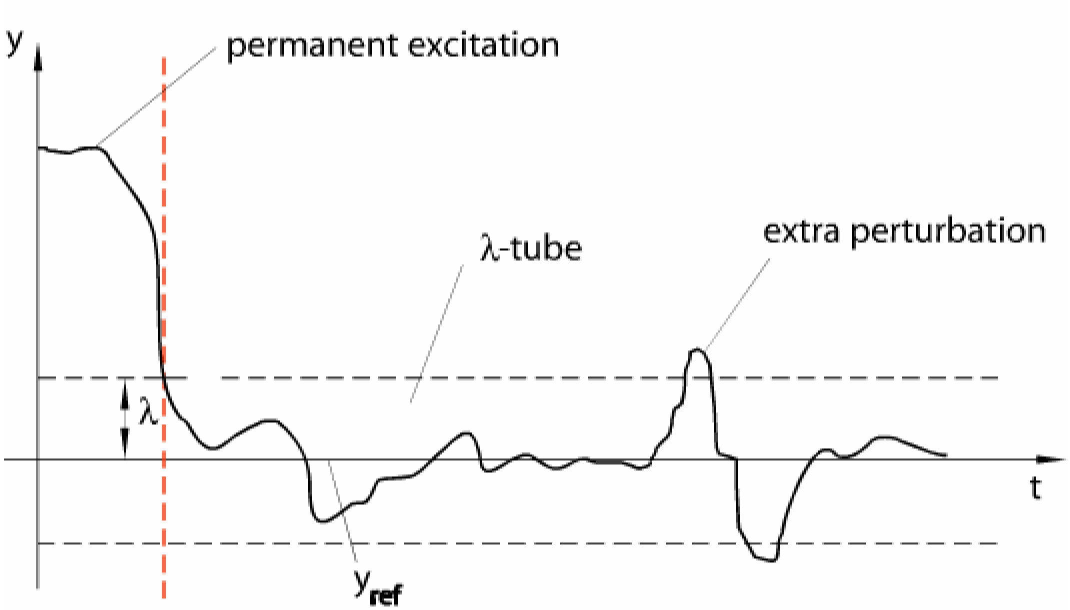
Passive Mode



- stabilize the system under permanent excitation

- while enabling to detect external extra-perturbations (e.g. sensory contact, detect wake of swimming fish)

λ-stabilization

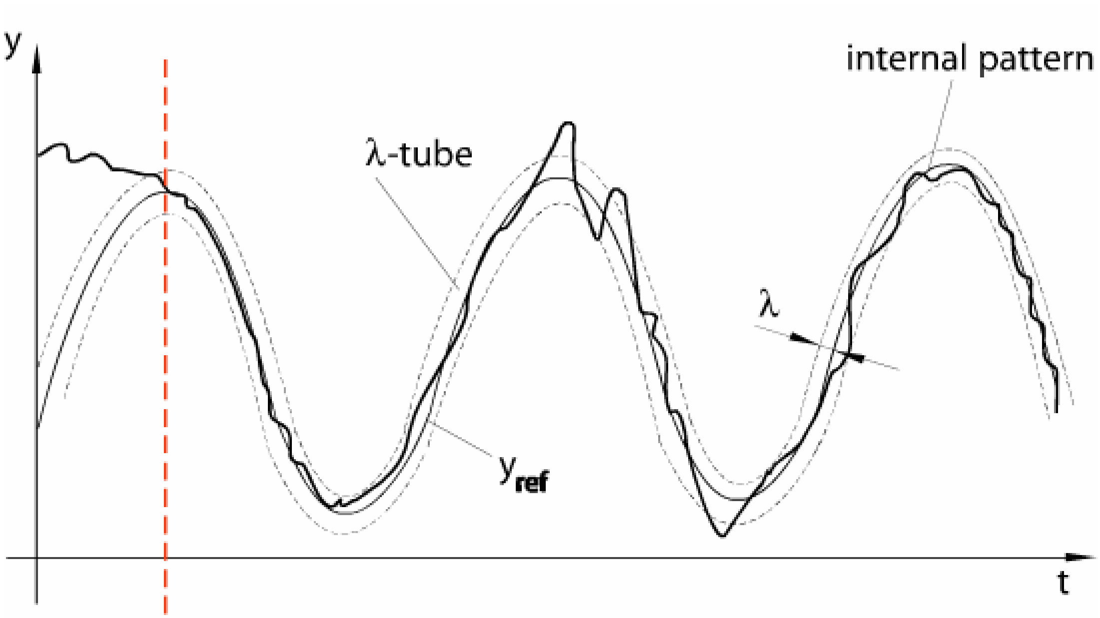


Active Mode

- track an internally generated oscillatory motion pattern

- enable the system to recognize external disturbances of this pattern (caused, e.g., by wind or surface contact scanning of surface texture)

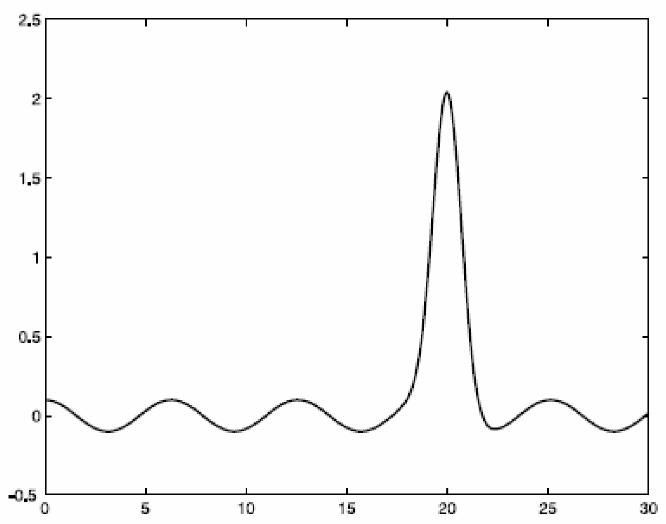
λ-tracking



Simulations

<u>vibrissa:</u> $m = 0.000\,003\,\mathrm{kg},\ c = 5.7\,\frac{\mathrm{N}}{\mathrm{m}},\ d = 0.2\,\frac{\mathrm{Ns}}{\mathrm{m}},\ L = 0.04\,\mathrm{m},\ a = \frac{L}{10} = 0.004\,\mathrm{m}$

<u>environment:</u> $t \mapsto F(t) = 0.1\,\cos(t) + 2\,e^{-(t-20)^2}\,\mathrm{N}$
(small permanent oscillation with a gust of wind)



<u>modes of operation:</u>
passive mode

$$t \mapsto \varphi_{\mathrm{ref0}}(t) = 0\,\mathrm{rad}$$

active mode 1 – exploratory whisking

$$t \mapsto \varphi_{\mathrm{ref1}}(t) = 0.8\,\sin(2\pi\,5\,t)\,\mathrm{rad}$$

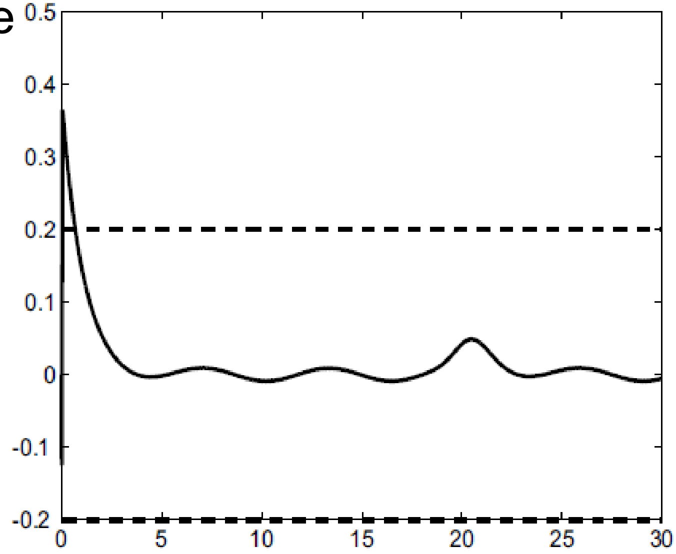
active mode 2 – foveal whisking

$$t \mapsto \varphi_{\mathrm{ref2}}(t) = 0.2\,\sin(2\pi\,25\,t)\,\mathrm{rad}$$

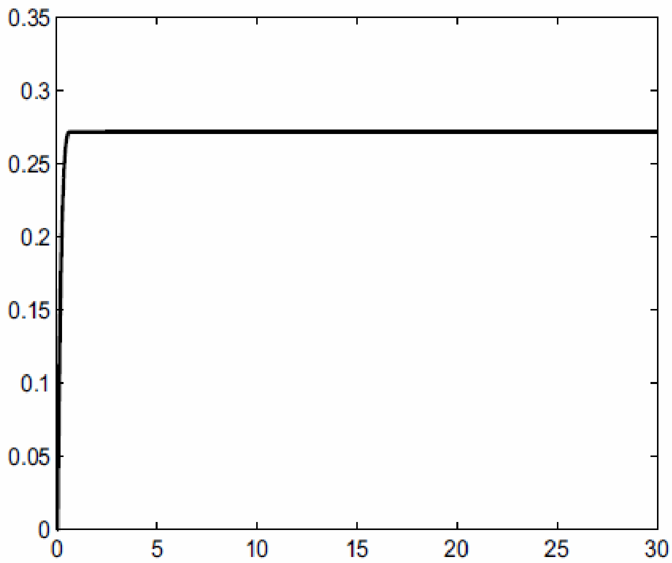
Active Mode 1

$$e(t) := \varphi(t) - \varphi_{\mathrm{ref}}(t)$$
$$M_u(t) = -\left[k(t)\, e(t) + \kappa\, k(t)\, \dot{e}(t)\right]$$
$$\dot{k}(t) \quad = \quad \gamma\Big(\max\big\{0, \|e(t)\| - \lambda\big\}\Big)^2$$

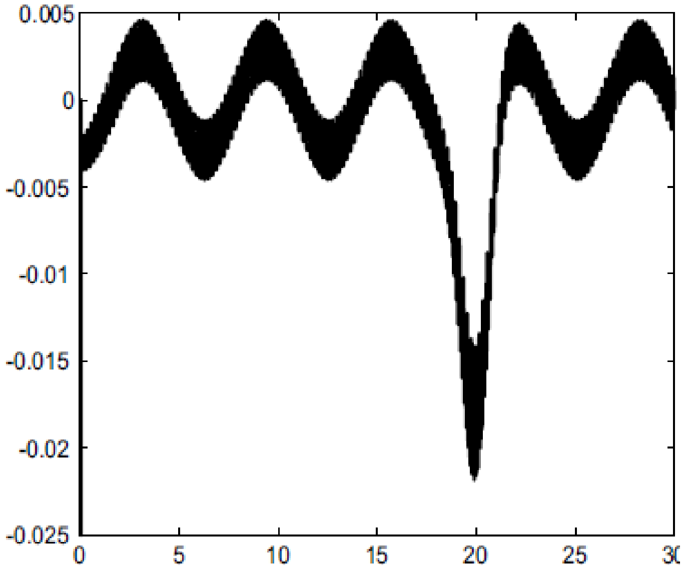
Error vs. time



Gain vs. time



Control torque vs. time



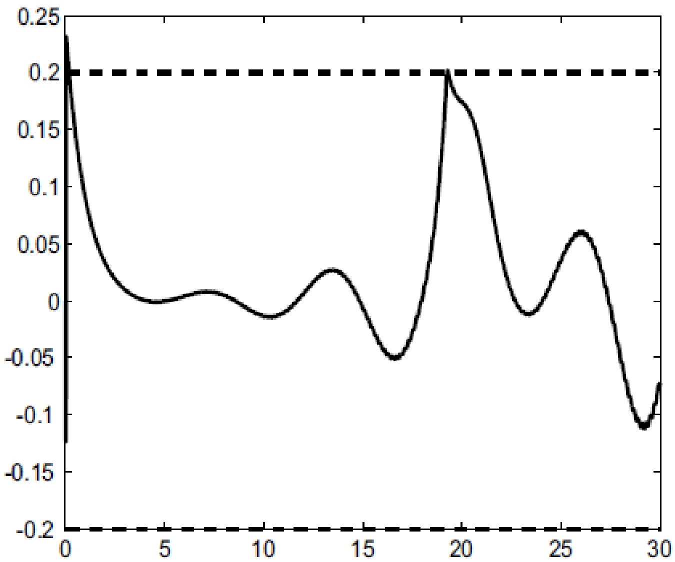
- good tracking
- convergence of the gain
- hard to detect the gust in system variables e and k
- control torque reflects peak

Active Mode 1 $e(t) := \varphi(t) - \varphi_{\text{ref}}(t)$

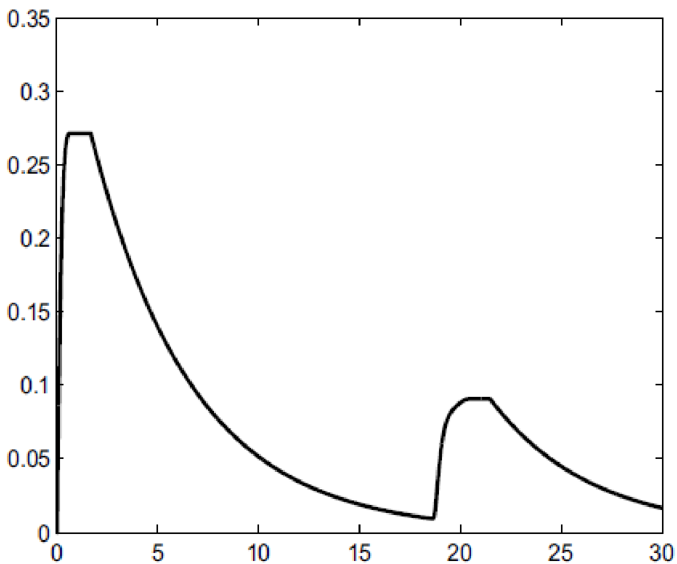
$$M_u(t) = -\left[k(t)\,e(t) + \kappa\,k(t)\,\dot{e}(t)\right]$$

$$\dot{k}(t) = \begin{cases} \gamma\,\left(\|e(t)\| - \lambda\right)^2, & \text{if } \|e(t)\| \geq \lambda + 1 \\ \gamma\,\left(\|e(t)\| - \lambda\right)^{0.5}, & \text{if } (\lambda+1) > \|e(t)\| \geq \lambda \\ 0\,, & \text{if } \left(\|e(t)\| < \lambda\right) \wedge (t - t_E < t_d) \\ -\sigma\,k(t)\,, & \text{if } \left(\|e(t)\| < \lambda\right) \wedge (t - t_E \geq t_d) \end{cases}$$

Error vs. time



Gain vs. time



- good tracking
- control as before
- detect superim-posed impulse in observing k

Part II: Vibrissae – 5. Modeling – Stage 1

Short summary:

- adaptive control is promising in application to vibrissa systems

- it allows for both modes of operation (passive or active)

- not easy to detect solitary excitations

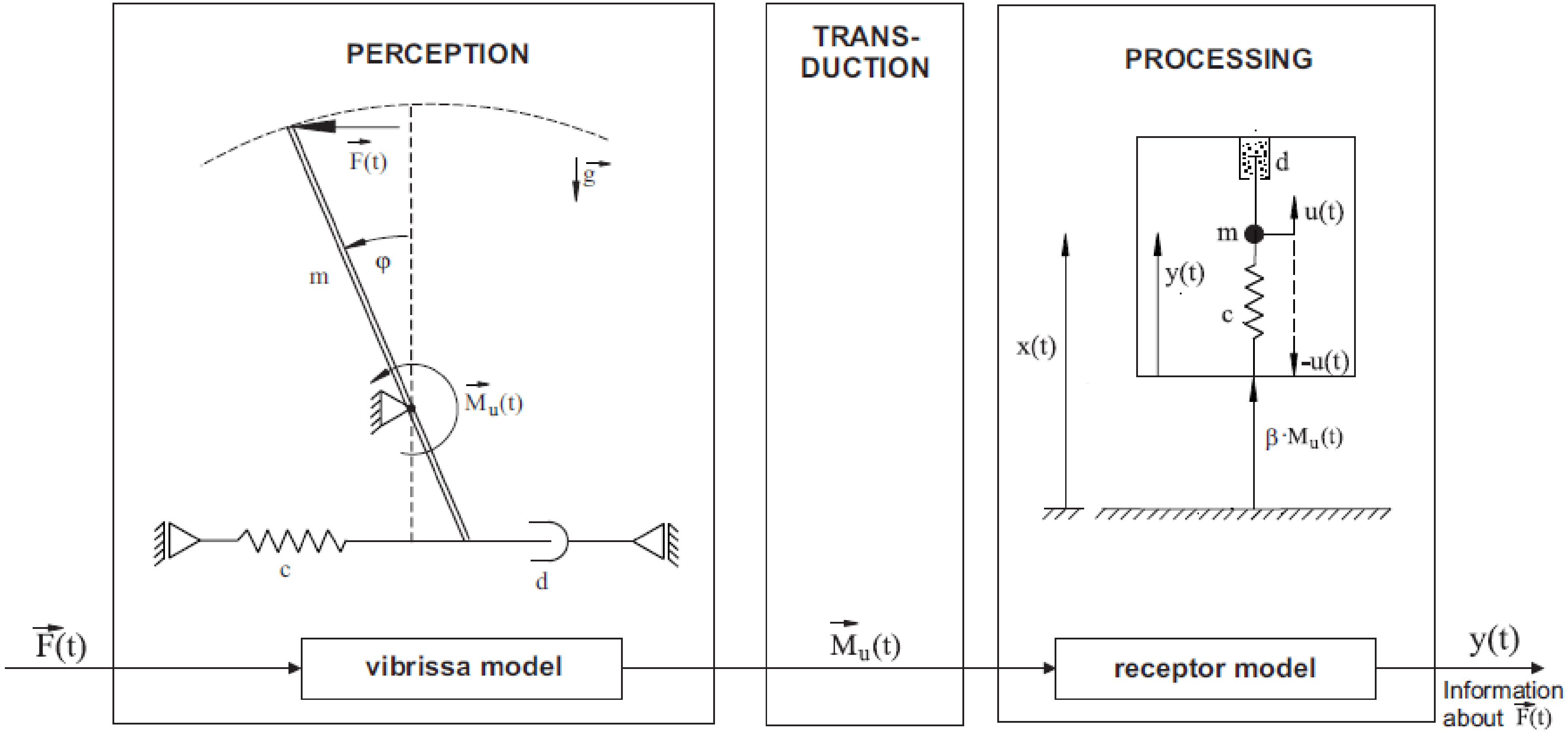
- somestimes observe e, k or control input

- some identification techniques to uniformly observe one observable
  → which one?

