THRUST MEASUREMENT FOR FLAPPING-FLIGHT COMPONENTS

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ANIPROP GbR, Göttingen

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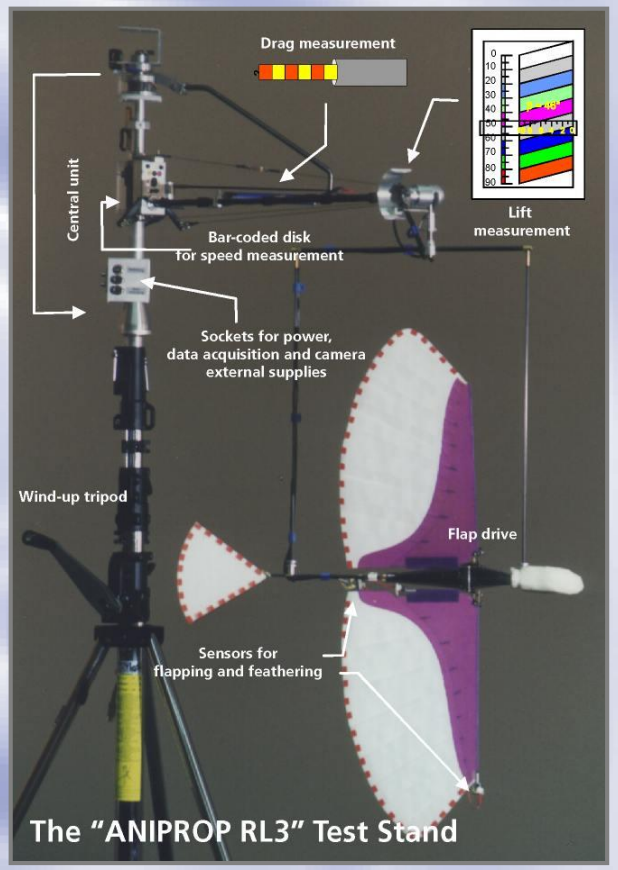

The "ANIPROP RL3" Test Stand

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** Freelance precision mechanic, Berlin, Germany.

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Overview

- **Introduction …….**
  - Concept of the test stand ANIPROP RL3
  - Features
- **Operating the Apparatus ….**
  - Data acquisition
  - Obtaining velocity, lift and drag
- **Efficiency of Animal Flight ..**
  - Key issue: Passive and active torsion
  - Overall efficiency
  - Measurement of electromechanical efficiency
- **Thrust Measurement …….**
  - Two modes: “Tethered” and “free”
  - Typical measurement “tethered” mode
  - Theoretical approach to the “free” mode
- **Summary and Outlook ……..**
  - The technical perspective of our research
  - Current state-of-the-art

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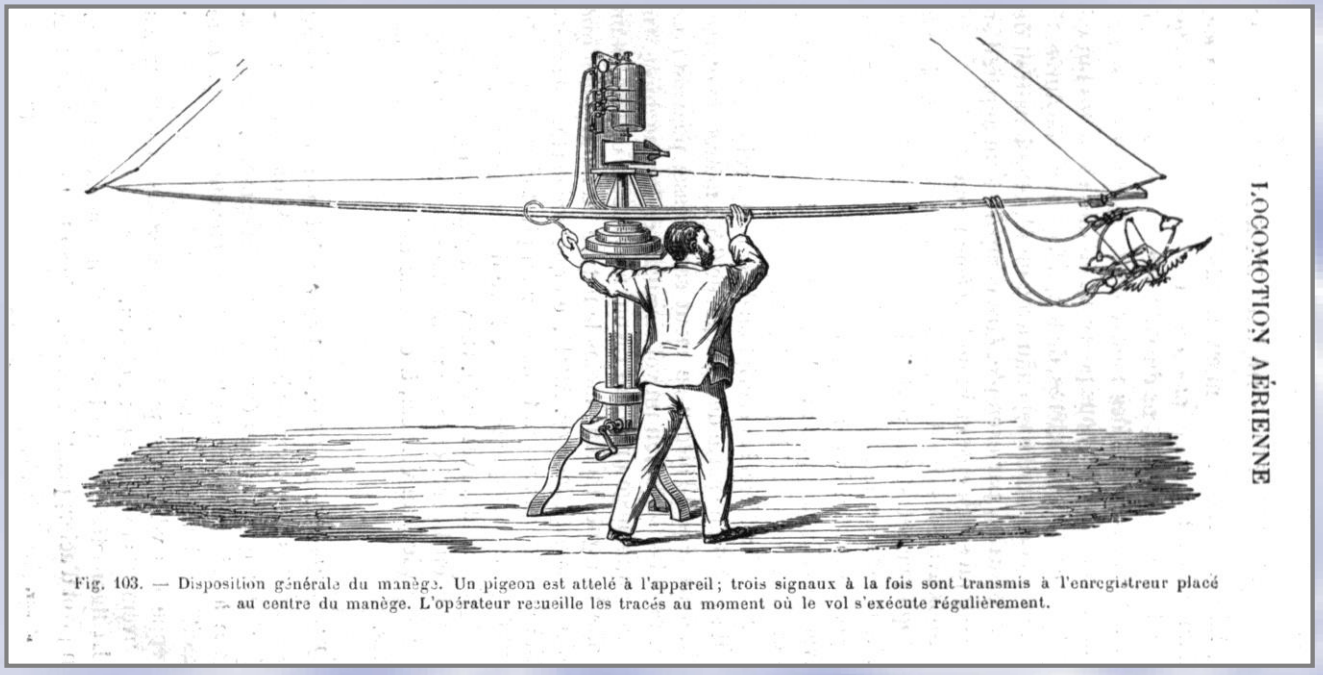
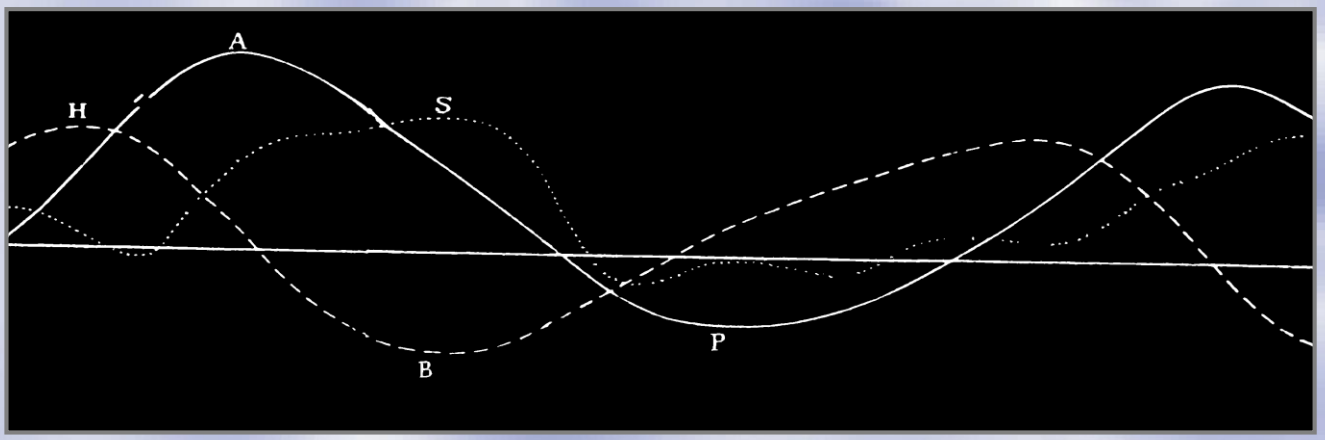


Fig. 103. — Disposition générale du manège. Un pigeon est attelé à l'appareil; trois signaux à la fois sont transmis à l'enregistreur placé au centre du manège. L'opérateur recueille les tracés au moment où le vol s'exécute régulièrement.