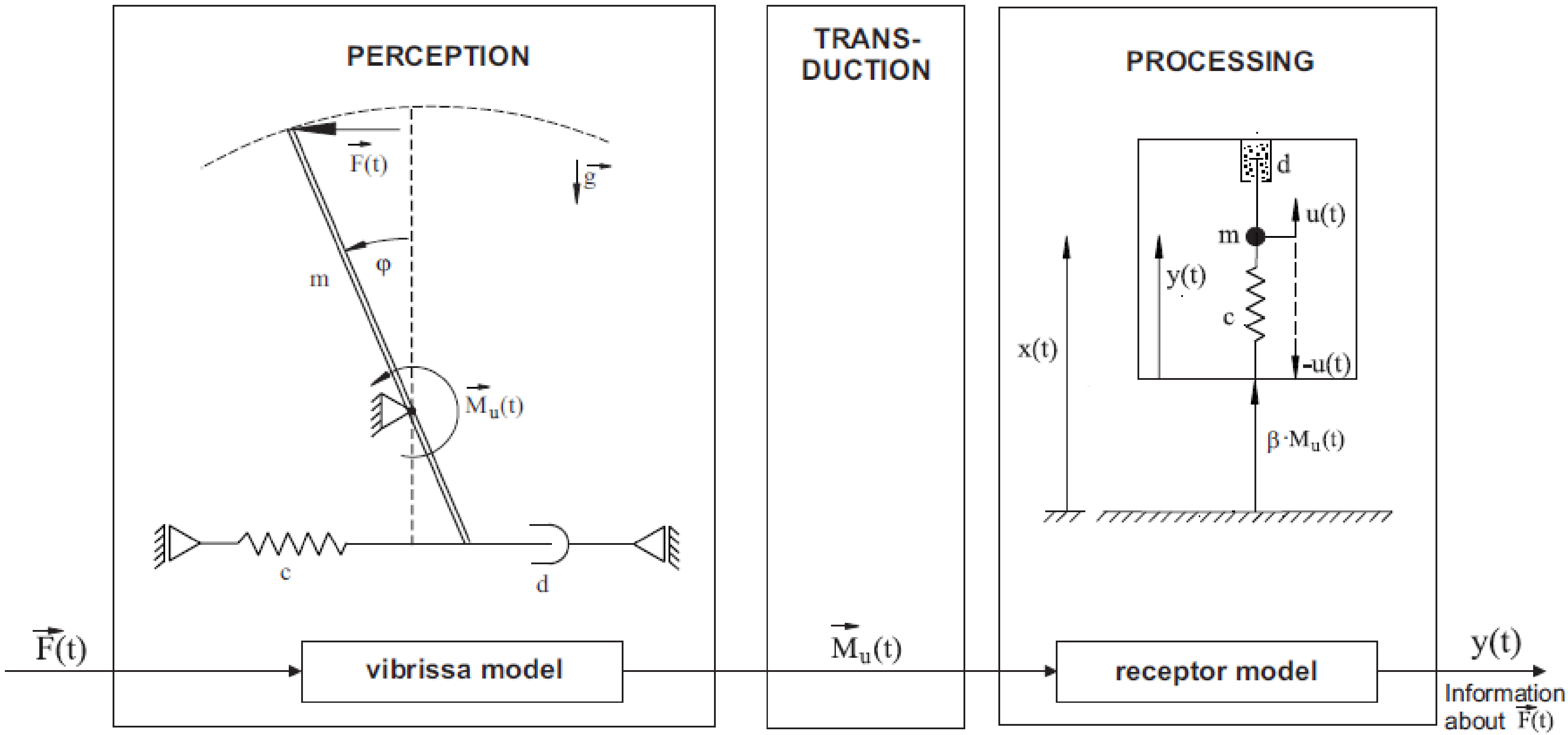
- Stage 2: seperate extra receptor from vibrissa system, as in paradigm

Part II: Vibrissae – 5. Modeling – Stage 2

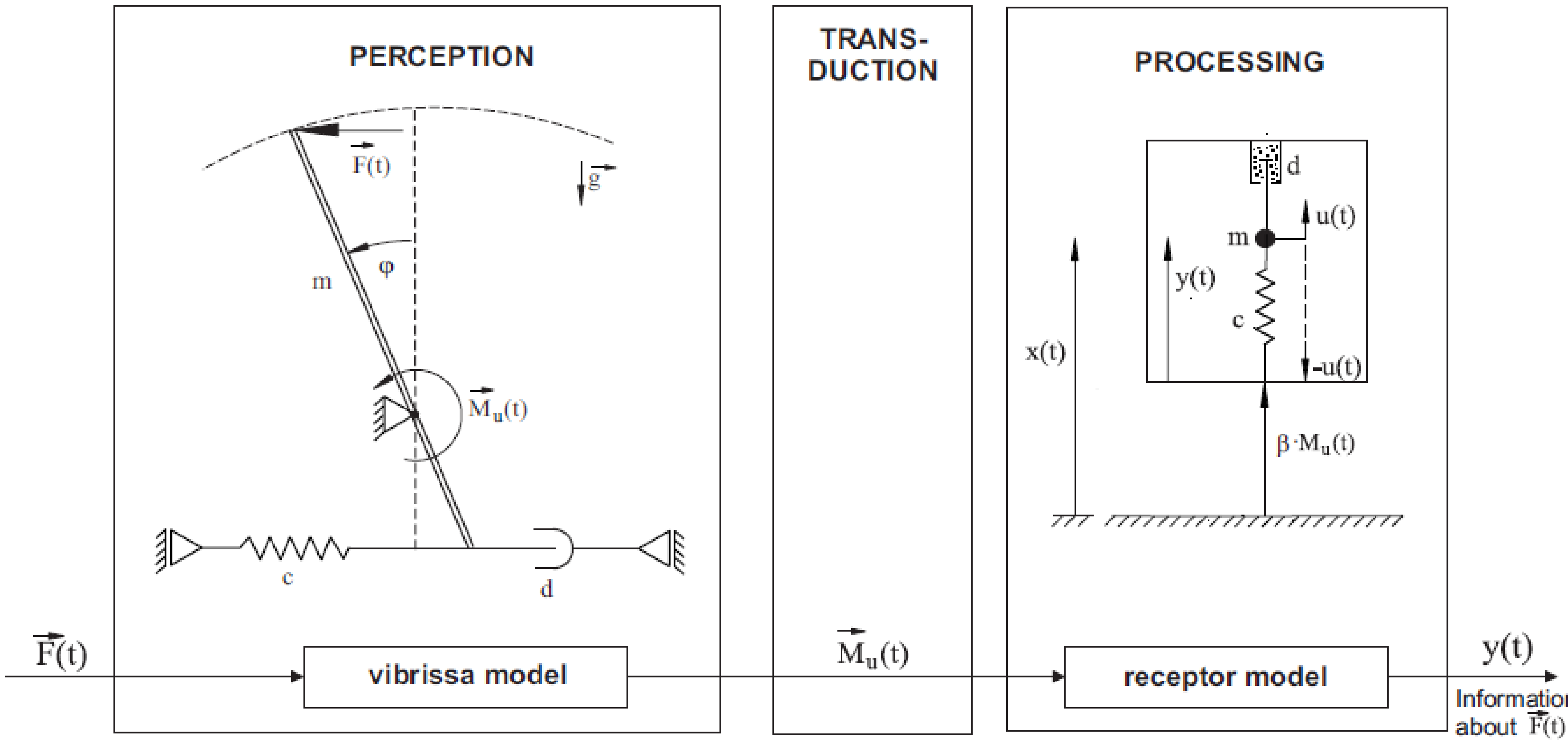
First – perception: external excitations deflect the vibrissa,
it serves as a perception of vibrations



Second - transduction: control the blood supply to achieve passive/active mode, information about the needed supply transmitted to receptor cells



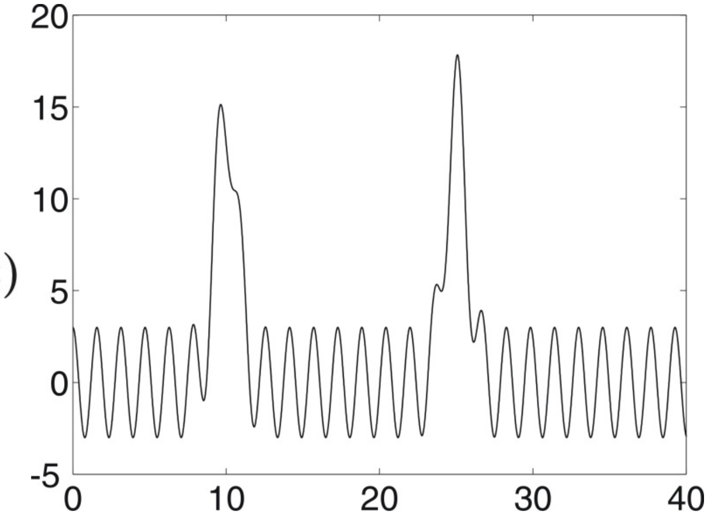
Third – processing: information analyzed in a receptor cell in such a way to identify some important information about the excitation



Part II: Vibrissae – 5. Modeling – Stage 2

environment: $g = 9.81\,,\, t \mapsto F(t) = 0.3\,\cos(4\,t) + 15\,e^{-(t-10)^2} + 15\,e^{-(t-25)^2}$

controller: $\lambda = 0.2 \approx 0.064\,\pi\,,\, \gamma = 50\,,\, k_0 = 0$



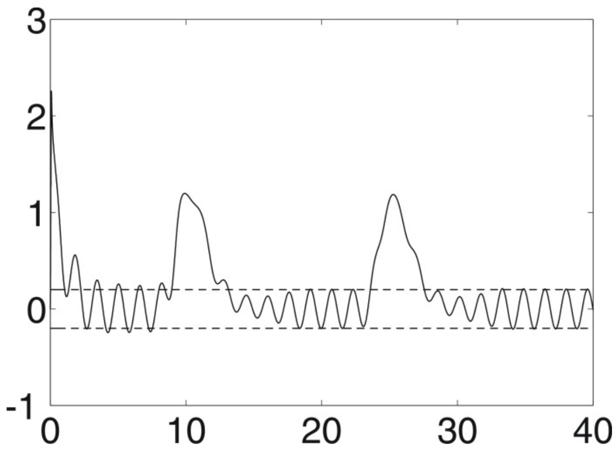
reference signals for modes:

λ-stabilization (passive mode): $t \mapsto \varphi_{\text{ref}}(t) = 0$

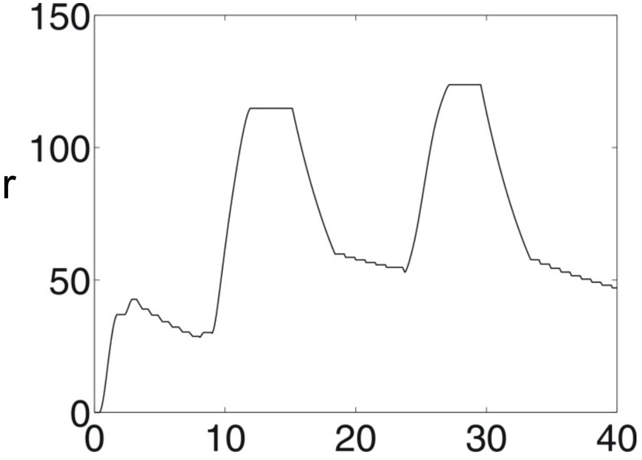
λ-tracking (active mode): $t \mapsto \varphi_{\text{ref}}(t) = \dfrac{\pi}{8}\,\sin(5\,t)$

Passive Mode

Output of vibrissa

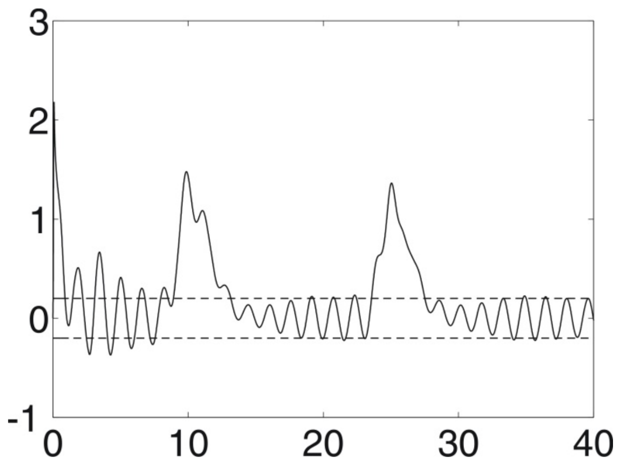


Receptor gain

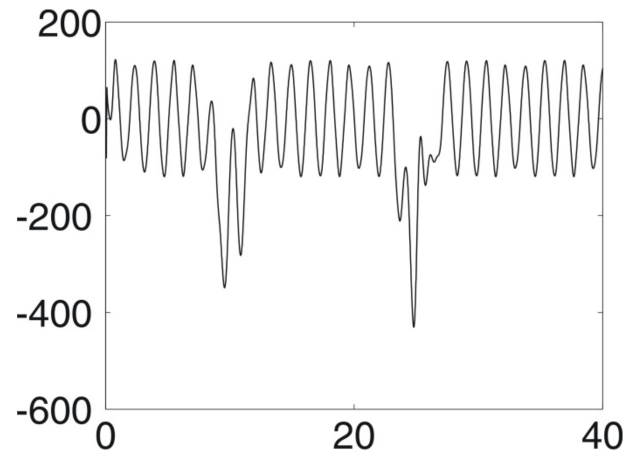


Active Mode

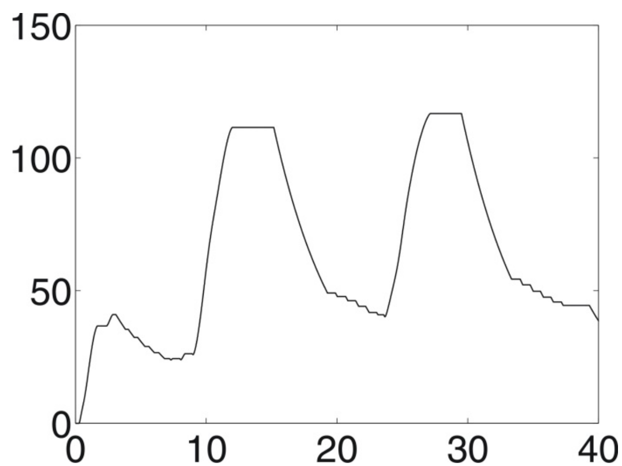
Output of vibrissa



transmitted torque signal



Receptor Gain



- both adaptive controllers work (for vibrissa and receptor)
- transmitted torque is analyzed in the receptor
- interesting: detect superimposed impulse in observing receptor gain *k(.)*

Part II: Vibrissae – 5. Modeling – Stage 2

Short summary:

- numerical simulations have shown that this system exhibit also sensibility and adaptivity

- the vibrissa system reacts well to numerous forces

- disturbing forces can clearly be recognized in observing the course of the control torque → suitable observable as input to receptor model

- the receptor model rapidly suppresses the persisting stimuli and shows good reactions to sudden deflections

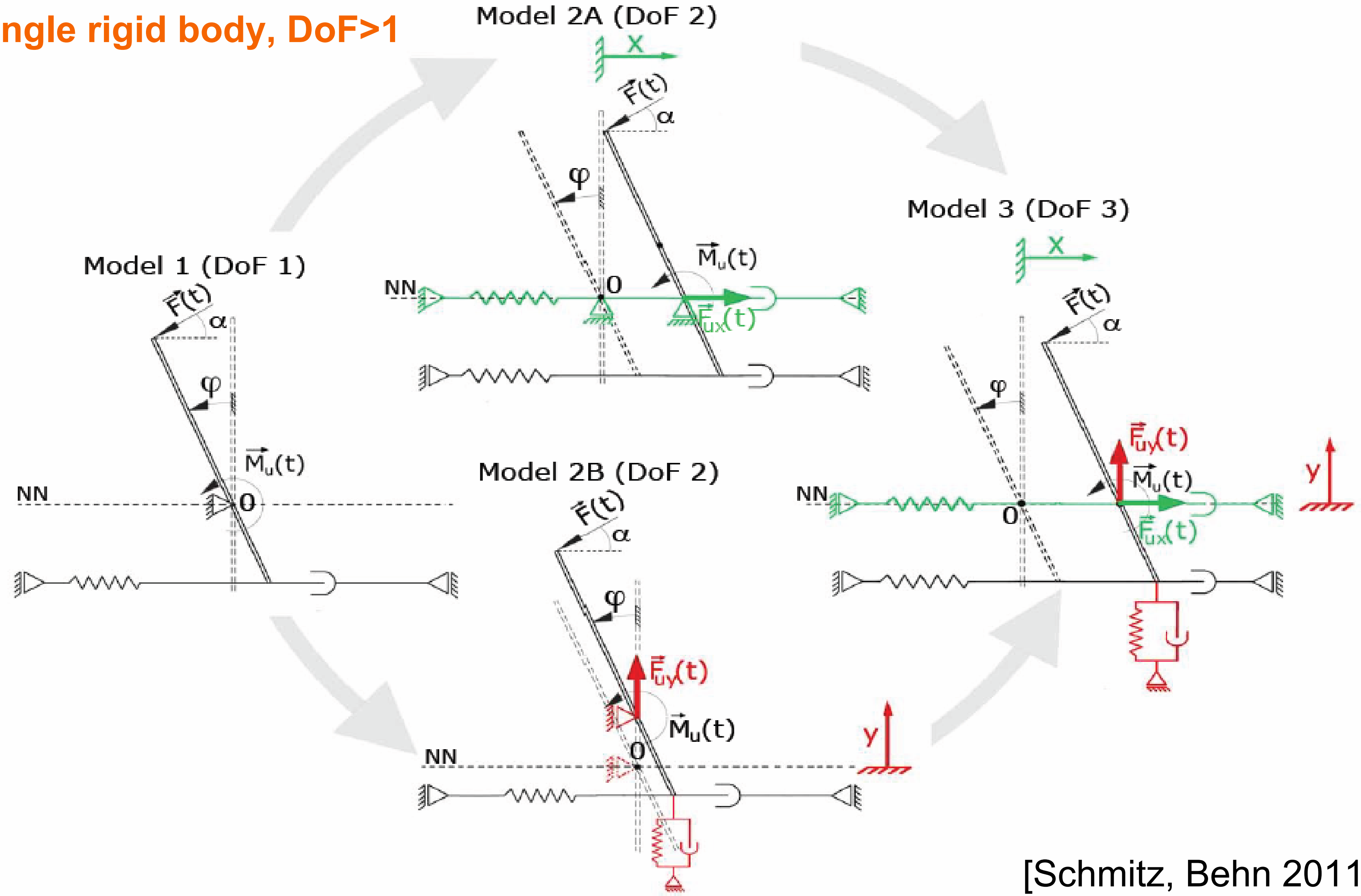
- main outcome: the „output“ of the receptor y, k or u is simultanously immanent in the control torque!
  → further investigations will focus on the perception model