Top: Étienne-Jules Marey,
***Le Vol des Oiseaux*,**
Éd. G. Masson, Paris 1890.
French Physiologist (1830-1904) in Paris. Developed the Chrono-photography for moving events and also did basic research on animal flight.

Bottom: Étienne-Jules Marey,
La Machine Animale
Éd. F. Alcan, Paris 1891.
Fig. 110 showing three degrees of motion (from left to right): Flapping (HB[1]), Feathering (S[2]) and Lagging (AP[3]), measured against a buzzard. The traces of the needles from the pressure sensors on soot-covered cylindrical recorders are an important historic document.

1 Mouvement de haut en bas
2 Torsion de l'articulation scapulo-humérale
3 Avant et arrière (le bord postérieur est relevé)

Predecessor: Étienne-Jules Marey

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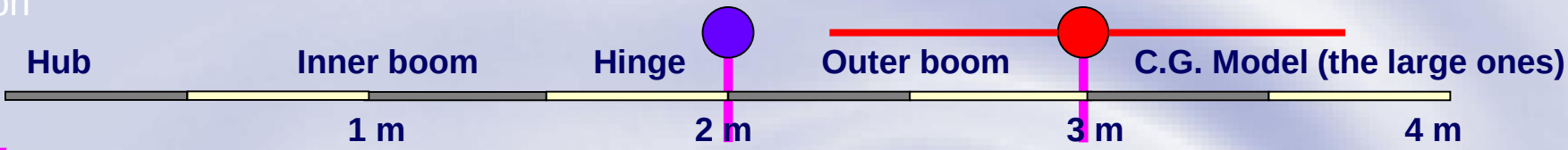

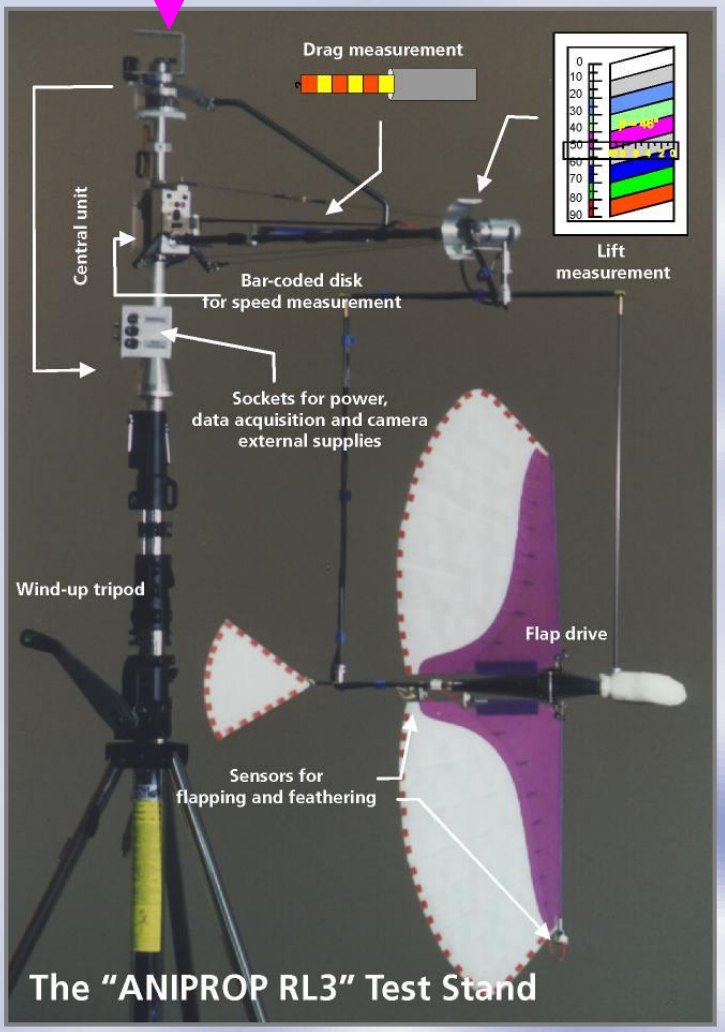

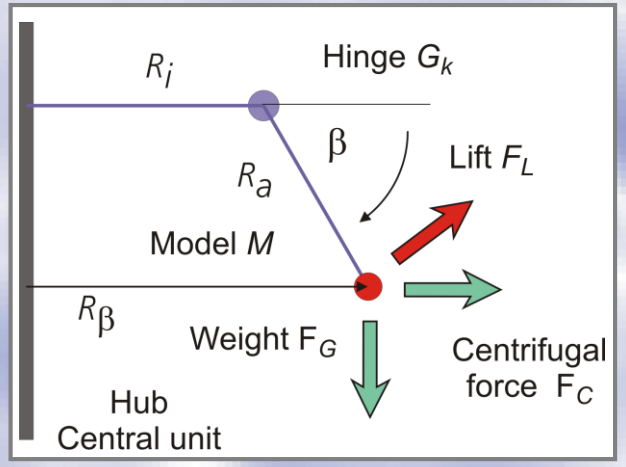

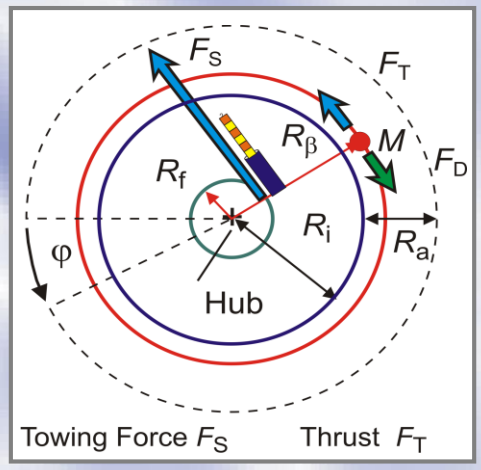

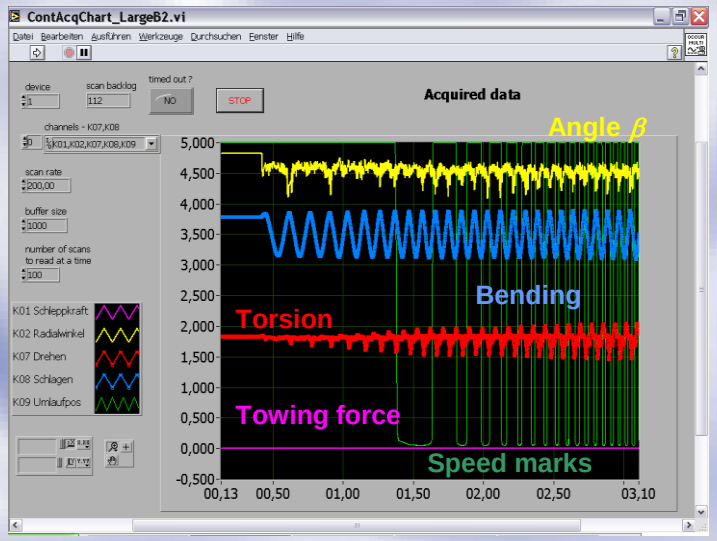

The rotating boom of the test stand consists of two rods, which are connected to each other by a hinge named *joint-head* G_k with one degree of freedom. The *inner boom* R_i remains horizontal during the motion, the *outer boom* R_a is in a vertical position for the boom at rest.