- Drawback: perception of horizontal forces only

- New goal: models for identification of disturbing forces with a larger range of angles of attack

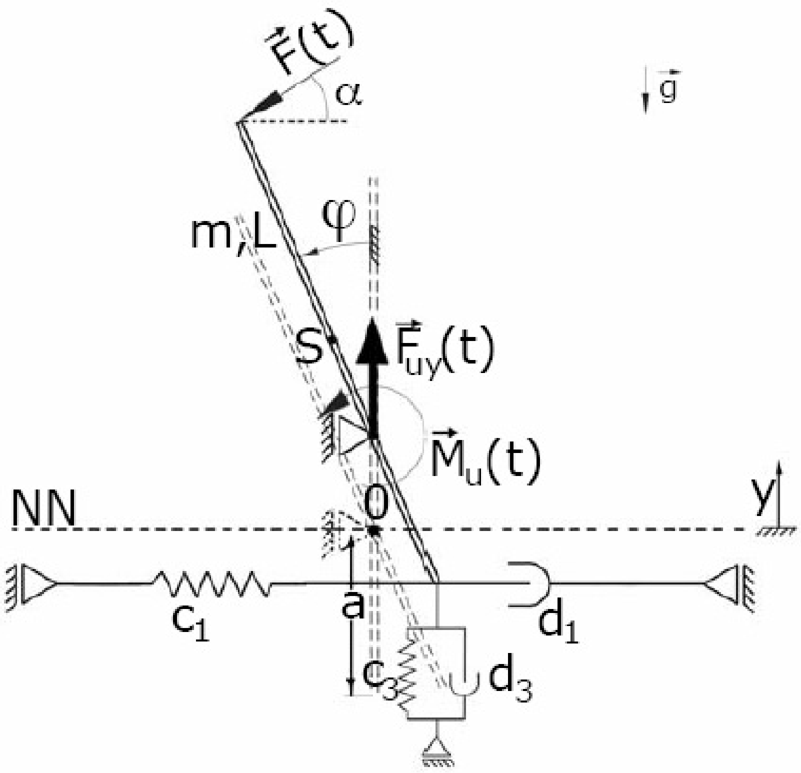
Part II: Vibrissae – 5. Modeling – Stage 3

Single rigid body, DoF>1



[Schmitz, Behn 2011]

Equations of motion for Model 2B



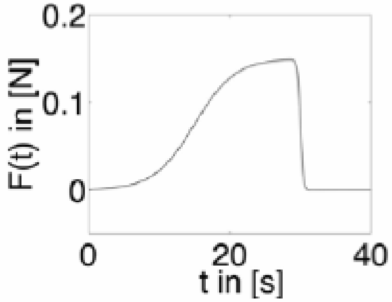
$$\ddot{y}(t) = \frac{1}{m}\Big[m\left(\frac{L}{2}-a\right)\big[\ddot{\varphi}(t)\sin(\varphi(t)) + \dot{\varphi}(t)^2\cos(\varphi(t))\big] - d_3\dot{y}(t) - c_3 y(t) - mg - F(t)\sin(\alpha) + F_{uy}(t)\Big]$$

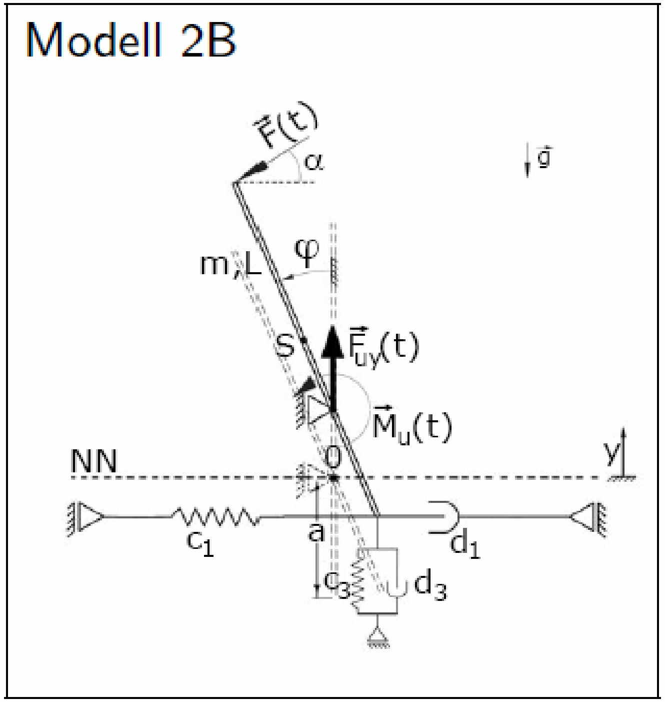
$$\ddot{\varphi}(t) = \frac{1}{J_{0z}}\Big[m\left(\frac{L}{2}-a\right)\big[\ddot{y}(t)\sin(\varphi(t)) + g\sin(\varphi(t))\big] - d_1 a^2\cos^2(\varphi(t))\dot{\varphi}(t) - c_1 a^2\sin(\varphi(t))\cos(\varphi(t)) + (L-a)F(t)\cos(\varphi(t)-\alpha) + M_u(t)\Big]$$

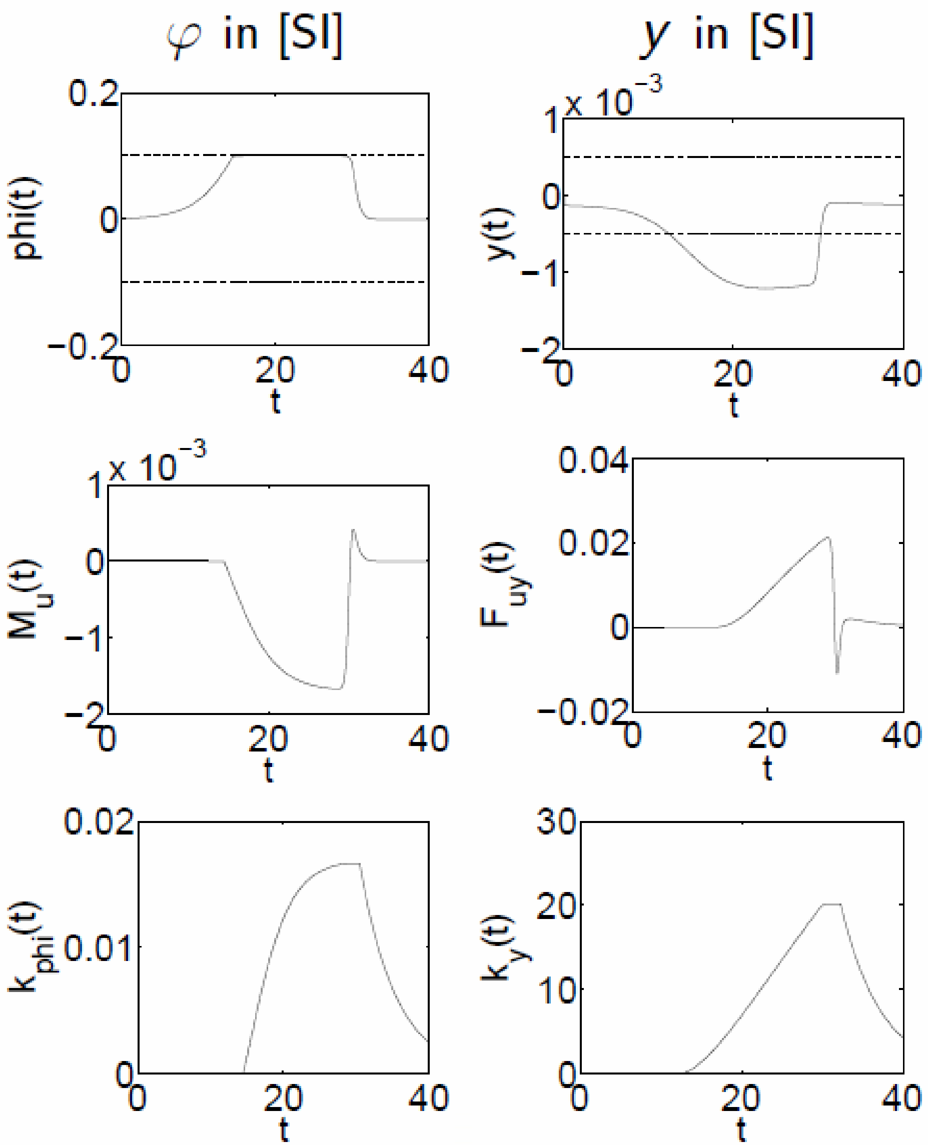
$y(0) = 0 \qquad \dot{y}(0) = 0 \qquad \varphi(0) = 0 \qquad \dot{\varphi}(0) = 0$

In the passive mode

Disturbing force attacking with $\alpha = 45^\circ$

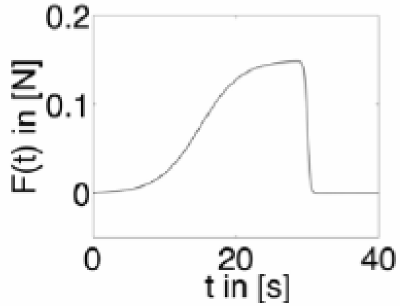




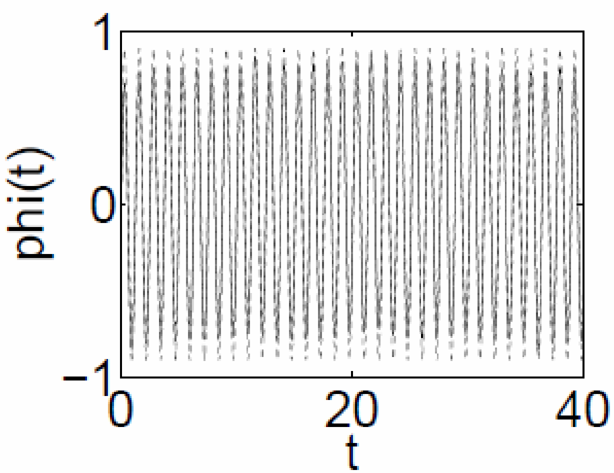


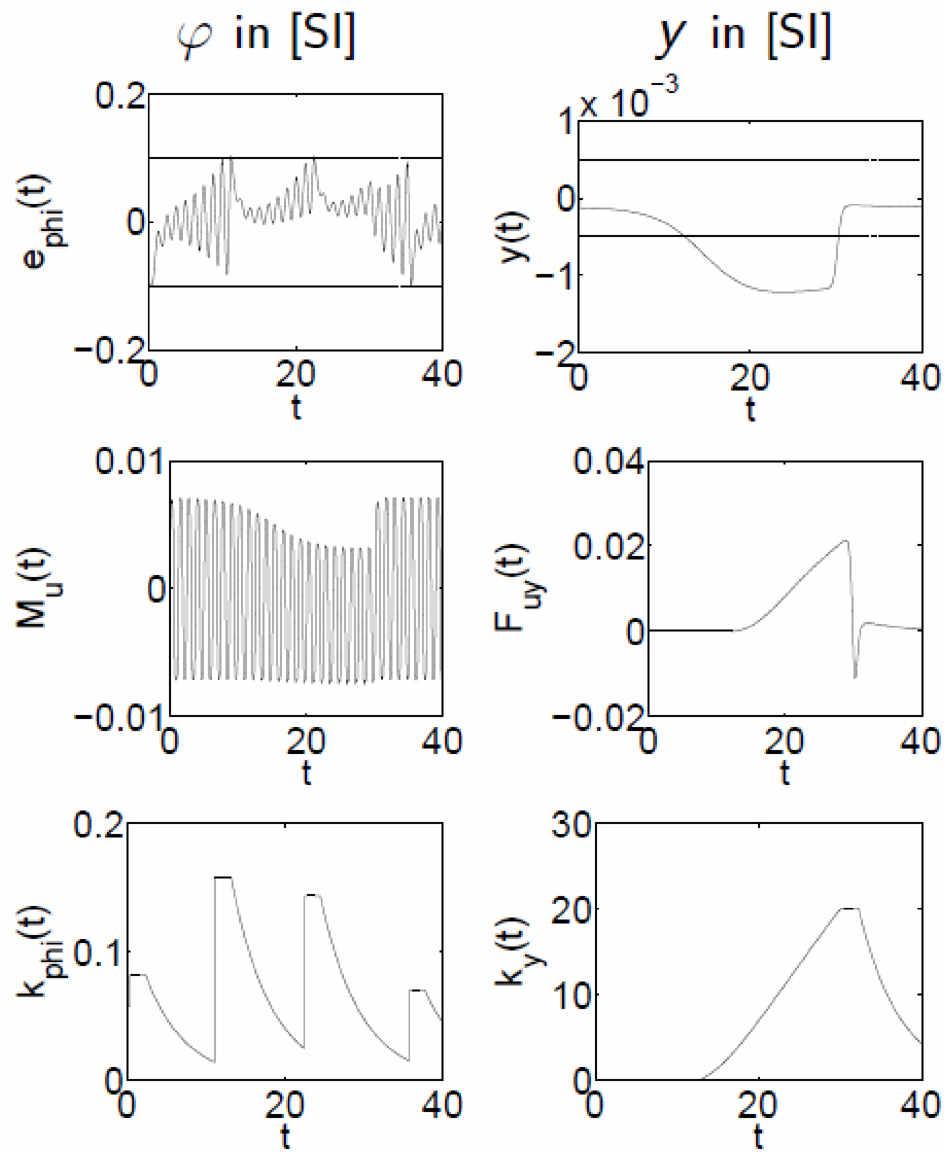
In the active mode

Disturbing force attacking with $\alpha = 45^\circ$



$$\varphi_{ref} = 0.8\sin(5t)$$





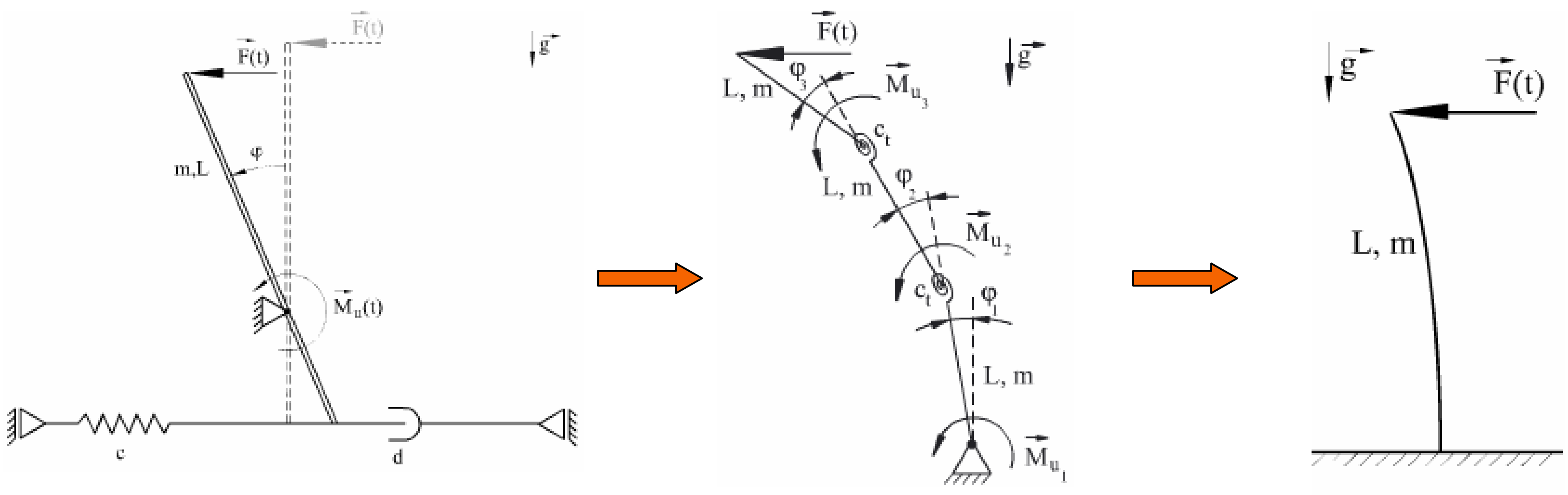
Goal: identification of disturbing forces attacking with any angle

Results: with model 2B disturbance forces can be identified in the passive and active mode for angles of attack reaching from $\alpha = 0^\circ$ tc 90°

→ increase elasticity, possible in 2 ways:

a) rigid multi-body system models – Stage 4

b) elastic beam models:
investigation of mechanical models with infinte DoF – Stage 5



DOF=1 DOF=3 DOF=infinity

Part II: Vibrissae – 5. Modeling – Stage 5

Remind: Vibrissa is elastical, hollow and conically shaped

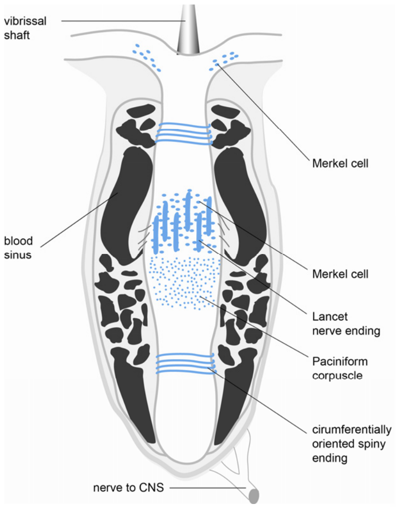
Function hypotheses in literature:

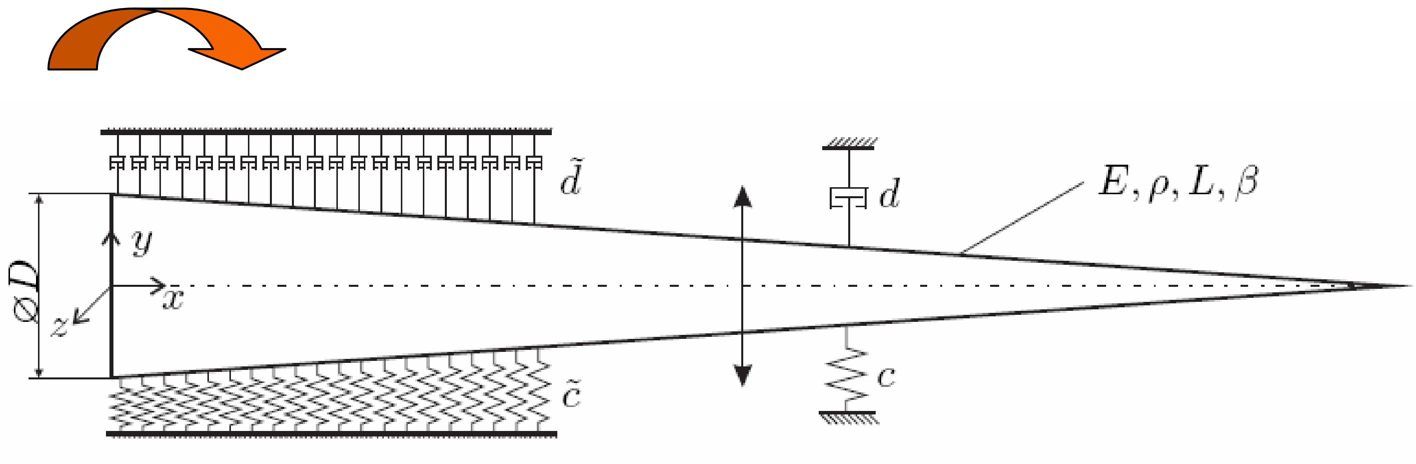
- The elasticity and the conical shape of the hair are relevant for the functionality of the vibrissa.
- The viscoelastic properties of the support (FSC) are controlled by the blood pressure in the blood sinus.
- The vibrissae are excited with or close to their resonance frequencies during the active mode.