Apparatus by Felix Scharstein and Wolfgang Send

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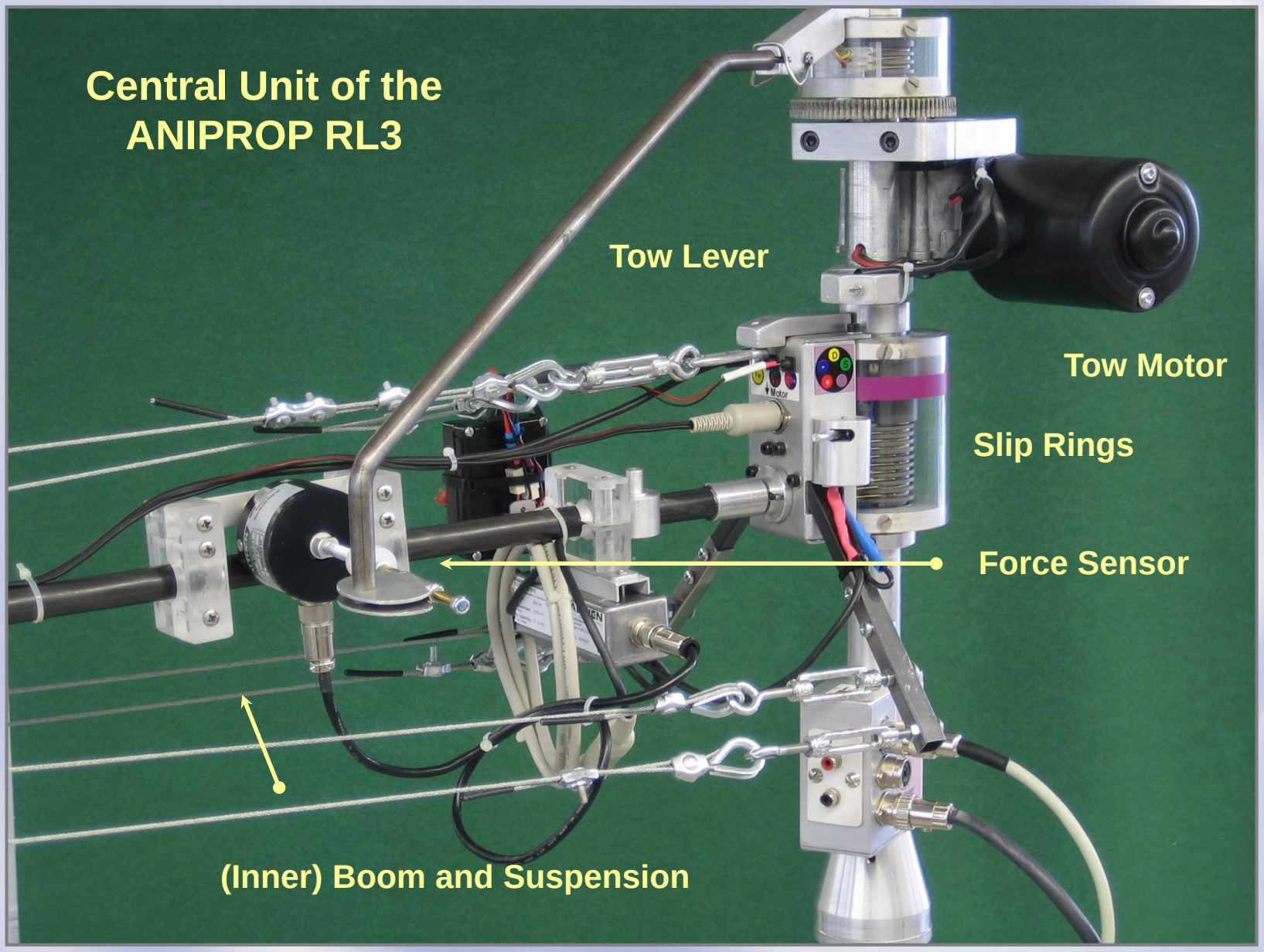

0.6 m

0.4 m

0.2 m

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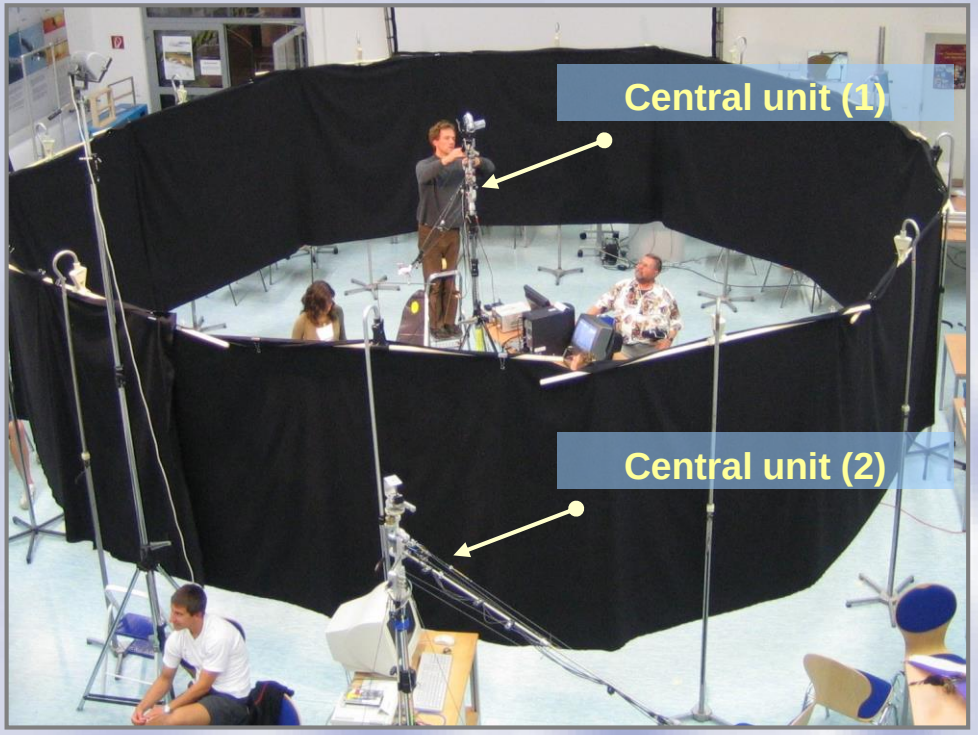
Player C: Player D:



A unique view: Two RL3 test stands at the same time in use.

The black curtain, forming the "theatre", surrounds the RL3 for observations in the comoving frame.

The movie gives an impression of the outstanding performance of K. Saupe's artificial bird.

Nevertheless: Passive torsion only results in a flapping frequency by far too high in comparison to real birds.

At the DLR_School_Lab in Göttingen

XLAB International Science Camp 2005

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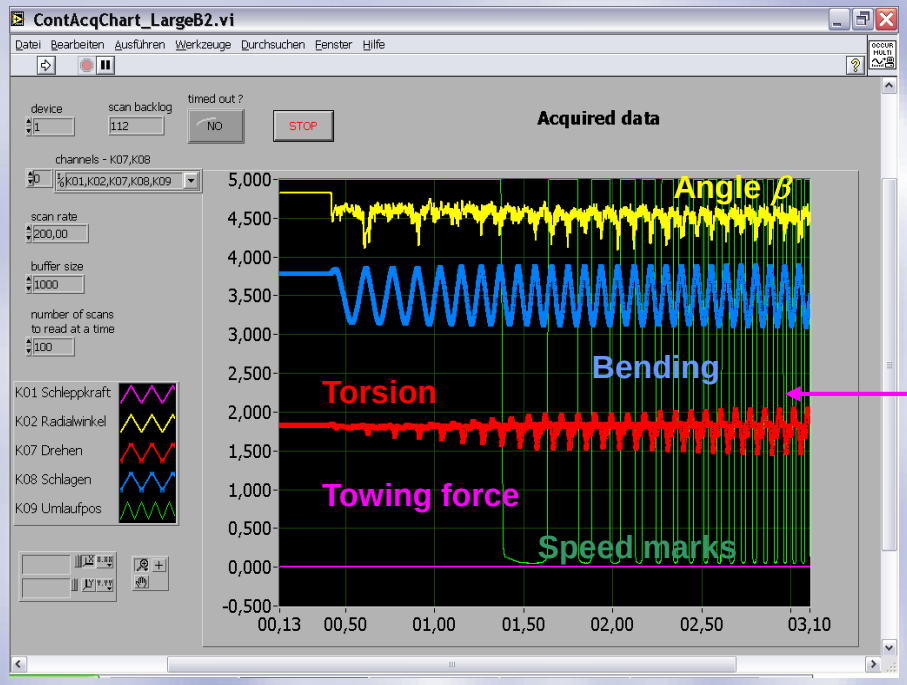
1	Towing force
2	Centrifugal angle
3	Voltage tow motor
4	Voltage flapping device
5	Current tow motor
6	Current flapping device
7	Pitch angle (feathering)
8	Plunge angle (flapping)
9	Speed marks
10	Position marks



- **Velocity**

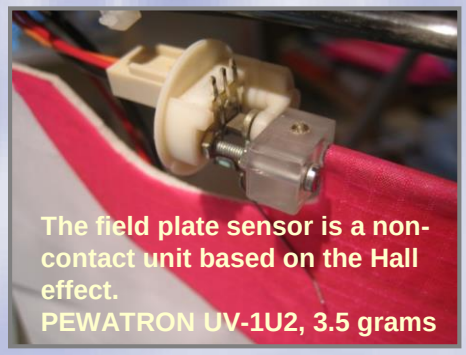
An A/D card converts the signals for digital processing in a computer.

<u>Speed marks</u> are sent 180 times per revolution, i.e. every 2 degrees.

The position mark is sent once per revolution.

One "species" among our artificial birds is equipped with sensors for the flapping angle and for the wing torsion measured at the wing tip .

The signals reveal the effect of the required structural softness of the wings: The air cushion caused by the plunging motion twists the wing after a few periods which then leads to more and more thrust.



The field plate sensor is a non-contact unit based on the Hall effect.
PEWATRON UV-1U2, 3.5 grams

Data Acquisition and Evaluation

Velocity, Pitch Angle and Plunge Angle

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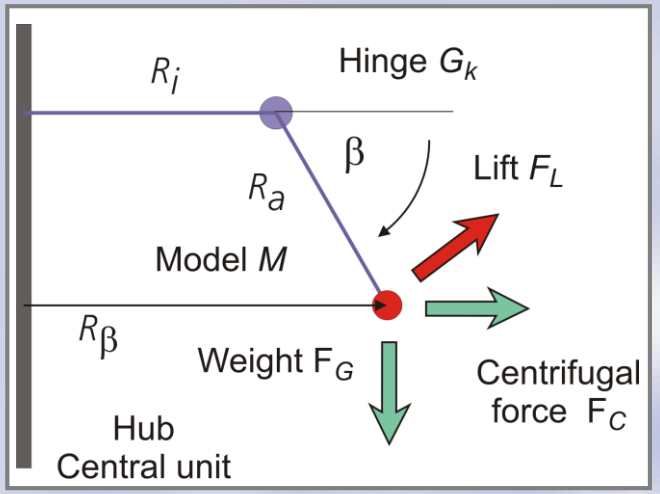


$$R_\beta = R_i + R_a \cdot \cos\beta$$

$$F_L = M \cdot \cos\beta \cdot \left[g - \omega^2 \cdot R_\beta \cdot \tan\beta\right]$$

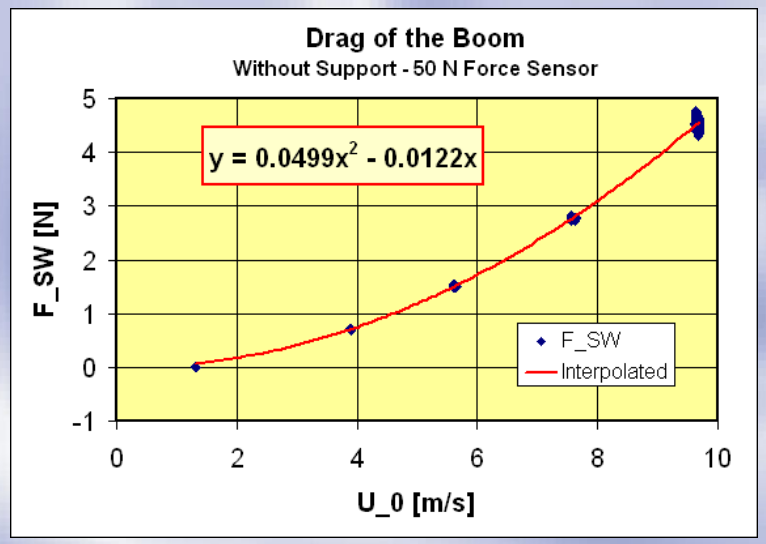
- **Lift**

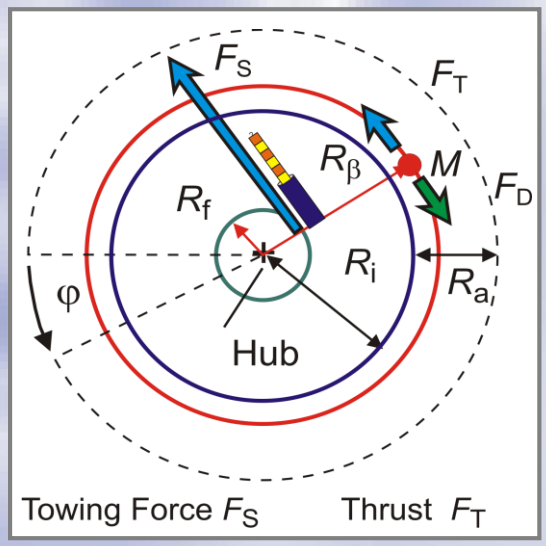
The presence of a lift force "disturbs" the relation for the circular motion [in square brackets], $\omega = 2\pi / T$. T time for one revolution of the boom, $\omega = 2\pi\, d\varphi / dt$ respectively.

- **Drag**

The measured force has to be corrected by the drag of the boom.