Global goal:

- computation of EFs for dimensioning and / or parameter identification (e.g., external forces)
- maybe observing shift of the spectrum of EFs (due to controllable FSC)

Part II: Vibrissae – 5. Modeling – Stage 5a - EF

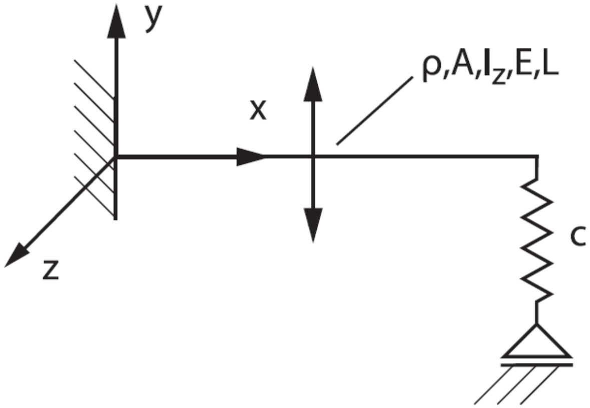




<u>Intermediate goals:</u>

- investigating innovative models of a flexible vibrissa with a viscoelastic support (discrete or continuously distributed)
- analytical computation of EFs of beams depending on material and geometry
- numerical verification using FEM / MBS
- drawing conclusion to complex systems

Example:



PDE: $\ddot{v}(x,t) + k^4\, v''''(x,t) = 0\,, \quad \text{with} \quad k^4 := \dfrac{E\,I_z}{\varrho\,A}$

BC:

$① : v(0,t) = 0\ \forall t \geq 0$

$② : v'(0,t) = 0\ \forall t \geq 0$

$③ : v''(L,t) = 0\ \forall t \geq 0$

$④ : v'''(L,t)\,E\,I_z - c\,v(L,t) = 0\ \forall t \geq 0$

EVE: $$\lambda^3\,L^3\ (1+\cosh(\lambda\,L)\ \cos(\lambda\,L)) + \gamma_c\ (\cosh(\lambda\,L)\ \sin(\lambda\,L) - \cos(\lambda\,L)\ \sinh(\lambda\,L)) = 0$$

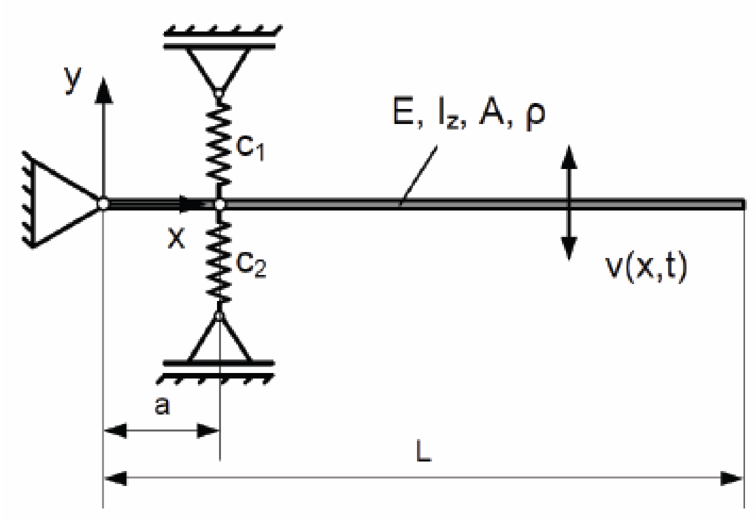
with $\gamma_c := \dfrac{c}{c_S} = \dfrac{c}{\frac{E\,I_z}{L^3}} = \dfrac{c\,L^3}{E\,I_z}$

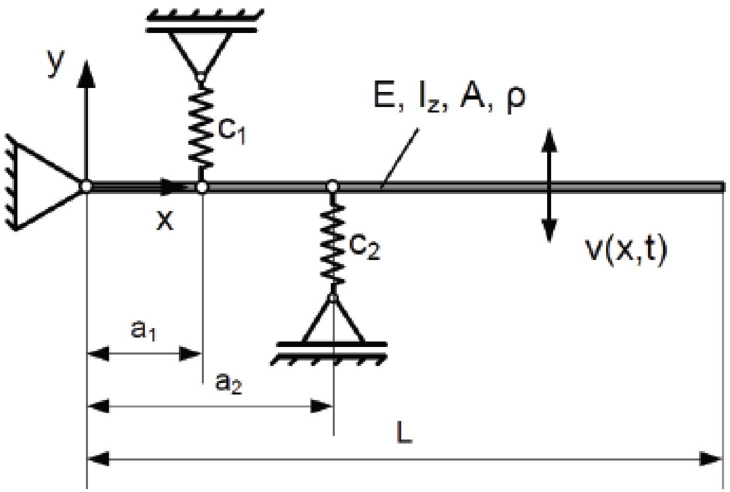
Results:

$\gamma_c = 1$

		steel beam		$B2$ vibrissa	
j	λ_j	ω_j	f_j	ω_j	f_j
1	$2.010\,\frac{1}{L}$	653.008	103.929	843.189	62.369
2	$4.704\,\frac{1}{L}$	3576.197	569.169	4617.724	341.566
3	$7.857\,\frac{1}{L}$	9977.433	1587.958	12883.248	952.955
4	$10.996\,\frac{1}{L}$	19544.181	3110.553	25236.203	1866.685
5	$14.138\,\frac{1}{L}$	32305.127	5141.521	41713.630	3085.496

First steps: conservative systems



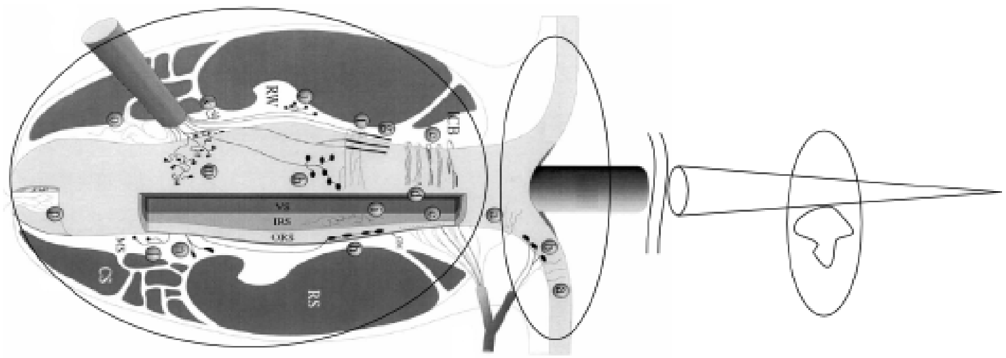


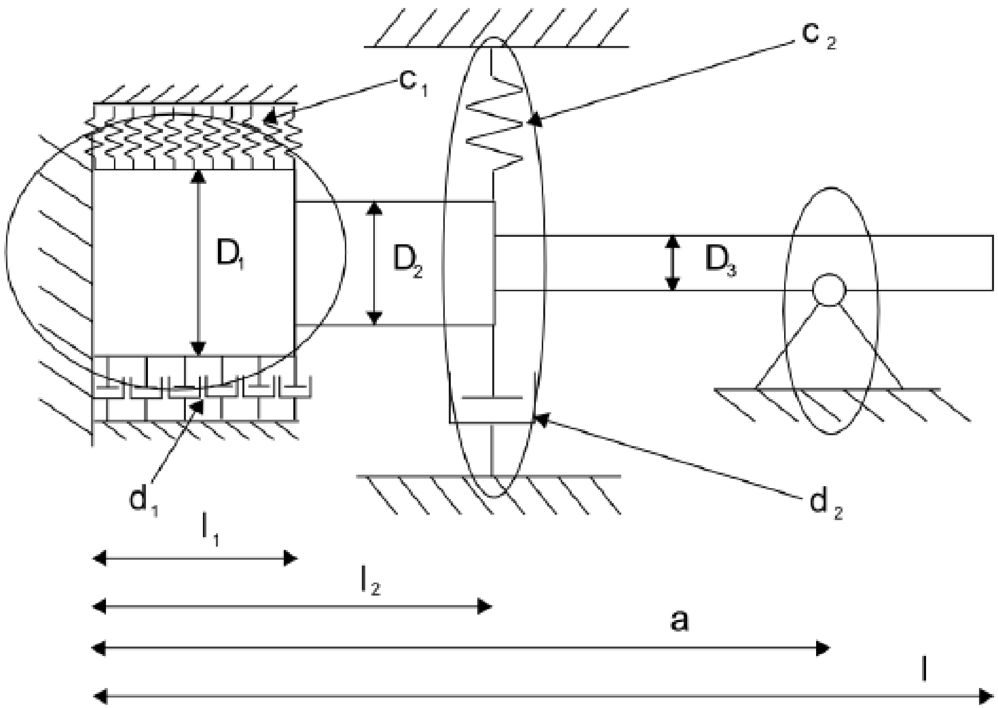
Modeling: - one and two levels of support compliance: FSC and skin

Drawback: - pivot does not match reality
- no damping is considered

Findings (obvious as in literature):
- massive influence of the support on the eigenfrequencies
- massive influence of the conical and hollow shape

Part II: Vibrissae – 5. Modeling – Stage 5a - EF



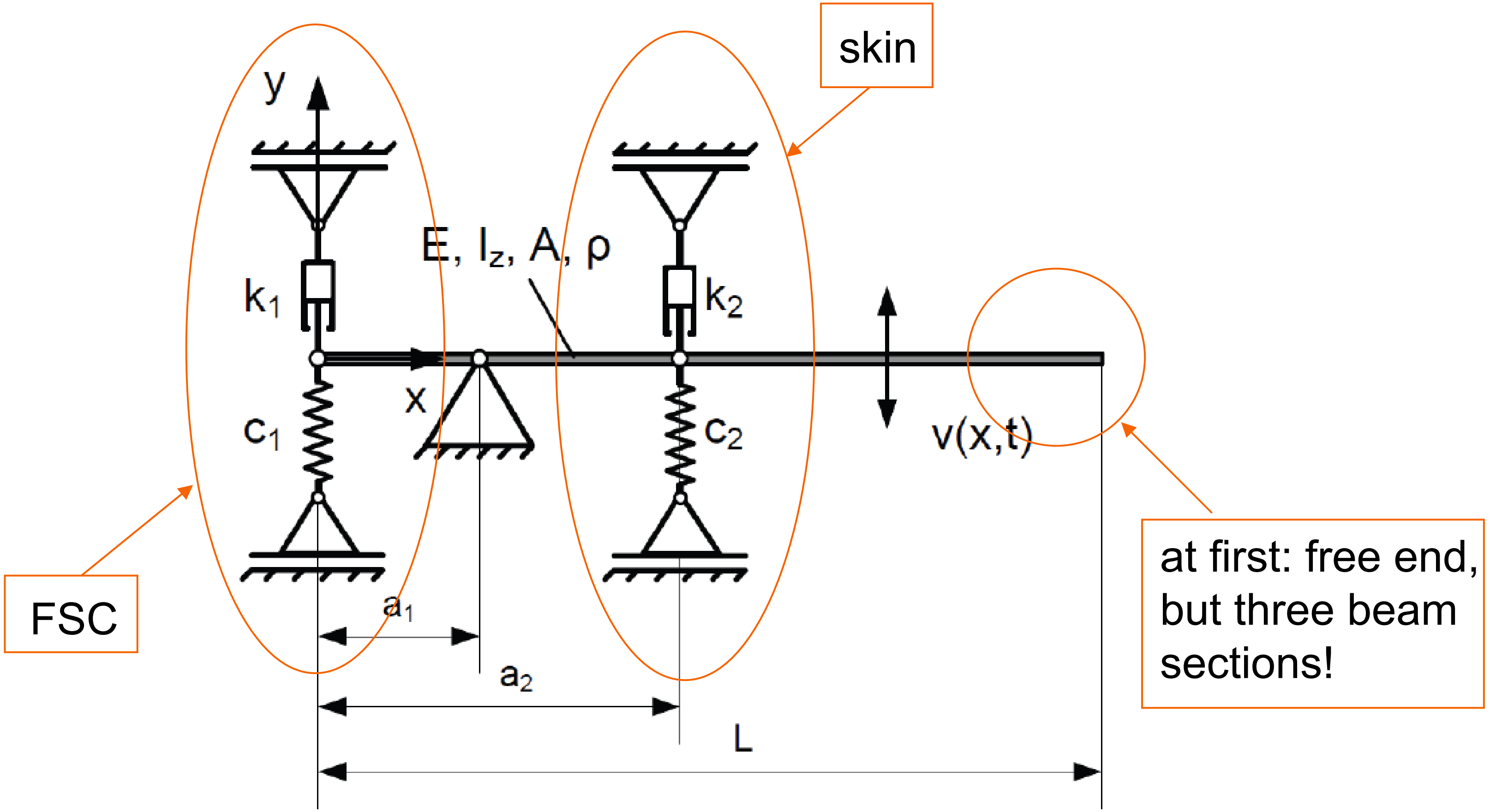


Investigating the influence of fundamental properties of the vibrissa from biology to the natural frequencies:

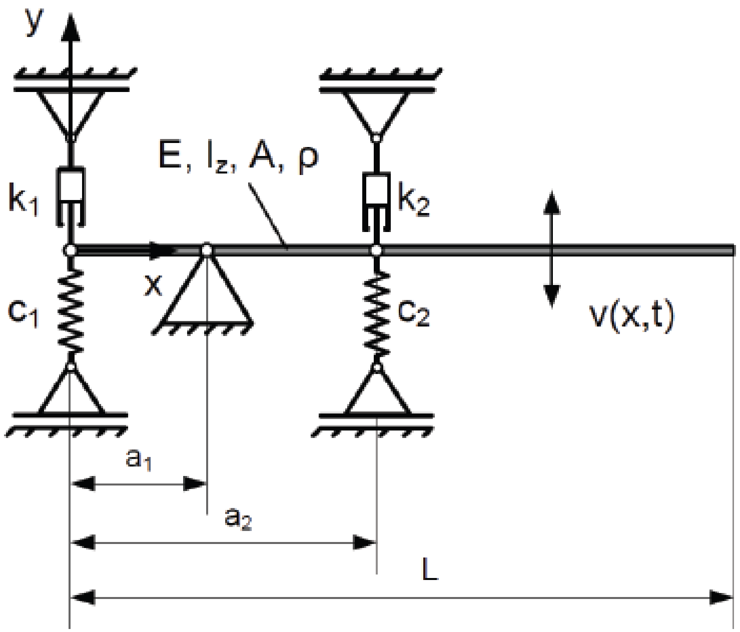
- conical shape / various cross-sections
- viscoelastic foundation due to FSC
- discrete viscoelastic support due to skin
- bearing due to (sudden) object contact

Part II: Vibrissae – 5. Modeling – Stage 5a - EF

Next steps: non-conservative systems



12 boundary condition ⟶ MVR ⟶ EVE (analytically) ⟶ EV & NF (numerically)



Parameters of B2-vibrissa in [Neimark et. al. 2003]

$$a_1 = 3\,\mathrm{mm}\,, a_2 = 4\,\mathrm{mm}$$

$$r = 0.1\,\mathrm{mm}\,, \text{ and } L = 40\,\mathrm{mm}$$

$$c_1 = c_{\mathrm{FSC}} = 80\,\frac{\mathrm{N}}{\mathrm{m}}\,, k_1 = d_{\mathrm{FSC}} = 0.5\,\frac{\mathrm{Ns}}{\mathrm{m}}$$

$$c_2 = c_{\mathrm{skin}} = 5.7\,\frac{\mathrm{N}}{\mathrm{m}}\,, \text{ and } k_2 = d_{\mathrm{skin}} = 0.2\,\frac{\mathrm{Ns}}{\mathrm{m}}$$

$$E = 2.3\,\mathrm{GPa} \text{ and } \varrho = 238.732\,\frac{\mathrm{kg}}{\mathrm{m}^3}$$

TABLE CALCULATION FOR THE STEEL BEAM.

	undamped		damped		
j	λ_j	ω_j	λ_j	ω_j	δ_j
1	3.946	2517.314	$2.017 - 0.271\,I$	645.851	176.755
2	7.448	8965.159	$4.941 - 0.085\,I$	3944.771	135.721
3	10.800	18852.940	$8.297 - 0.005\,I$	11126.480	129.665
4	14.004	31698.644	$11.650 + 0.068\,I$	21936.355	257.106
5	16.934	46348.499	$15.023 + 0.150\,I$	36477.396	727.763

as expected

TABLE CALCULATION FOR THE B2 VIBRISSA.

	undamped		damped		
j	λ_j	ω_j	λ_j	ω_j	δ_j
1	1.990	384.836	$1.993 + 0.033\,I$	385.694	12.594
2	4.988	2416.865	$5.151 + 0.067\,I$	2577.281	66.675
3	8.354	6779.153	$8.651 + 0.047\,I$	7270.715	78.835
4	11.703	13306.010	$12.119 + 0.037\,I$	14267.203	87.093
5	15.058	22027.360	$15.586 + 0.031\,I$	23599.899	95.129