$$F_D = (R_f / R_\beta) \cdot F_S$$





Data Acquisition and Evaluation

Lift and Drag

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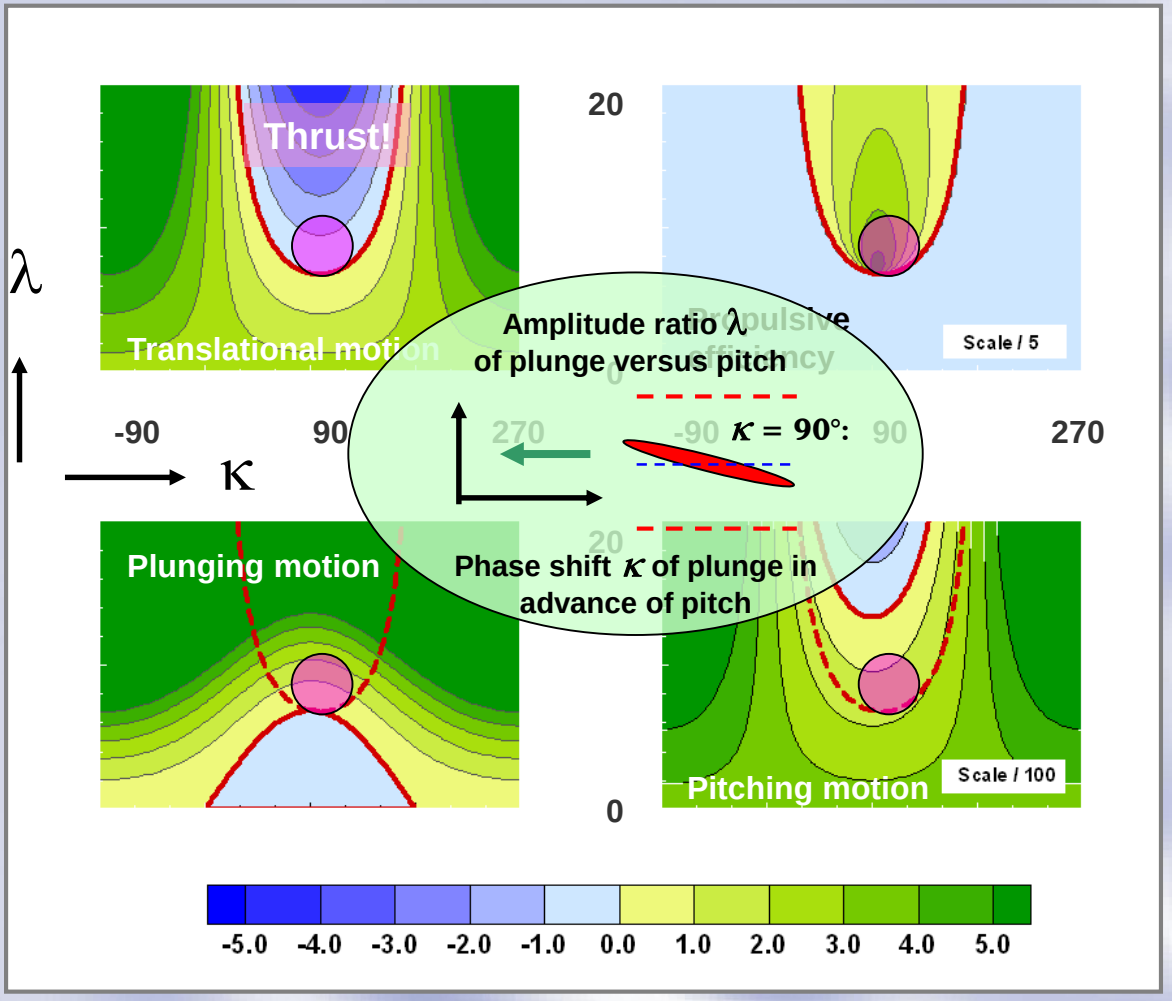

Mean power coefficients for three degrees of freedom

- **Translational motion**
- **Plunging motion**
- **Pitching motion**

Propulsive efficiency:

$$\eta_T = \frac{thrust\ \ power\ \ gained}{power\ \ pitch + plunge}$$

Active pitch results in high efficiency

Favourable working point

Note: For power calculation normal forces only; no thrust for pure plunging motion assumed.

Basic mechanism in 2D motion

Solution dates back to H.G. Küssner (1935) and Th. Theordorsen (1936).

W. Send, *The Mean Power of Forces and Moments in Unsteady Aerodynamics*, ZAMM **72** (1992), 113-132

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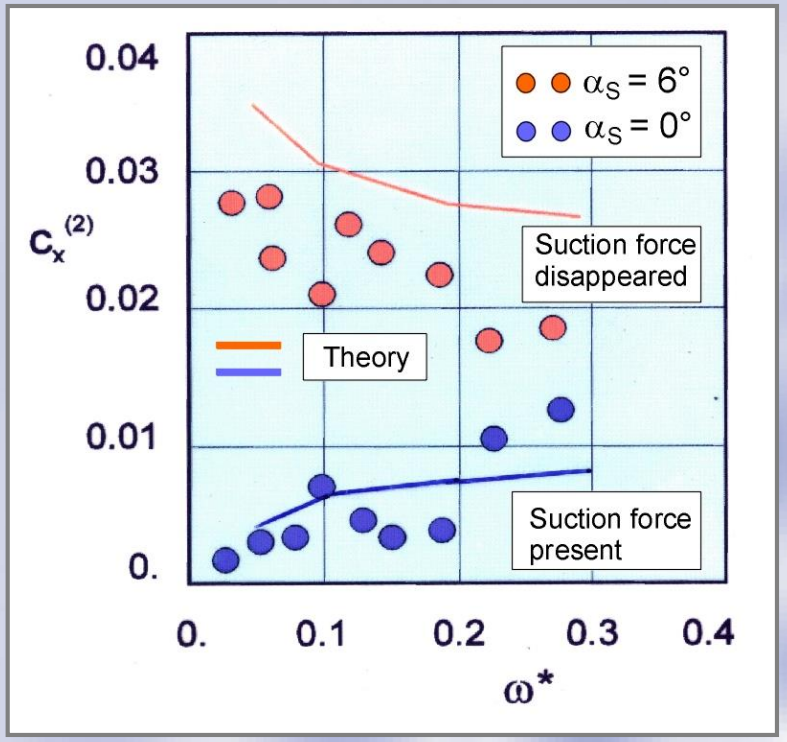

Data selected from Windsor's results*. Negative suction force reduces the mean drag, if it is present. Theory includes (blue line) or ignores (red line) this second order term (NACA0012).

- **Flat plate theory**
  Unsteady mean drag coefficient $c_x^{(2)}$

.. After testing the ship a few times in gliding, Hans Werner [Krause] tried the first flapping-wing flights. The result was quite disappointing, since we could not see any improvement of the glide angle. At least the effect was so small that the measured Katzmayr effect did not show up, and the twisting of the wings, even with this light construction, did not occur. At first we did not know what to do next.
To find out how to improve things I made some tests with a model wing, and I clearly observed that a stiff wing in flapping motion did not produce any forward thrust. I then remembered that some of the stories from early years told about a flexible trailing edge. I therefore enlarged the outer portion of the wing by the addition of a flexible (single bamboo sticks) Zanonia-like rear surface as shown in the sketch. The piece was not very large but what a difference in propulsive action was caused by this change! …

Lippisch A M. Man Powered Flight in 1929, *Journal of the Royal Aeronautical Society*, Vol. 64 (July 1960), 395-398.

No Propulsion by a Pure Plunging Motion? – A Potential Answer

Still a very controversial issue among aerodynamicists.

* Windsor R I. *Measurement of Aerodynamic Forces on an Oscillating Airfoil.*
US Army Aviation Materiel Laboratories Fort Eustis VA,USAAVLABS Technical Report 69-98, 1970.

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- **Overall or total efficiency**

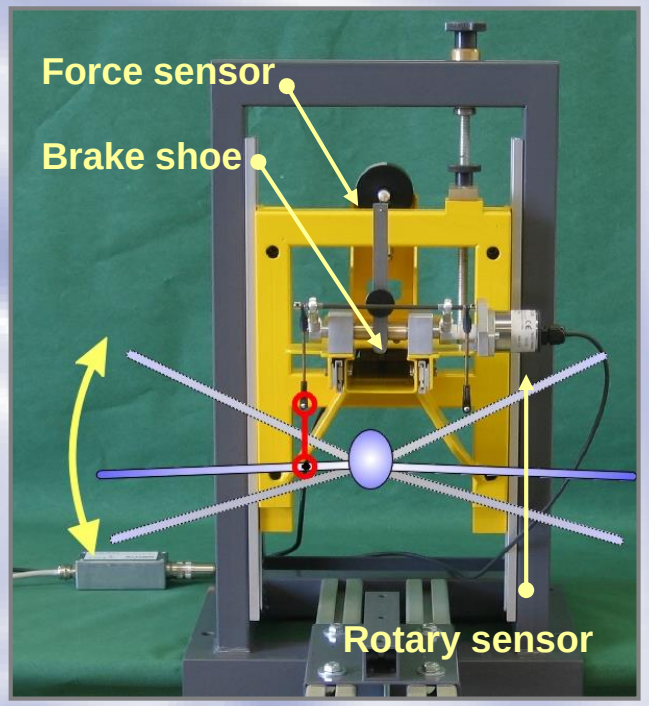
$$\eta_{total} = \frac{gained\ thrust\ power}{supplied\ electric\ power}$$

- **Aerodynamic or propulsive efficiency**

$$\eta_{aero} = \frac{gained\ thrust\ power}{supplied\ mechanical\ power}$$

- **Electromechanical efficiency**

$$\boxed{\eta_{mech} = \frac{availabe\ mechanical\ power}{supplied\ electric\ power}}$$



Prony brake **for the measurement of electromechanical efficiency of flapping-flight components - sketch of the wing motion.**

<u>Note:</u> The verification of aerodynamic efficiency critically depends on the proper determination of the electro-mechanical efficiency.

$$\eta_{aero} = \frac{\eta_{total}}{\eta_{mech}}$$

Electromechanical Efficiency

A prerequisite for determining the aerodynamic efficiency of artificial birds.

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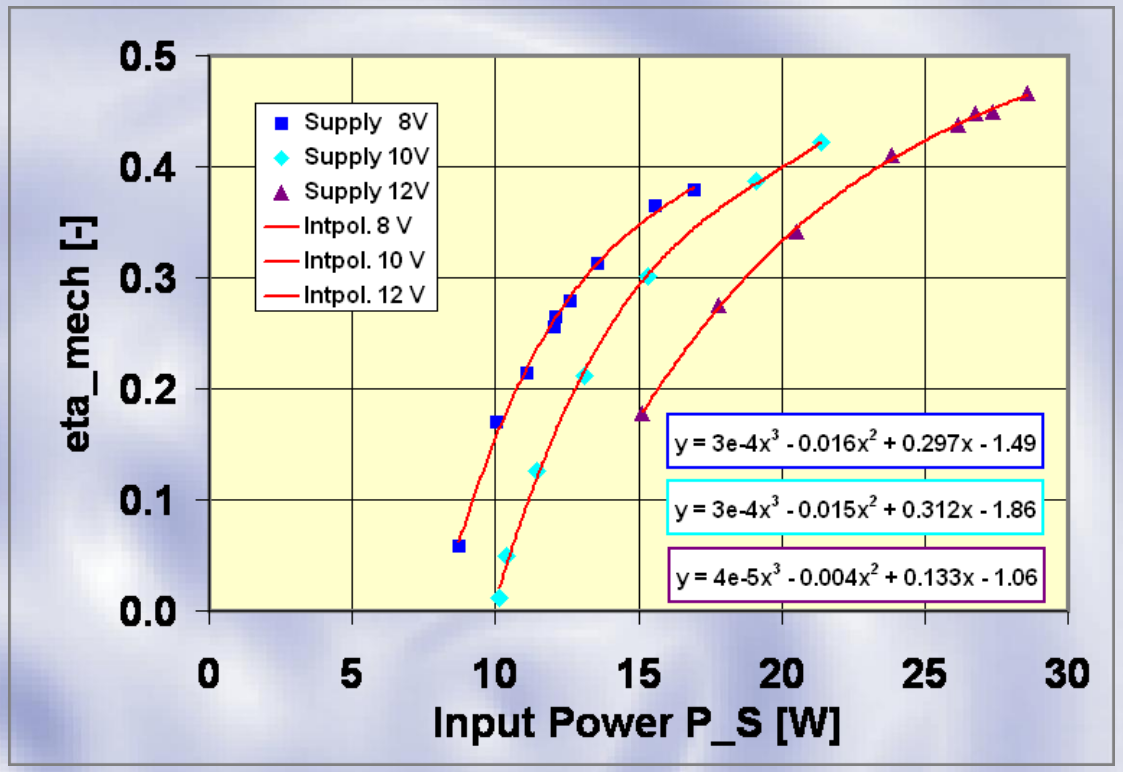
- **Electromechanical efficiency**

Typical result from the measurement of electromechanical efficiency using the *Prony brake.*

The engine map for the electric drive shows a complex behaviour. The charts have to be implemented into the programme which evaluates aerodynamic efficiency.



$$\eta_{total} = \eta_{aero} \cdot \eta_{mech}$$

$$\eta_{aero} = \frac{\eta_{total}}{\eta_{mech}}$$

$$\eta_{mech} = \frac{availabe\ \ mechanical\ \ power}{supplied\ \ electric\ \ power}$$

Electromechanical Efficiency

A prerequisite for determining the aerodynamic efficiency of artificial birds.

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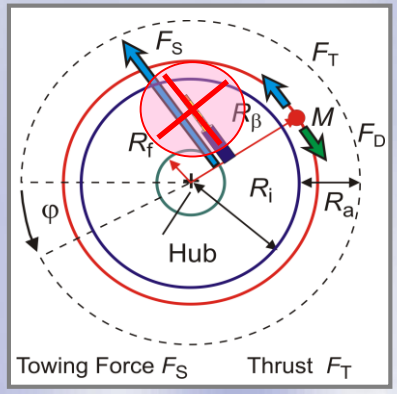
- **Mode 1: The "tethered" mode**

  The tethered mode uses the force sensor which tows the whole boom including the model.

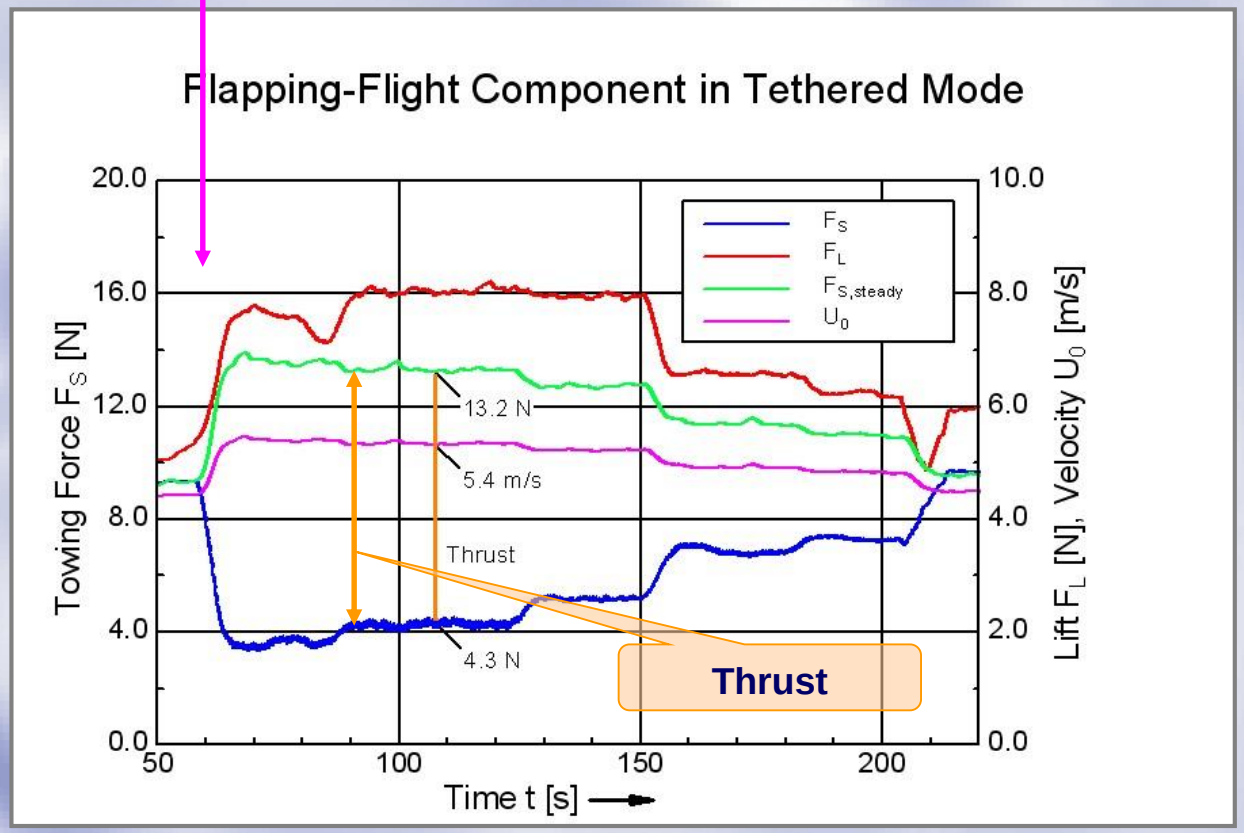
  Thrust easily is determined from the force measurement.