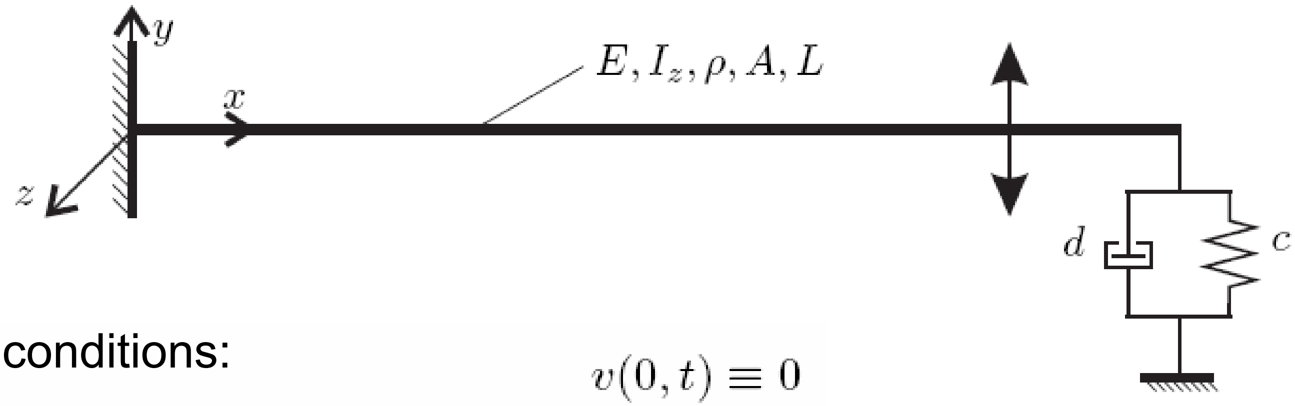
unlike behavior:
increasing natural frequencies if damped

Short summary:

- ⊖ Neglecting the conical shape of the vibrissa
- ⊕ Consideration of the support's compliance
  - · at skin level
  - · at the level of the FSC
- ⊕ Finding: massive influence of the support on the natural frequencies
- ⊕ Finding: influence of damping elements in the support
  - $\hookrightarrow$ massive for the 1^{st} natural frequency
  - $\hookrightarrow$ but: unlike behavior of the natural frequencies

⇨ Analyze simple systems to understand effects of boundary damping …

Simplification: model to analyze discrete damping effects
boundary viscoelastic end-support



Boundary conditions:

$$v(0,t) \equiv 0$$
$$v'(0,t) \equiv 0$$
$$v''(L,t) \equiv 0$$
$$EI_z\, v'''(L,t) - d\,\dot{v}(L,t) - c\,v(L,t) \equiv 0,$$

4-th boundary condition in form of a differential equation!
→ manipulation of this equation

$$-E^2 I_z^2 \left(\mathrm{X}'''(L)\right)^2 + 2EI_z c\,\mathrm{X}(L)\,\mathrm{X}'''(L) - c^2\,\mathrm{X}^2(L) - d^2\underline{\lambda}^4 k^4 \left(\mathrm{X}(L)\right)^2 = 0$$

$$E^2 I_z^2 \left(\mathrm{X}'''(L)\right)^2 - 2EI_z c\,\mathrm{X}(L)\,\mathrm{X}'''(L) + c^2\,\mathrm{X}^2(L) = \left[EI_z\,\mathrm{X}'''(L) - c\,\mathrm{X}(L)\right]^2$$

$$\Rightarrow \quad \left[EI_z\,\mathrm{X}'''(L) - c\,\mathrm{X}(L)\right]^2 = -d^2\underline{\lambda}^4 k^4 \left(\mathrm{X}(L)\right)^2$$

final form of 4th equation: $EI_z\,\mathrm{X}'''(L) - c\,\mathrm{X}(L) = \pm\mathrm{i}\,d\underline{\lambda}^2 k^2\,\mathrm{X}(L)$

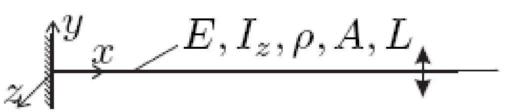
matrix of the matrix-vector-representation:

$$\mathbf{A}(\underline{\lambda}) = \left(\begin{array}{c:c:c:c} 1 & 0 & 1 & 0 \\ \hdashline 0 & \underline{\lambda} & 0 & \underline{\lambda} \\ \hdashline \begin{array}{l} EI_z\sin(\underline{\lambda}L)\,\underline{\lambda}^2 \\ \pm\mathrm{i}\,d\underline{\lambda}^2k^2\cos(\lambda L) \\ -c\cos(\underline{\lambda}L) \end{array} & \begin{array}{l} -EI_z\cos(\underline{\lambda}L)\,\underline{\lambda}^2 \\ \pm\mathrm{i}\,d\underline{\lambda}^2k^2\sin(\lambda L) \\ -c\sin(\underline{\lambda}L) \end{array} & \begin{array}{l} EI_z\sinh(\underline{\lambda}L)\,\underline{\lambda}^2 \\ \pm\mathrm{i}\,d\underline{\lambda}^2k^2\cosh(\lambda L) \\ -c\cosh(\underline{\lambda}L) \end{array} & \begin{array}{l} EI_z\cosh(\underline{\lambda}L)\,\underline{\lambda}^2 \\ \pm\mathrm{i}\,d\underline{\lambda}^2k^2\sinh(\lambda L) \\ -c\sinh(\underline{\lambda}L) \end{array} \\ \hdashline -\cos(\underline{\lambda}L)\,\underline{\lambda}^2 & -\sin(\underline{\lambda}L)\,\underline{\lambda}^2 & \cosh(\underline{\lambda}L)\,\underline{\lambda}^2 & \sinh(\underline{\lambda}L)\,\underline{\lambda}^2 \end{array}\right)$$

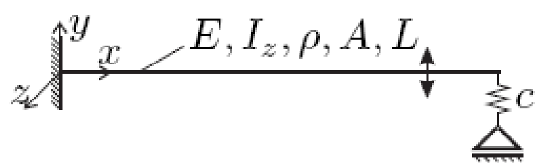
Equation to determine the eigenvalues:

$$\det\left(\mathbf{A}\left(\underline{\lambda}\right)\right) = -EI_z\underline{\lambda}^3 - EI_z\cos\left(\underline{\lambda}L\right)\cosh\left(\underline{\lambda}L\right)\underline{\lambda}^3 \pm \mathrm{i}\,dk^2\sin\left(\underline{\lambda}L\right)\cosh\left(\underline{\lambda}L\right)\underline{\lambda}^2 - c\sin\left(\underline{\lambda}L\right)\cosh\left(\underline{\lambda}L\right) \mp \mathrm{i}\,dk^2\cos\left(\underline{\lambda}L\right)\sinh\left(\underline{\lambda}L\right)\underline{\lambda}^2 + c\cos\left(\underline{\lambda}L\right)\sinh\left(\underline{\lambda}L\right) = 0$$

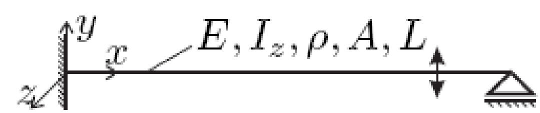
First test: equation exhibits known eigenvalue-equations of the following systems



$c = 0$ and $d = 0$



$d = 0$

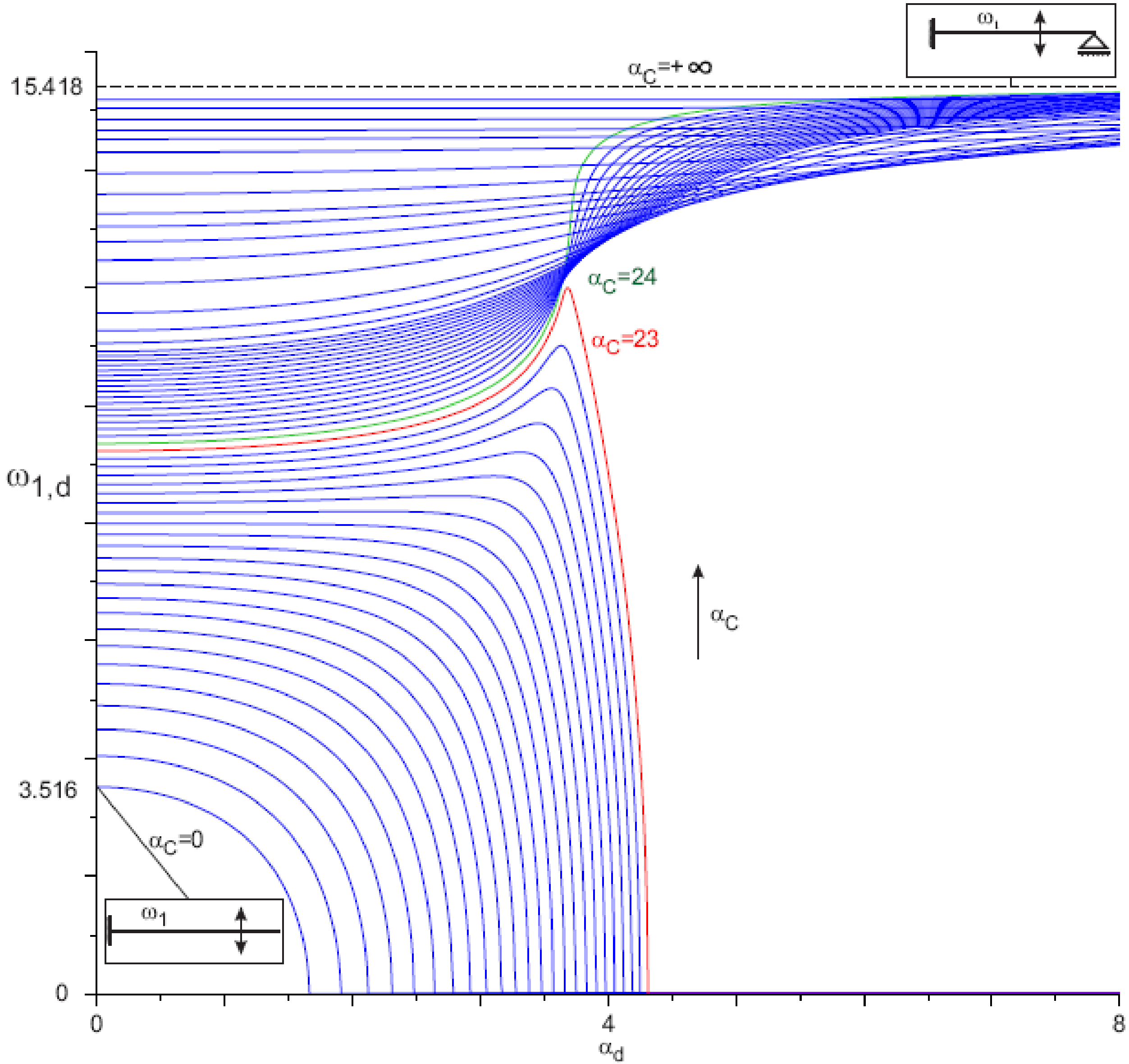


$c \to +\infty$ or $d \to +\infty$

Introduction of dimensionless parameters:

$$\alpha_c := \frac{c}{\frac{EI_z}{L^3}}$$

$$\alpha_d := \frac{L\,d}{\sqrt{\rho\,A\,E\,I_z}},$$



Determination using MAPLE:

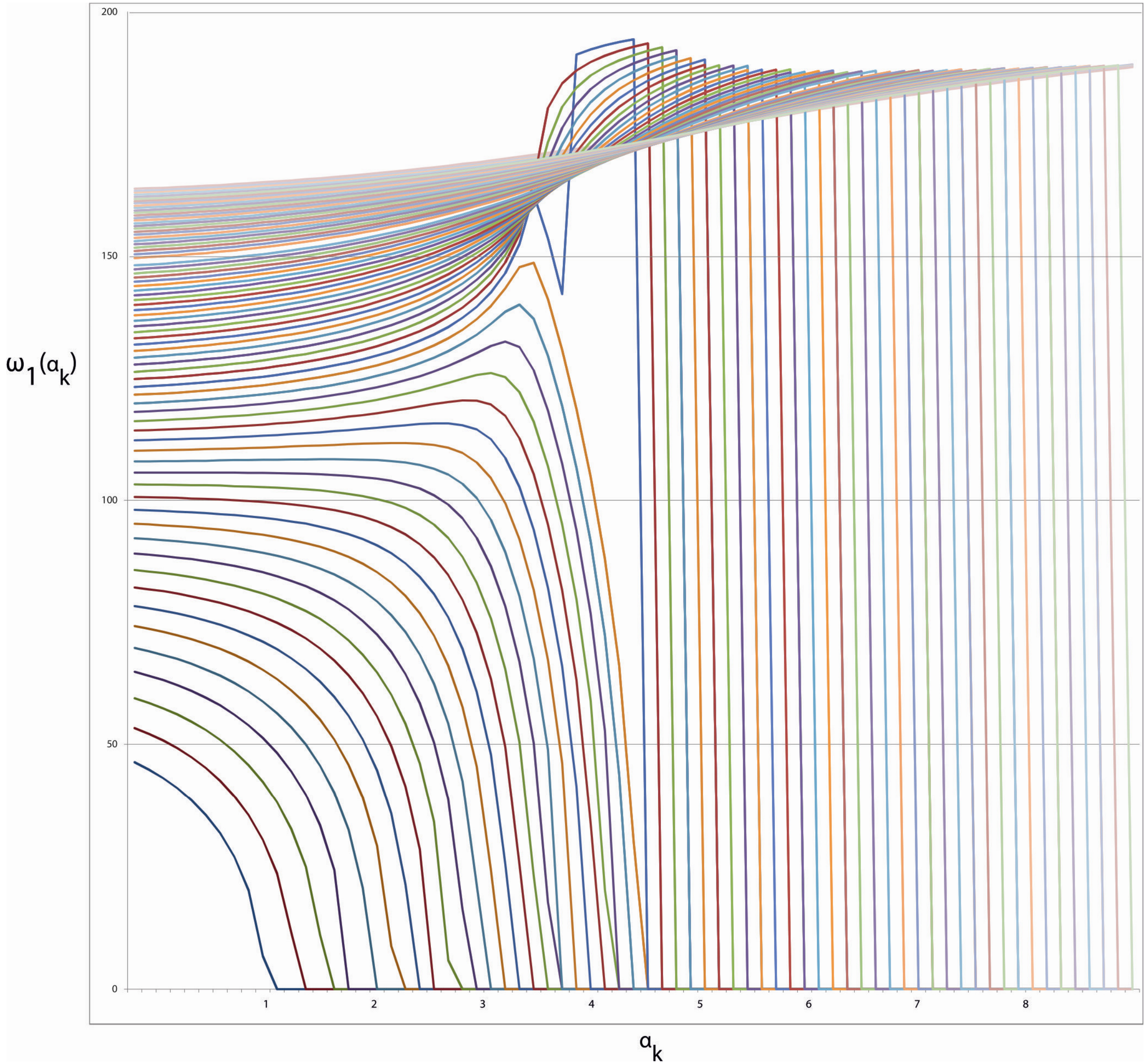
Verification ANSYS:

first natural frequency

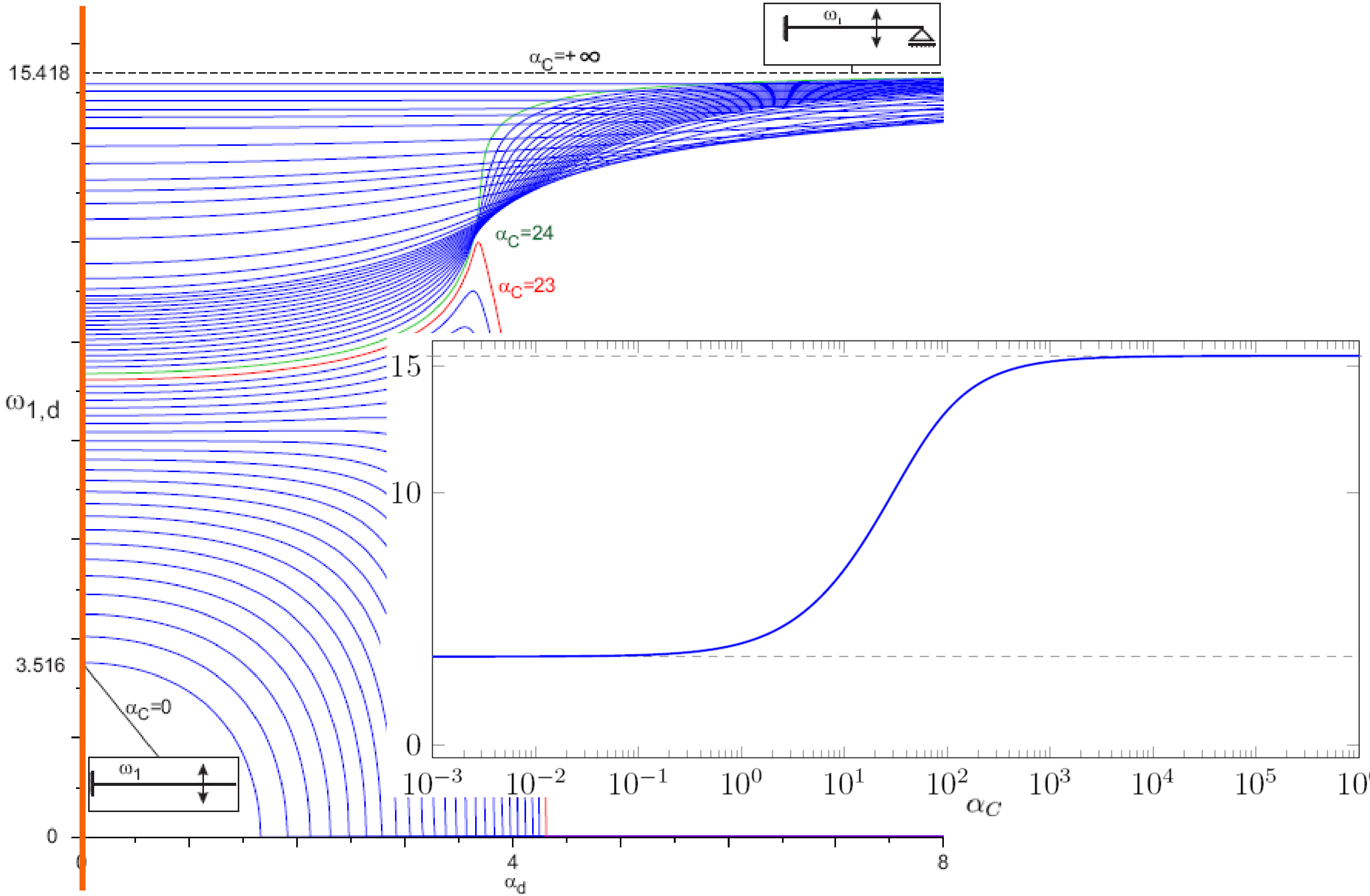
dependent on α_d

with parameter α_c

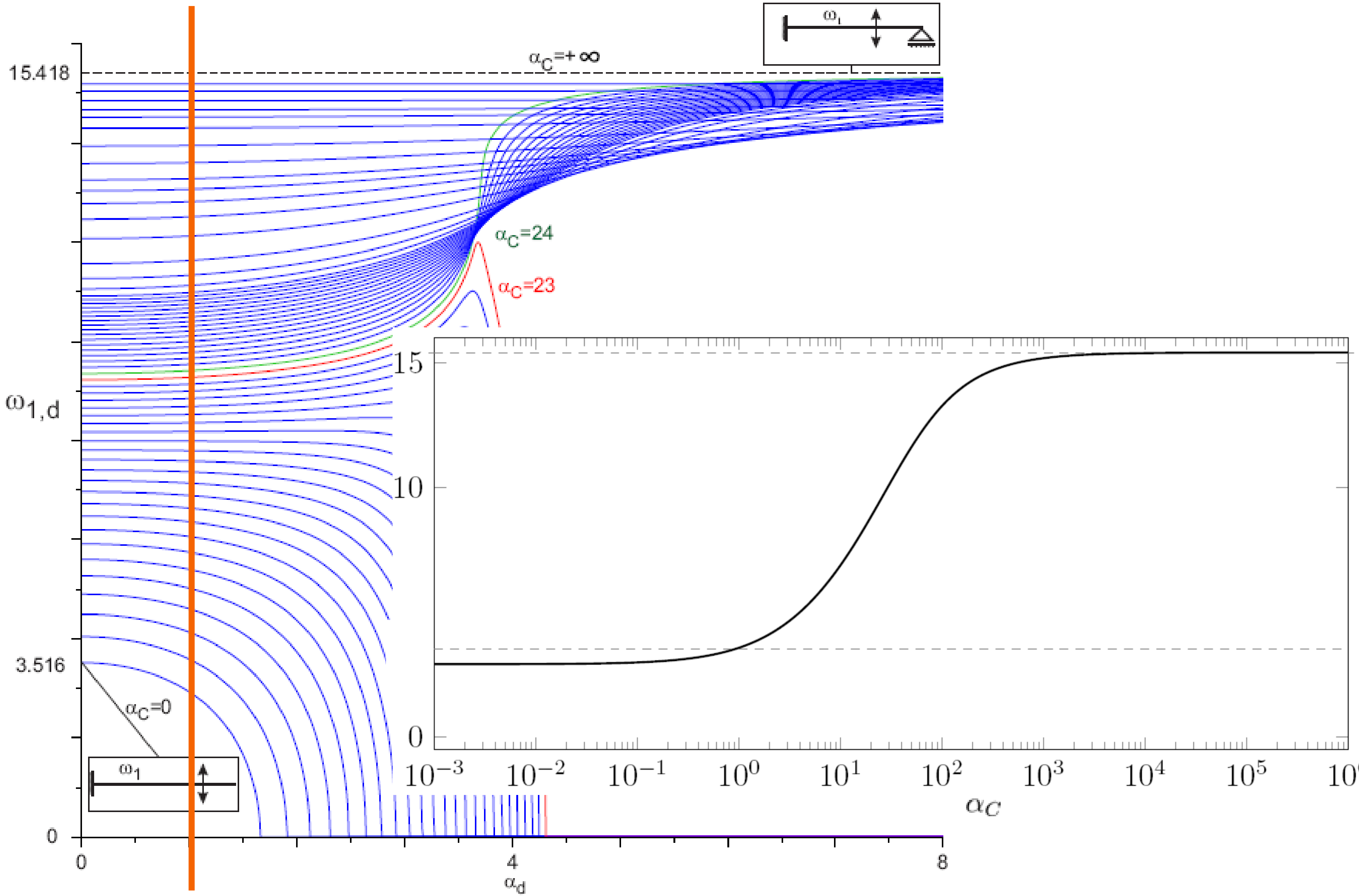
(using beam3 and combine14)



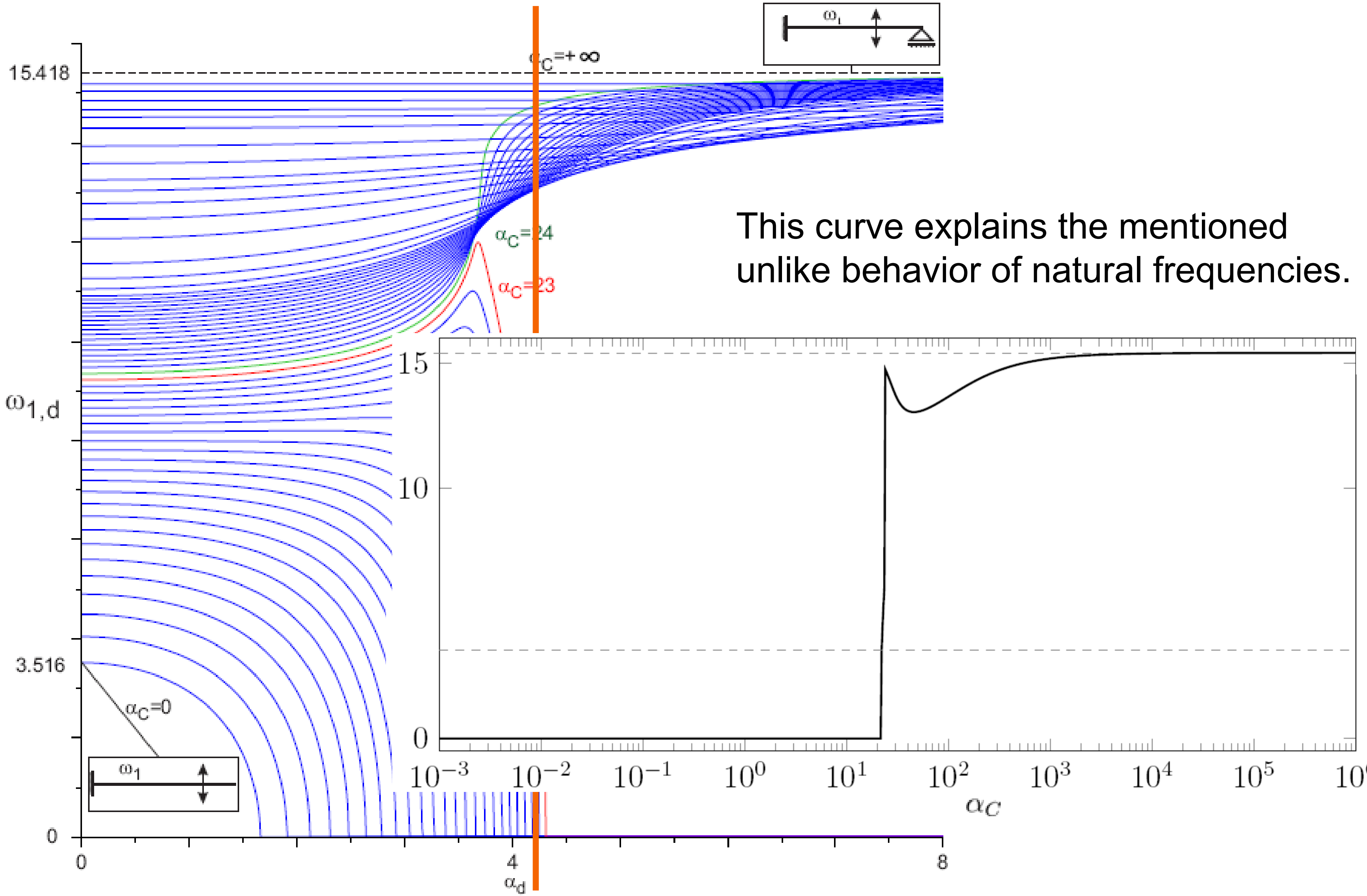
Part II: Vibrissae – 5. Modeling – Stage 5a - EF



Part II: Vibrissae – 5. Modeling – Stage 5a - EF



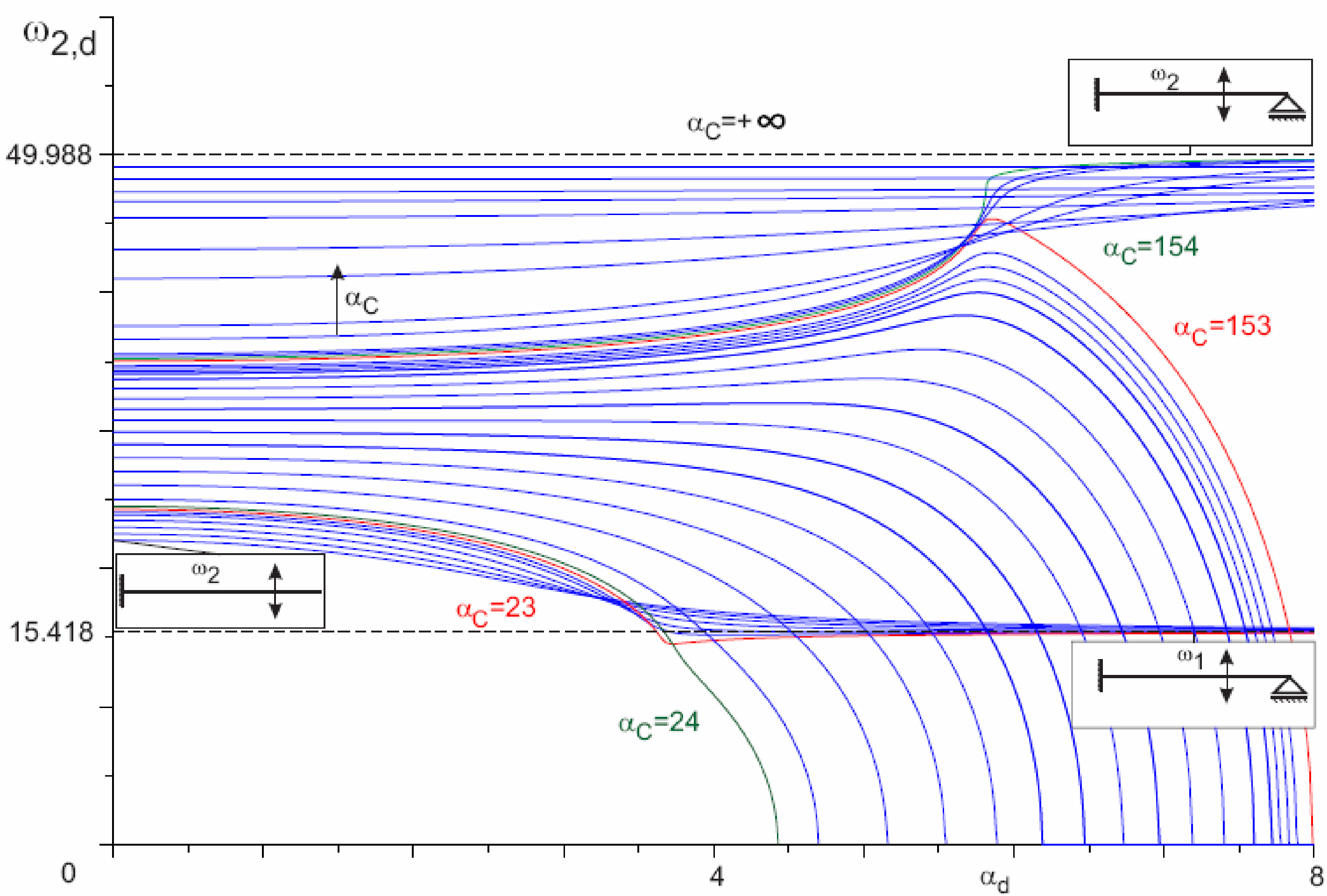
Part II: Vibrissae – 5. Modeling – Stage 5a - EF



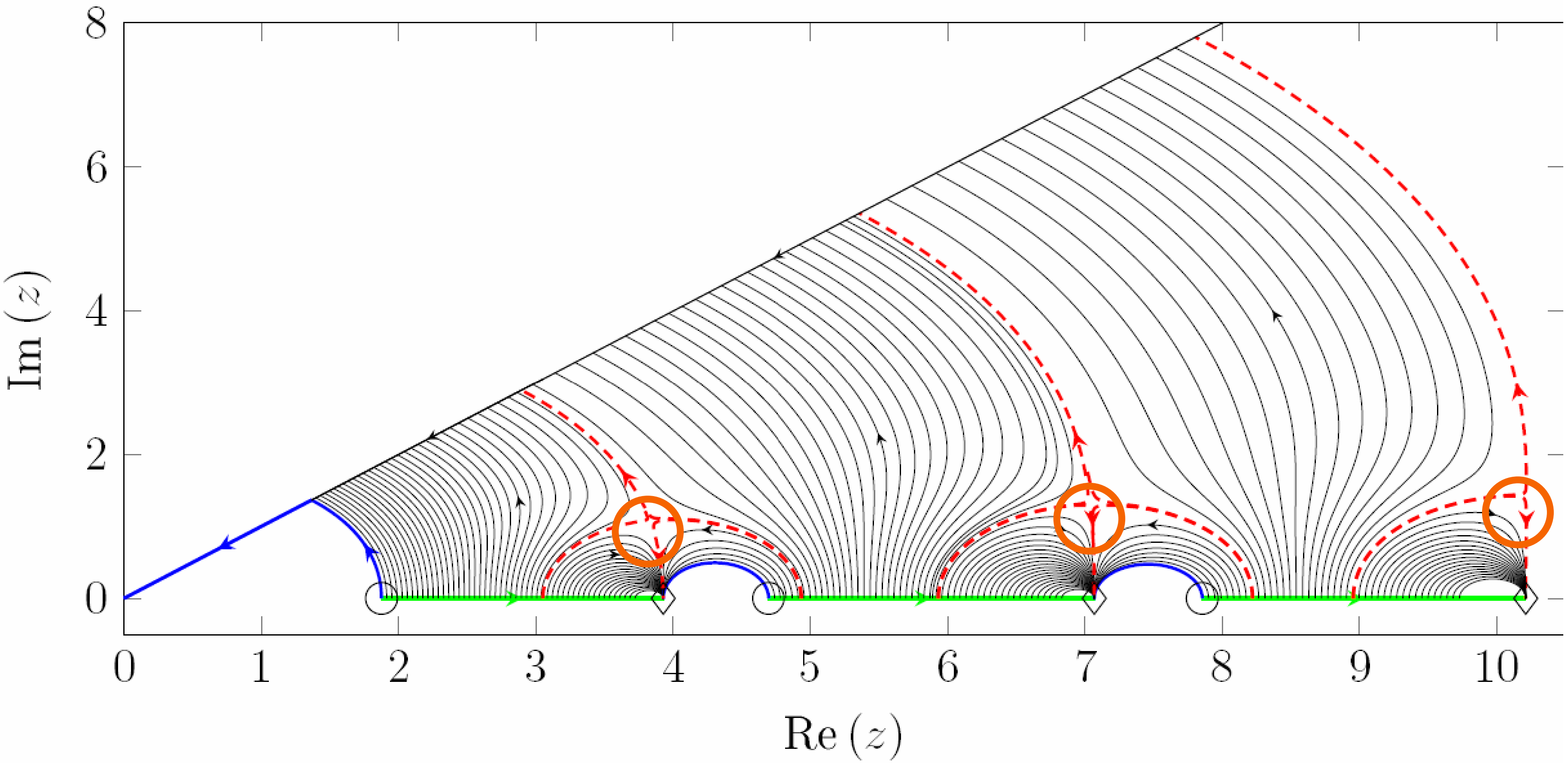
This curve explains the mentioned unlike behavior of natural frequencies.

Part II: Vibrissae – 5. Modeling – Stage 5a - EF

More complex and unlike behavior in observing the second (or other higher) natural frequencies:



Part II: Vibrissae – 5. Modeling – Stage 5a - EF



Existence of saddle points: 1^{st} for $\alpha^*_{C1} \approx 23.6562\,, \quad \alpha^*_{d1} \approx 3.6955$

2^{nd} for $\alpha^*_{C2} \approx 153.9398\,, \quad \alpha^*_{d1} \approx 5.8149$

$\vdots$

Conclusion from this stage:

- analytical treatment of beam vibrations to determine the spectrum of natural frequencies

- complex models due to complex structure of biological sensor

- unlike behavior in first models

- analysis of a special example:
  - boundary discrete damping and spring elements
  - classical assertions not valid: increase c then natural frequency will increase
  - this may explain the unlike behavior
  - 0-eigenfrequency – rigid-body motion, like strong damping, no oscillation

- still known, but not for beams

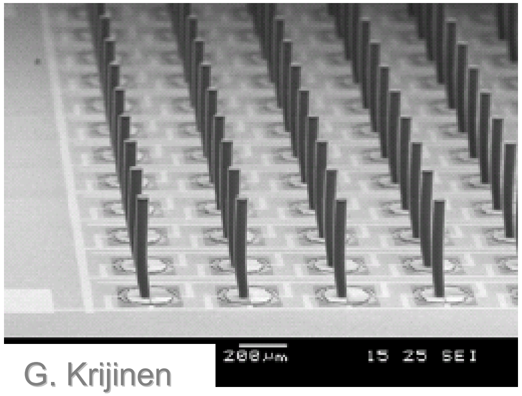
- idea: observe shift in spectrum of frequencies due to sudden obstacle contacts
  detect distance, not only contact / no contact

Part II: Vibrissae – 5. Modeling – Stage 5b - Distance

paradigms of tactile sensors for perception in applications:

- quality assurance (e.g., coordinate measuring machines)
- measurements of flow rates
- detection of packaged goods on conveyor belts