- **Mode 2: The "free" mode**

  The towing lever is removed. The model starts from the position at rest.

Thrust is turned on, then stepwise reduced.



Two Modes for Thrust Measurements

<u>Mode 1: The tethered mode</u> - Mode 2: The free mode

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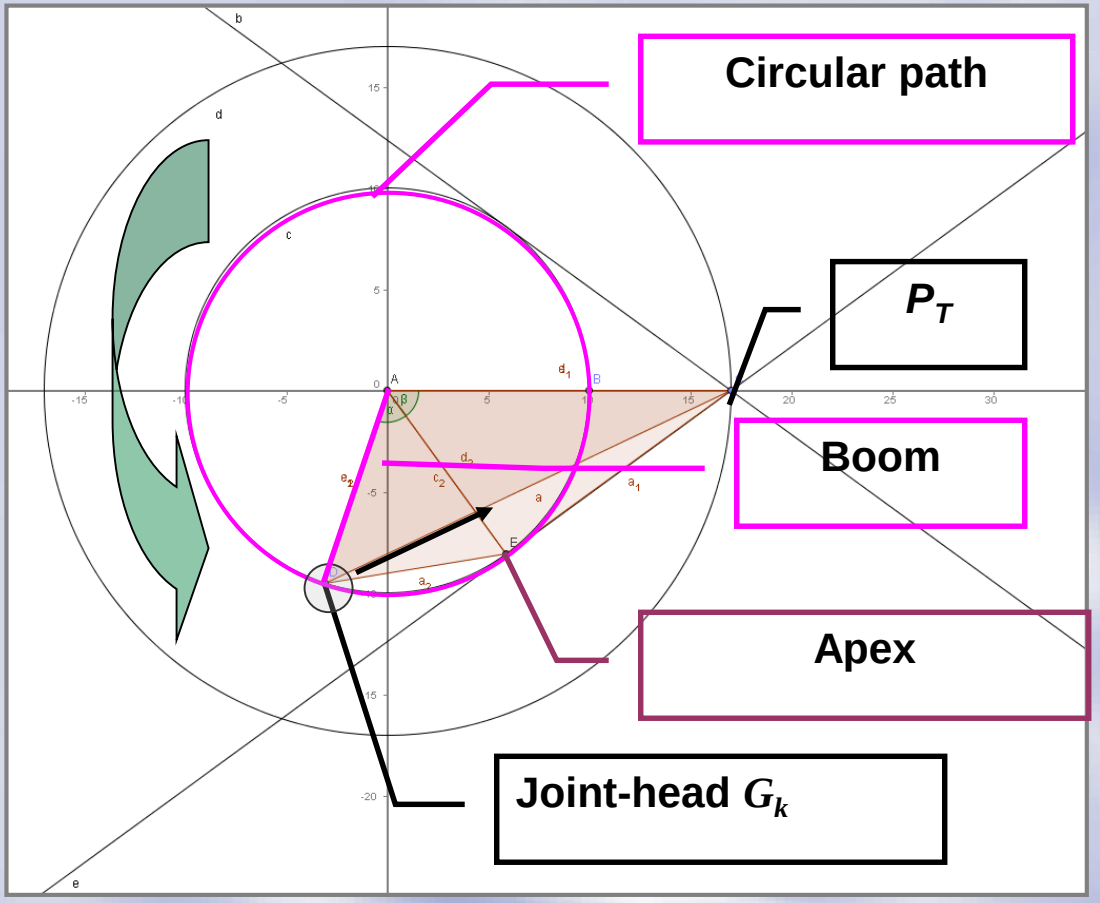
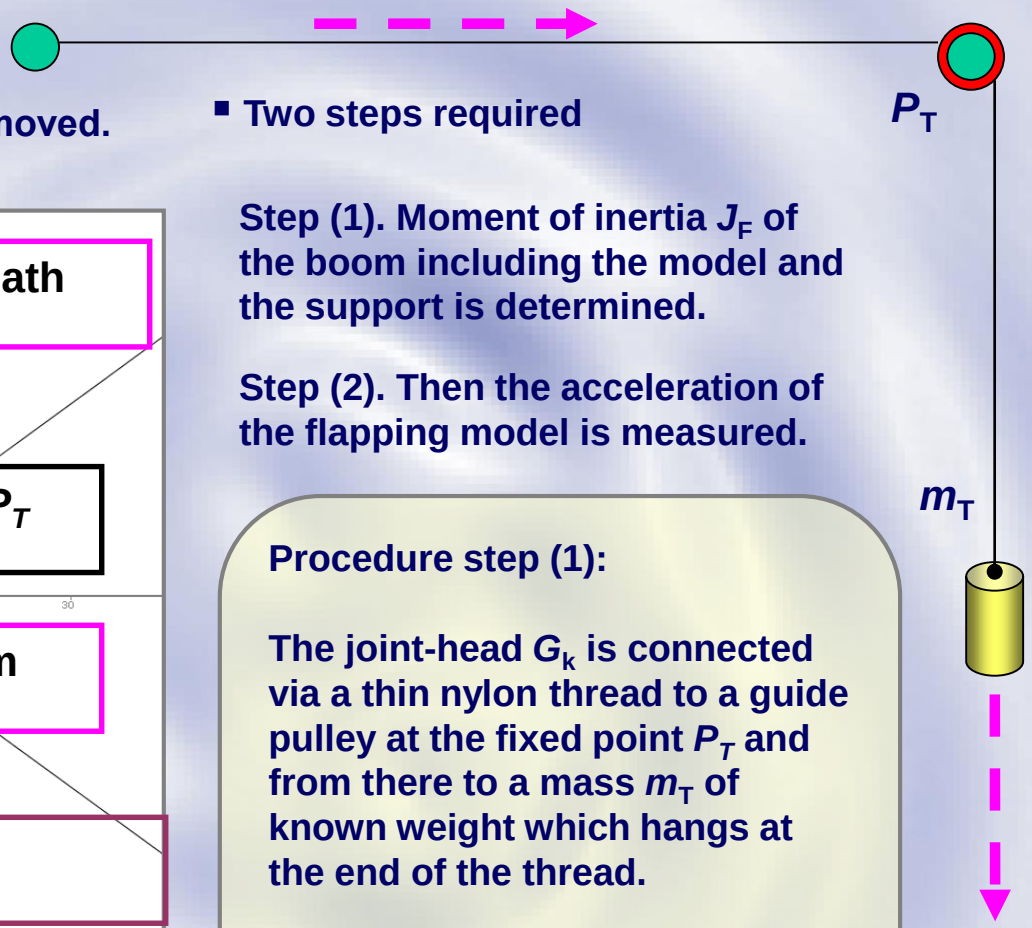
- **Mode 2: The "free" mode. The towing lever is removed. The model starts from the position at rest.**





- **Two steps required**

Step (1). Moment of inertia J_F of the boom including the model and the support is determined.

Step (2). Then the acceleration of the flapping model is measured.

Procedure step (1):

The joint-head G_k is connected via a thin nylon thread to a guide pulley at the fixed point P_T and from there to a mass m_T of known weight which hangs at the end of the thread.

Then, the joint-head G_k is released and the boom with all parts is accelerated.