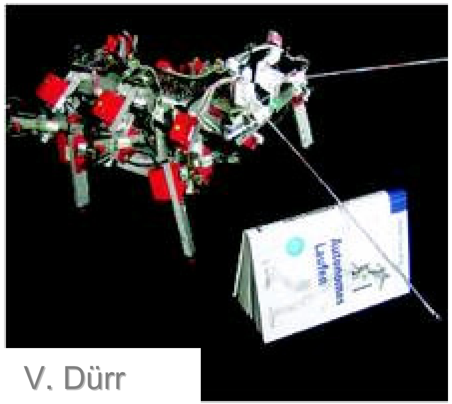
Microsystem Technology



G. Krijinen

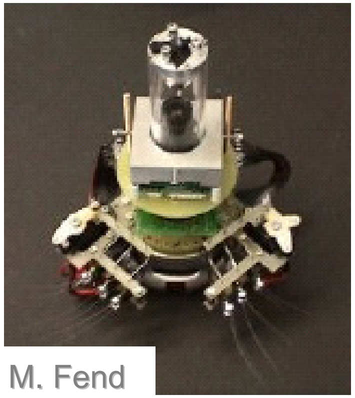
detection of flow rates

Robotics



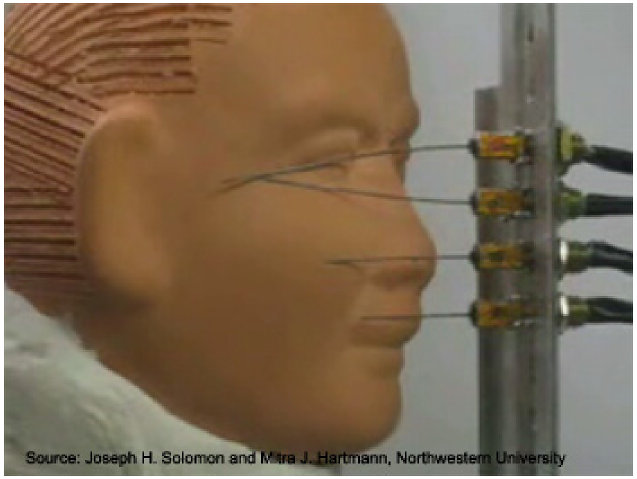
V. Dürr

object localization



M. Fend

detection of texture

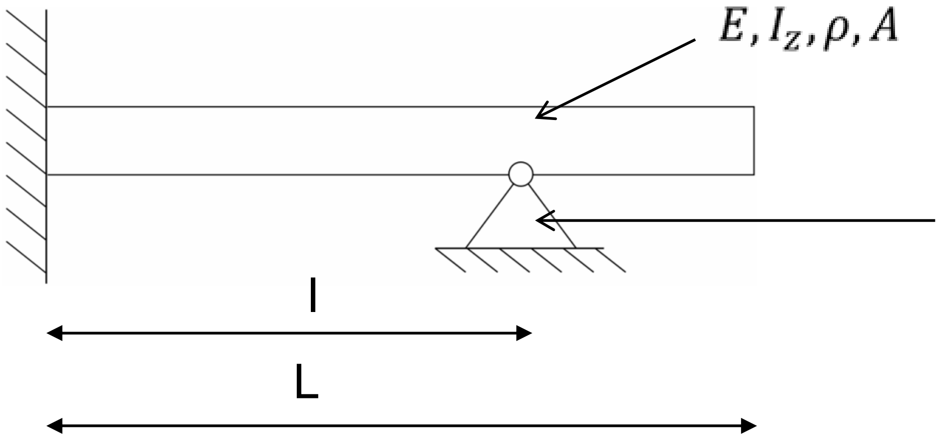


detection of contour

⟹ dynamic analysis of beam vibrations in Bionics

[Ueno et al. 1998]

model of the vibrissa



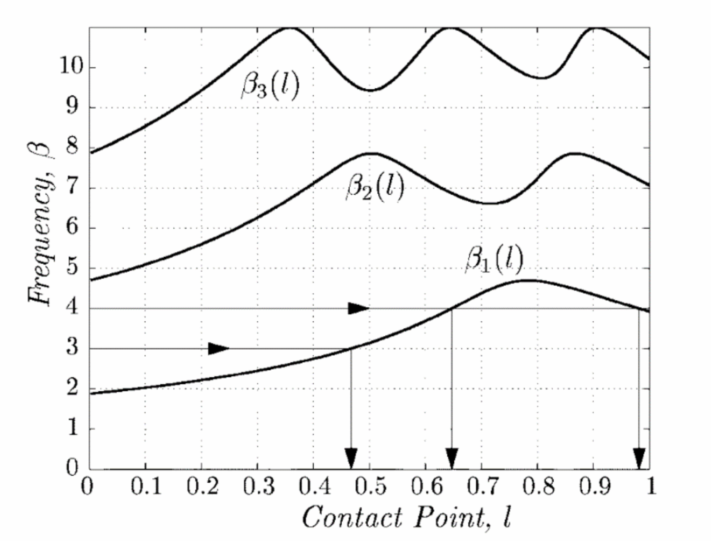
equation of motion: $\ddot{v}(x,t) + k^4 v''''(x,t) = 0$, with $k^4 := \frac{E\,I_Z}{\rho\,A}$

boundary and transition conditions:

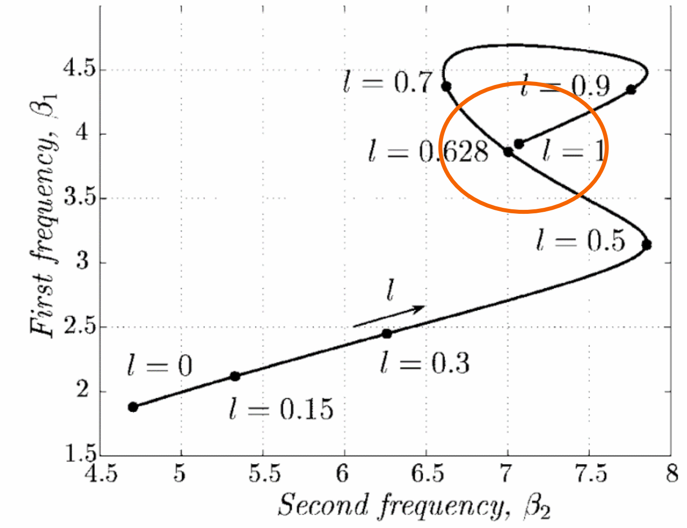
- $v_1(0,t) = 0$
- $v_1''(0,t) = 0$
- $v_1(l,t) = 0$
- $v_1(l,t) = 0$
- $v_1'(l,t) = v_2'(l,t)$
- $v_1''(l,t) = v_2''(l,t)$
- $v_2''(L,t) = 0$
- $v_2'''(L,t) = 0$

Part II: Vibrissae – 5. Modeling – Stage 5b - Distance

[Ueno et al. 1998]



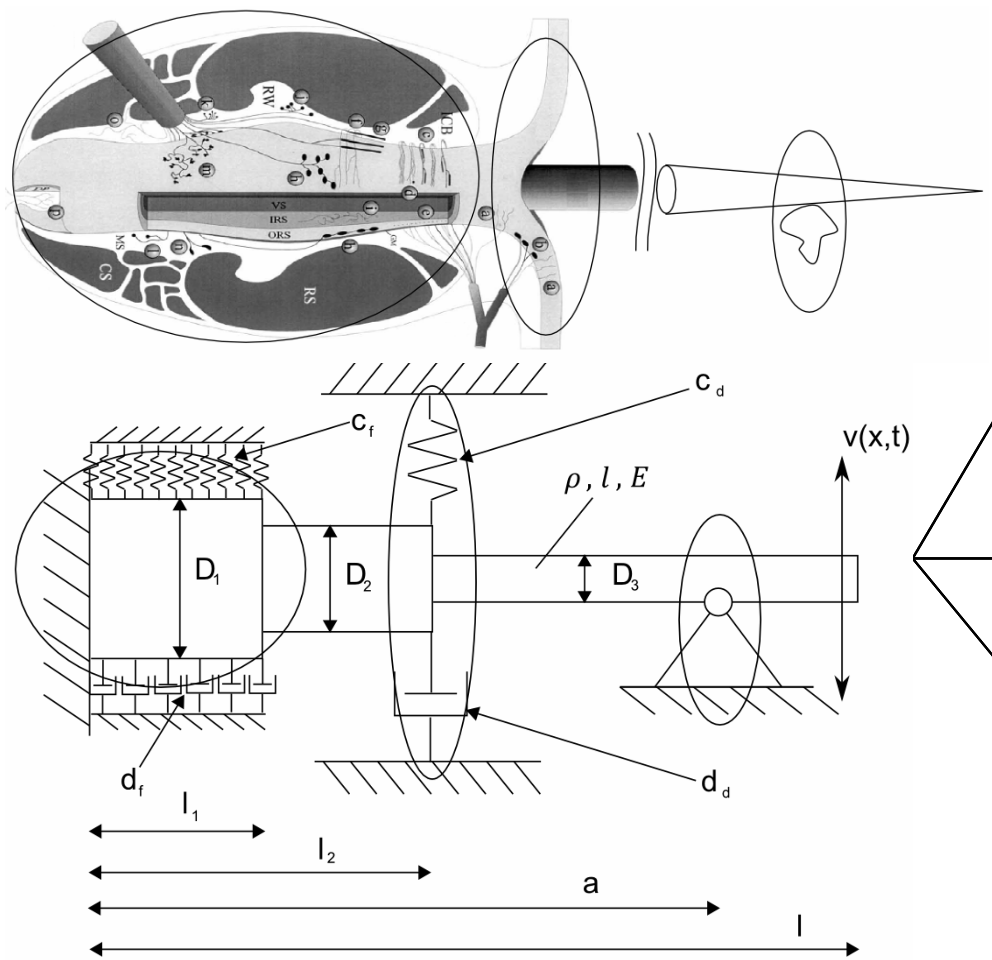
first three natural frequencies



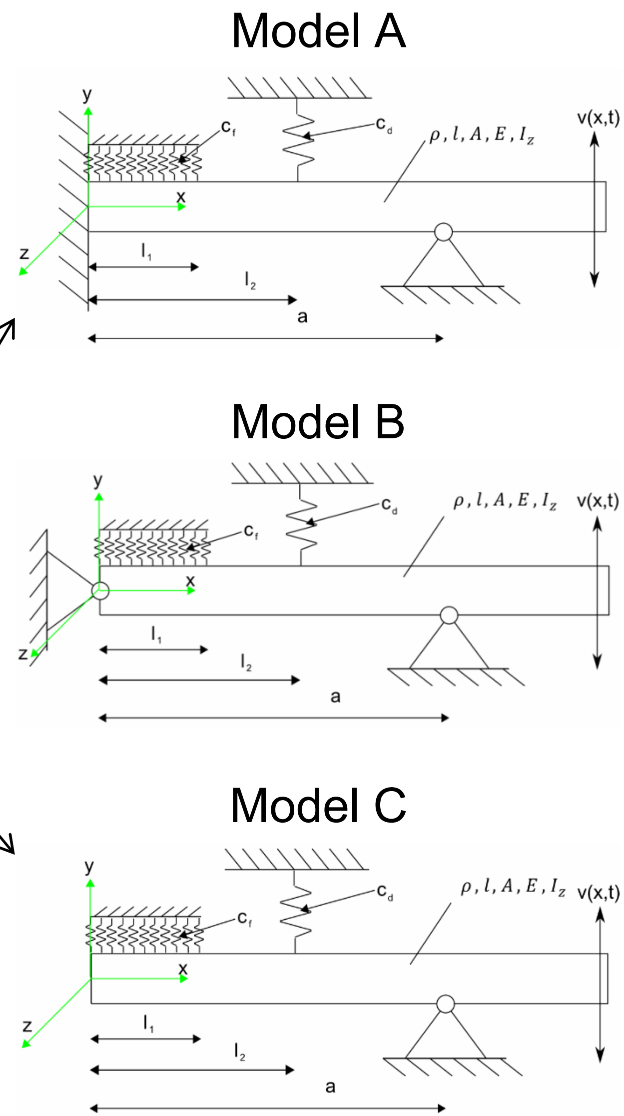
first vs. second natural frequency

- determination of the contact point with the first natural frequency is not possible
- determination of the contact point with the first two natural frequencies is quite hard

Modeling

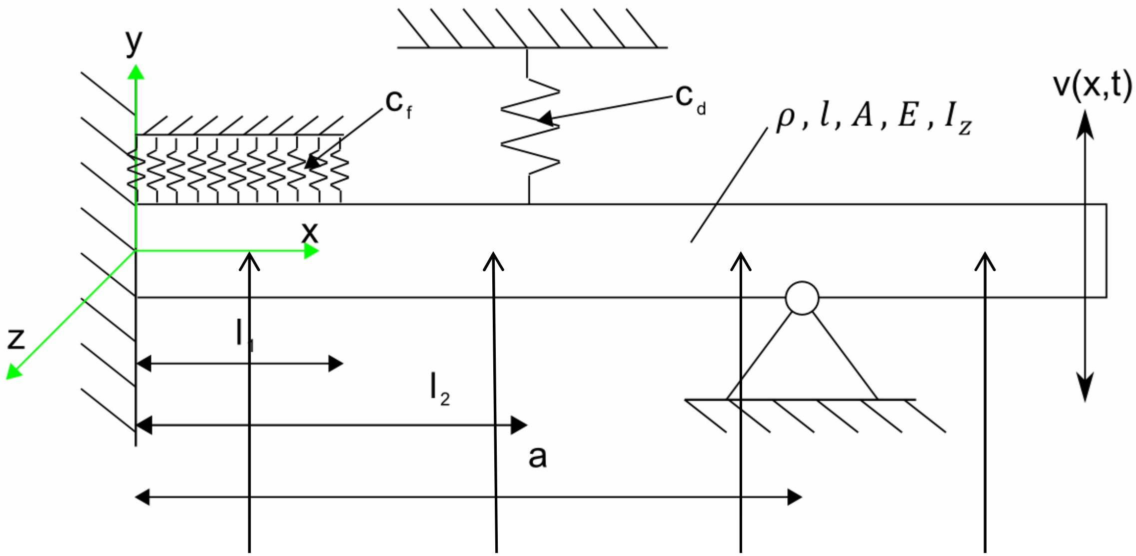


c d
c f
ρ, l, E
v(x,t)
D1
D2
D3
d f
d d
l1
l2
a
l



Model A
Model B
Model C
y
x
z
c f
c d
ρ, l, A, E, I z
v(x,t)
l1
l2
a

Investigations



$v_1(x,t)$, $x \in (0, l_1)$ $v_2(x,t)$, $x \in (l_1, l_2)$ $v_3(x,t)$, $x \in (l_2, a)$ $v_4(x,t)$, $x \in (a, l)$

$$\omega_1 = \omega_2 = \omega_3 = \omega_4$$

⇒ $\lambda_2 = \lambda_3 = \lambda_4$

⇒ $\lambda_2 = \sqrt[4]{\lambda_1^4 + \frac{c_f}{EI_z}}$

Only conservative systems due to problems presented before!

Part II: Vibrissae – 5. Modeling – Stage 5b - Distance

Conclusion from this stage:

- focus on dynamical analysis of vibrissa-like beams for obstacle distance detection
- development of several vibrissa-like beams which supports match better the real biological conditions
- idea: investigations of each eigenvalue spectrum
- development:
  - possibility to expand the eigenvalues curve with the discrete spring
  - determination of the contact point by means of two algorithms
- very first experiments show the effectiveness of the algorithms

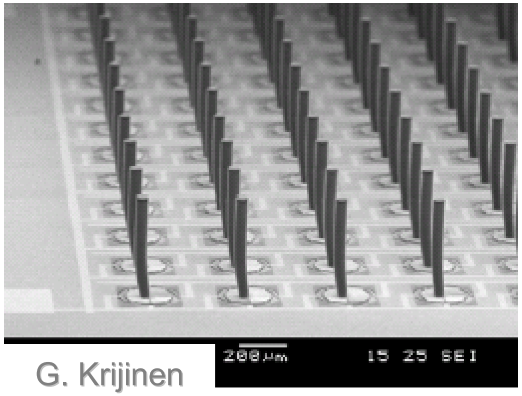
To be done:

- investigation of models with different cross-sections, pre-curvature, non-conservative
- improve experiments

Paradigms of tactile sensors for perception in applications:

- quality assurance (e.g., coordinate measuring machines)
- measurements of flow rates
- detection of packaged goods on conveyor belts

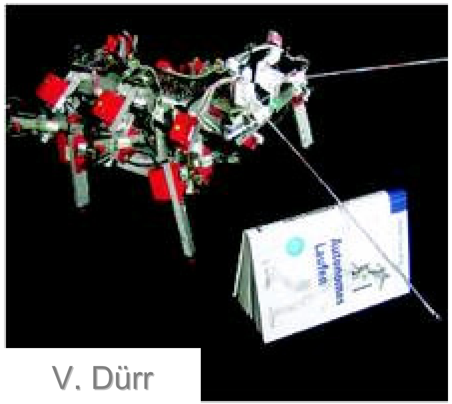
Microsystem Technology



G. Krijinen

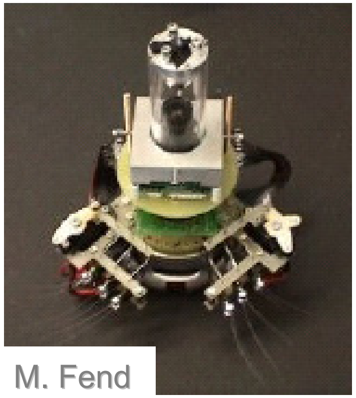
detection of flow rates

Robotics



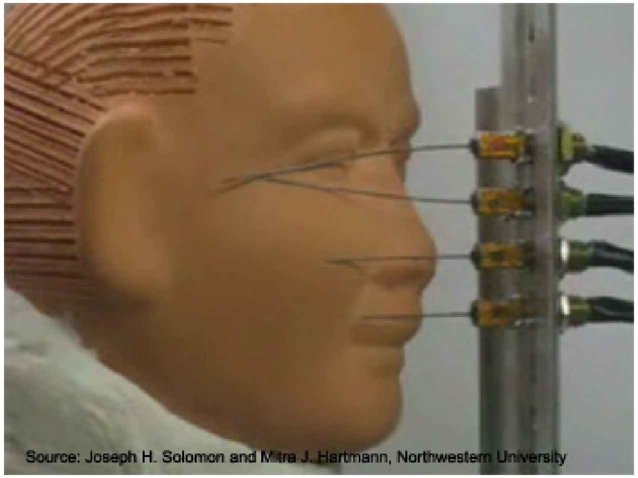
V. Dürr

object localization



M. Fend

detection of texture



Source: Joseph H. Solomon and Mitra J. Hartmann, Northwestern University

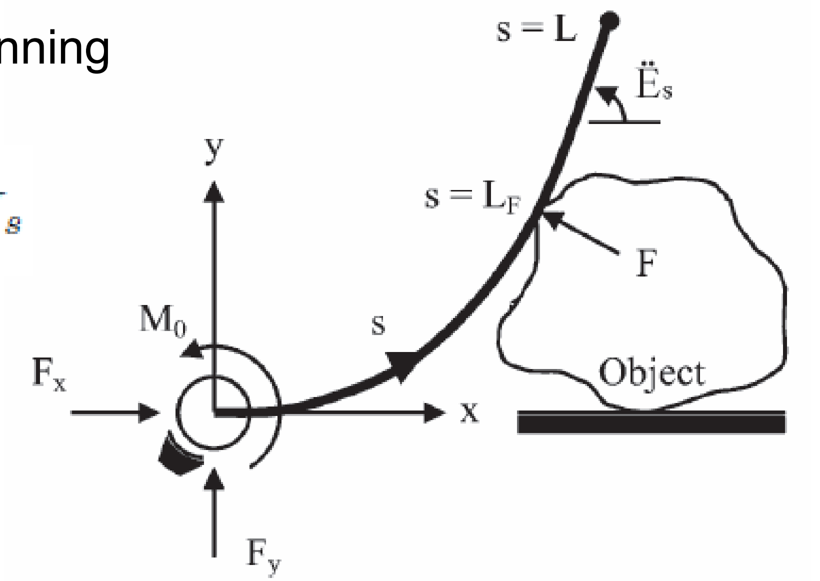
detection of contour

→ large deflection of beams in Bionics

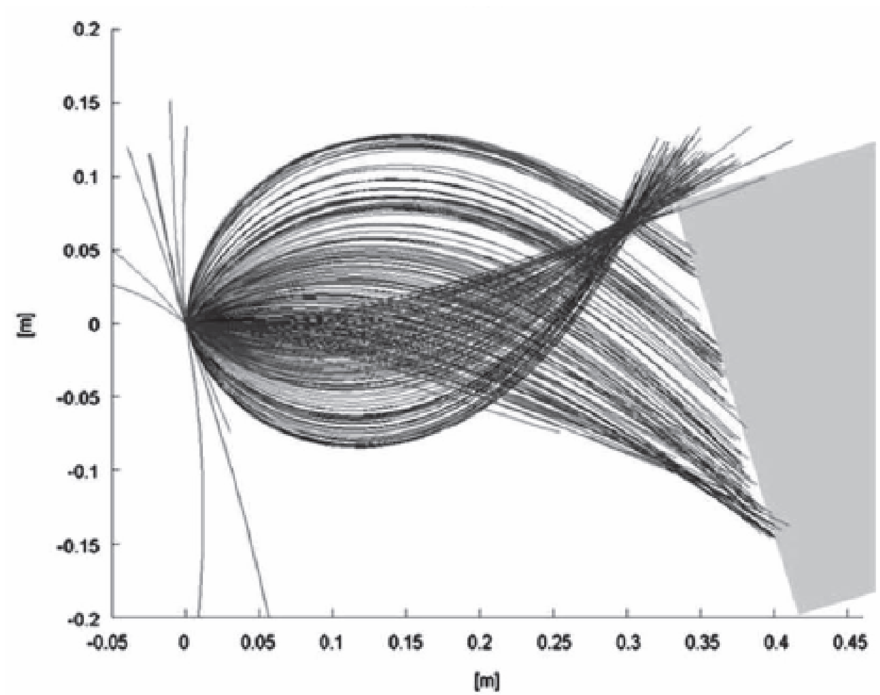
State of art

- most works focus on numerics from the beginning
  [Scholz, Rahn 2004]

$$\frac{dx}{ds} = \cos(\theta) \quad \frac{dy}{ds} = \sin(\theta) \quad E\,I_z\,\frac{d\theta}{ds} = M_s$$



$$M_s = \begin{cases} M_0 - F_y\,x + F_x\,y\,, & s \leqslant L_F\,, \\ 0\,, & s > L_F\,, \end{cases}$$



object fits in the field of computed vibrissae

Part II: Vibrissae – 5. Modeling – Stage 5c - Contour

State of art

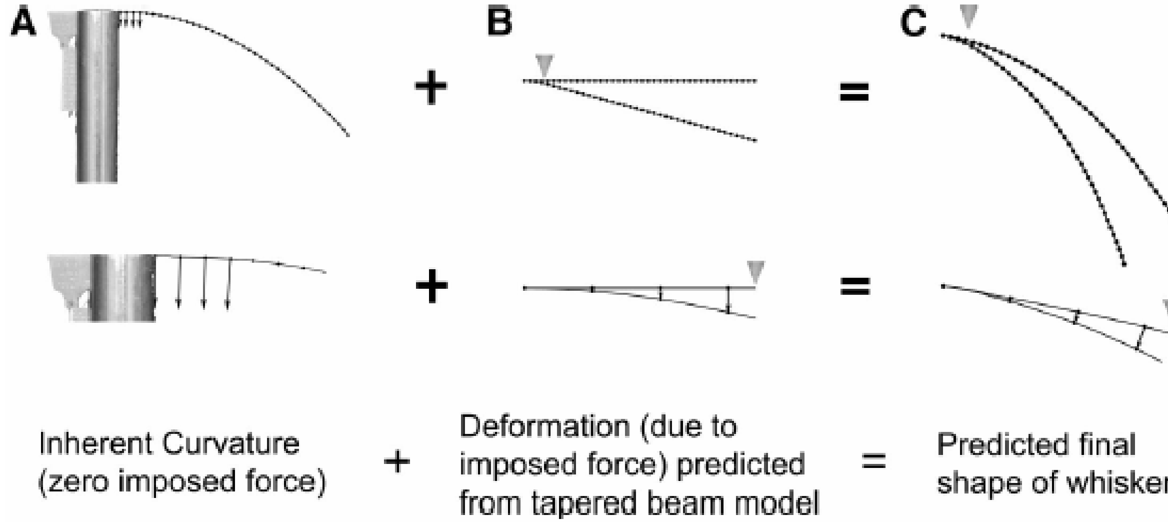
- BVP-solvers are used
  [Hires et al. 2013]

- linear theory is used
  [Birdwell et al. 2007]

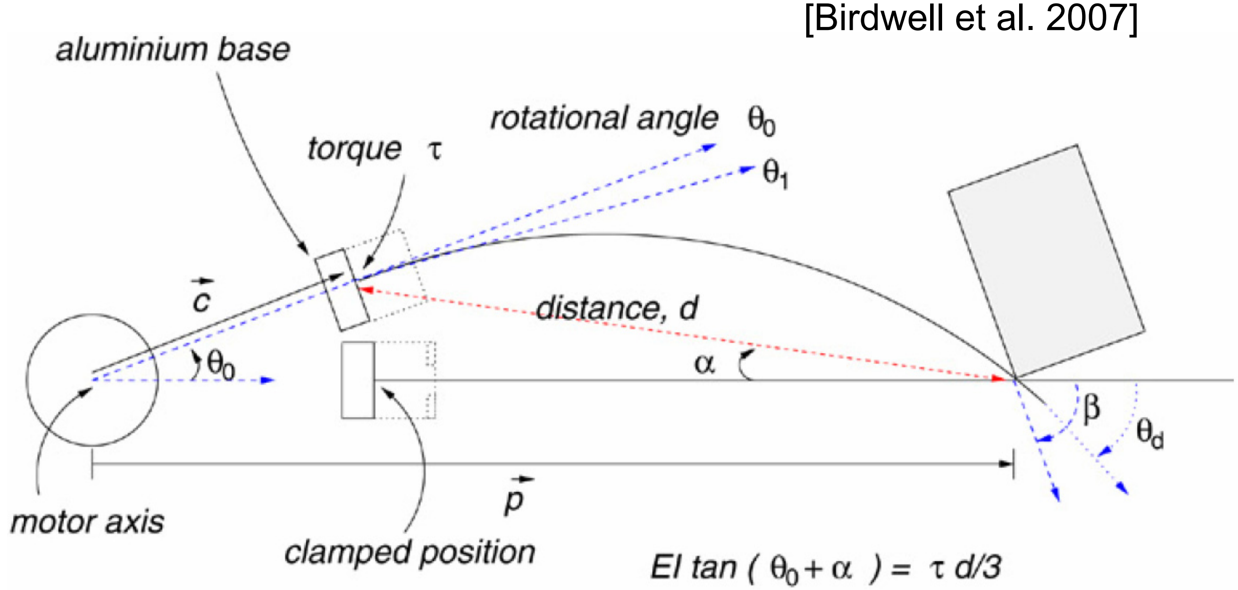
- rigid body systems are used as an approximation
  [Quist, Hartmann 2012]

- also finite differences
  [Pammer et al. 2013]
  and others are used
  [Kim, Möller 2007]

- no analytical treatment, skipping beam theories at early stages

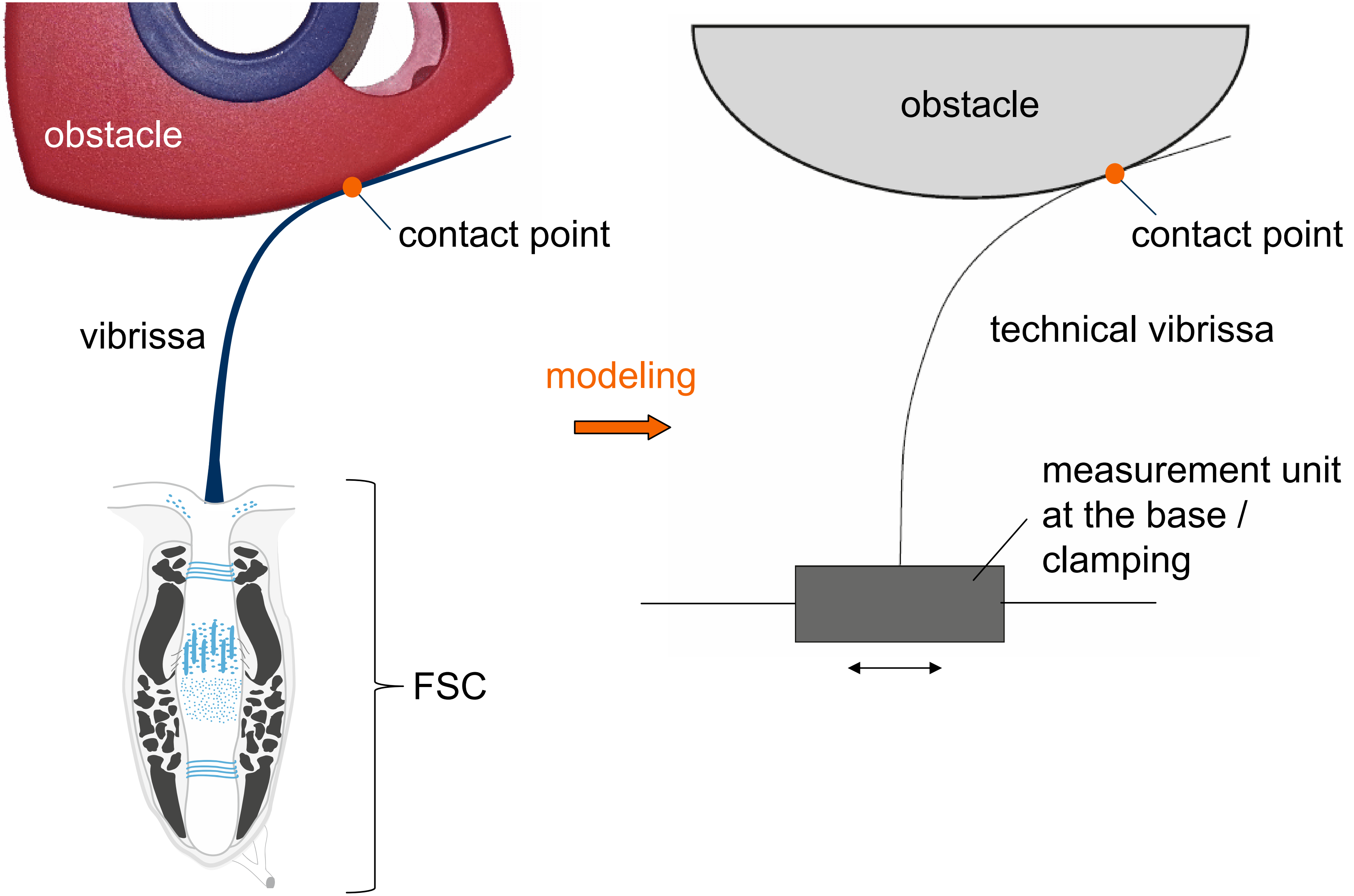


[Birdwell et al. 2007]



[Kim, Möller 2007]

Part II: Vibrissae – 5. Modeling – Stage 5c - Contour

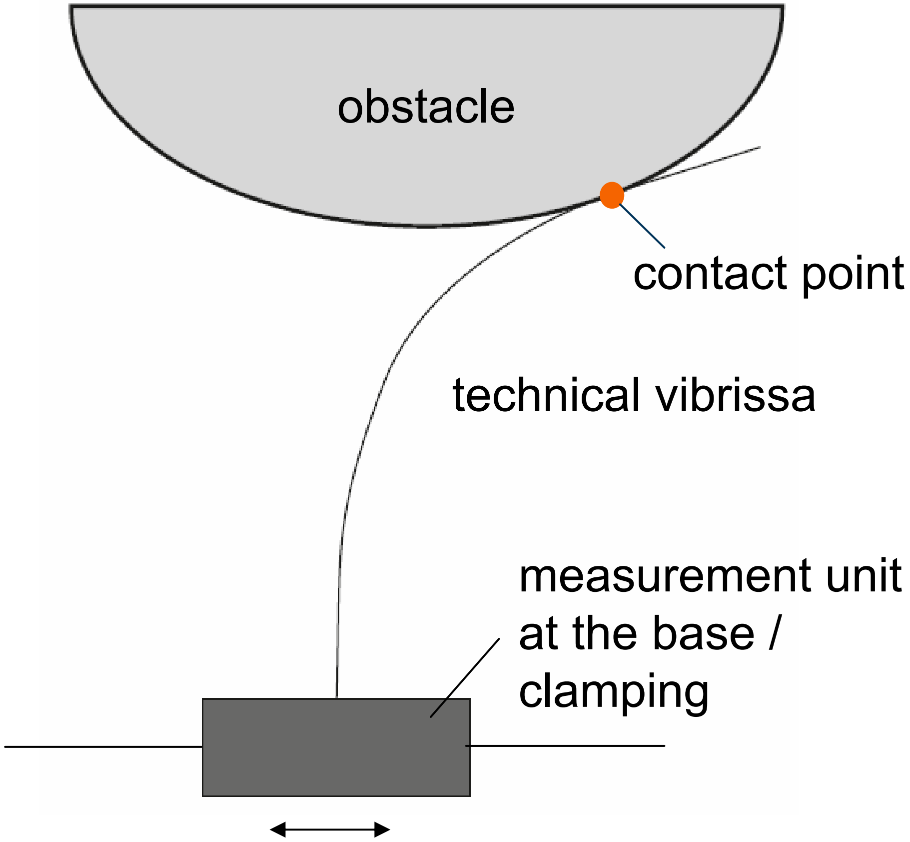


Assumptions on Contour:

•smooth, strictly convex
•ideal contact, i.e., contact force perpendicular to profile contour
•no friction taken into account

Assumptions on Vibrissa:

•straight beam (no pre-curvature)
•constant 2nd moment of area
•constant Young's modulus *E*
•Hooke's law of linear elasticity
•ignoring shear stress
•Euler-Bernoulli theory for large deflections
•support at base: clamping



Conclusions from this stage:

-analytical treatment of large deflections of beams

-generation of observables possible for strictly convex surfaces

-sweep has to be divided into two phases

-new insights:

- decision criterion for actual phase, decreases computations
- contact point computation
- no approximation of the problem
- profile contour reconstruction possible with one sweep

-reconstruction with previously computed observables: error within 10^{-6}

To be done:

- verification by an experiment
- include pre-curvature, conicity of the beam

} Presentation on Monday

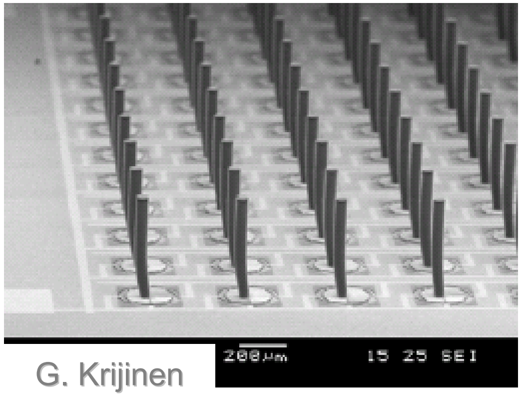
Session: Intelli 1

Part II: Vibrissae – 5. Modeling – Stage 5d - Texture

Paradigms of tactile sensors for perception in applications:

- quality assurance (e.g., coordinate measuring machines)
- measurements of flow rates
- detection of packaged goods on conveyor belts

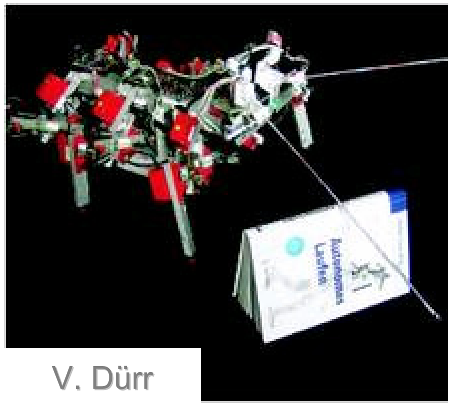
Microsystem Technology



G. Krijinen

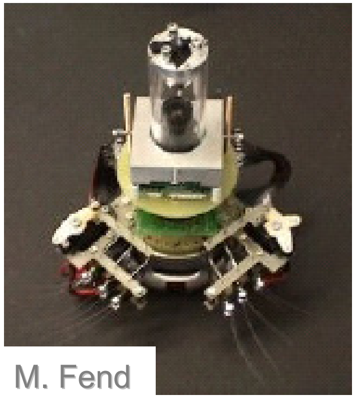
detection of flow rates

Robotics



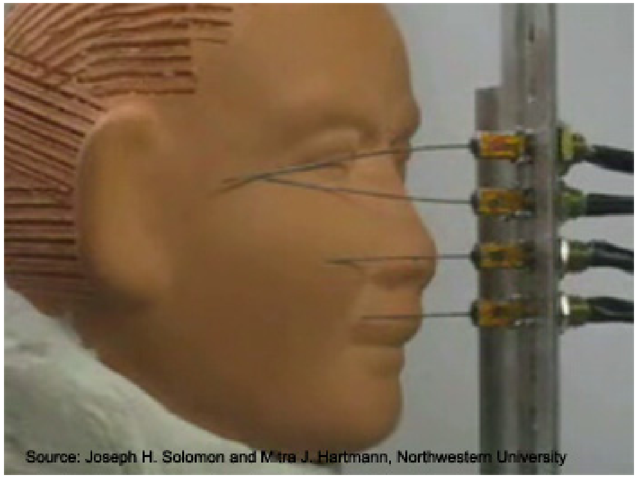
V. Dürr

object localization



M. Fend

detection of texture



detection of contour

→ Presentation on Monday – Sesssion: Intelli 2

Overall conclusions