Two Modes for Thrust Measurements

Mode 1: The tethered mode - <u>Mode 2: The free mode</u>

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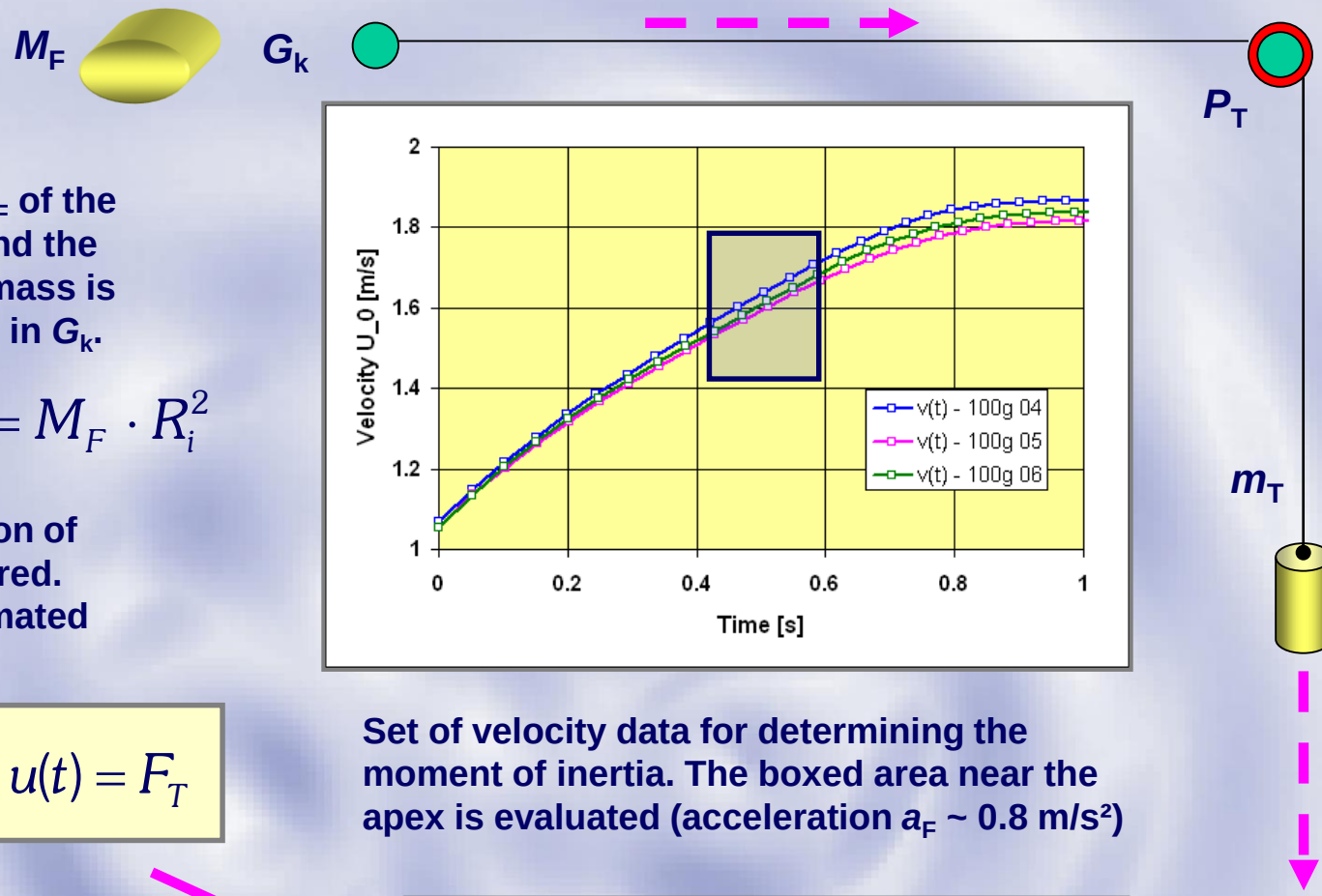

- **Two steps required**

Step (1). Moment of inertia J_F of the boom including the model and the support is determined. The mass is assumed to be concentrated in G_k.

$$m_T \cdot g = M_F \cdot a_F \,,\; J_F = M_F \cdot R_i^2$$

Step (2). Then the acceleration of the flapping model is measured. The circular path is approximated by a linear motion.

$$M_F \cdot \dot{u}(t) + r \cdot u^2(t) + k \cdot u(t) = F_T$$

- ***u(t)*** **velocity over time t**
- ***r*** **drag coefficient**
- ***k*** **friction coefficient**
- **F_T the unknown thrust**

Set of velocity data for determining the moment of inertia. The boxed area near the apex is evaluated (acceleration a_F ~ 0.8 m/s²)

General solution:

$$u(t) = -u_k + u_0 \cdot \tanh\left[(t - t_0)/t_c\right]$$

Thrust Measurement for Flapping-Flight Components

In the "free" mode the model starts from the position at rest.

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General solution:

$$u(t) = -u_k + u_0 \cdot \tanh\left[(t - t_0)/t_c\right]$$

u(t) **velocity over time t**

r **drag coefficient**

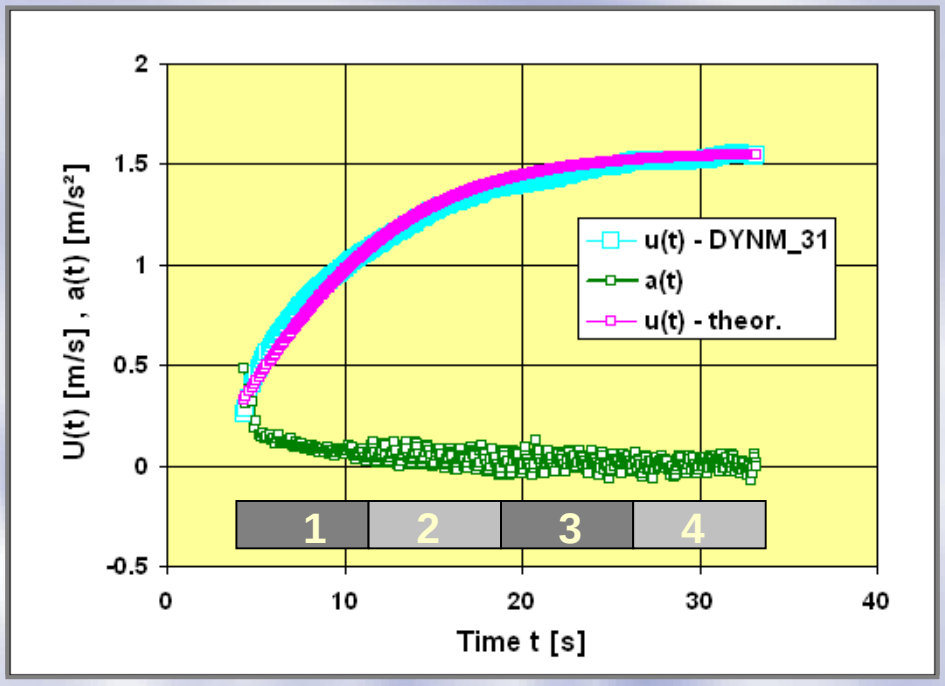
k **friction coefficient**

F_T **the unknown thrust**

Function *u(t)* from experimental data

Three unknown physical quantities

$$u_k = \frac{k}{2r},\ r \cdot \left(u_0^2 - u_k^2\right) = F_T,\ t_c = \frac{M_F}{r \cdot u_0}$$



Step (1). The set of *N* experimental data

$$\{n,\ t_n,\ u_n(t_n);\ n = 1, \ldots, N\}$$

is divided into four packages, and from each package any data

$$\{i,\ t_i,\ u_i(t_i);\ i = 1,2,3,4\}$$

repeatedly are selected.

Step (2). For the four unknown constants u_k, u_0, t_0 and t_c the system of four nonlinear equations is solved.

$$\{\ F_i(u_0,u_k,t_c,t_0) = -u_i - u_k + u_0 * \tanh\left((t_i - t_0)/t_c\right),\ i=1,2,3,4\ \}$$

Step (3). The *N*/4 solutions are averaged leading to a weighted result for the constants including error margins.

The solution provides the thrust data.

Thrust Measurement for Flapping-Flight Components

Solution procedure for determining the unknown thrust

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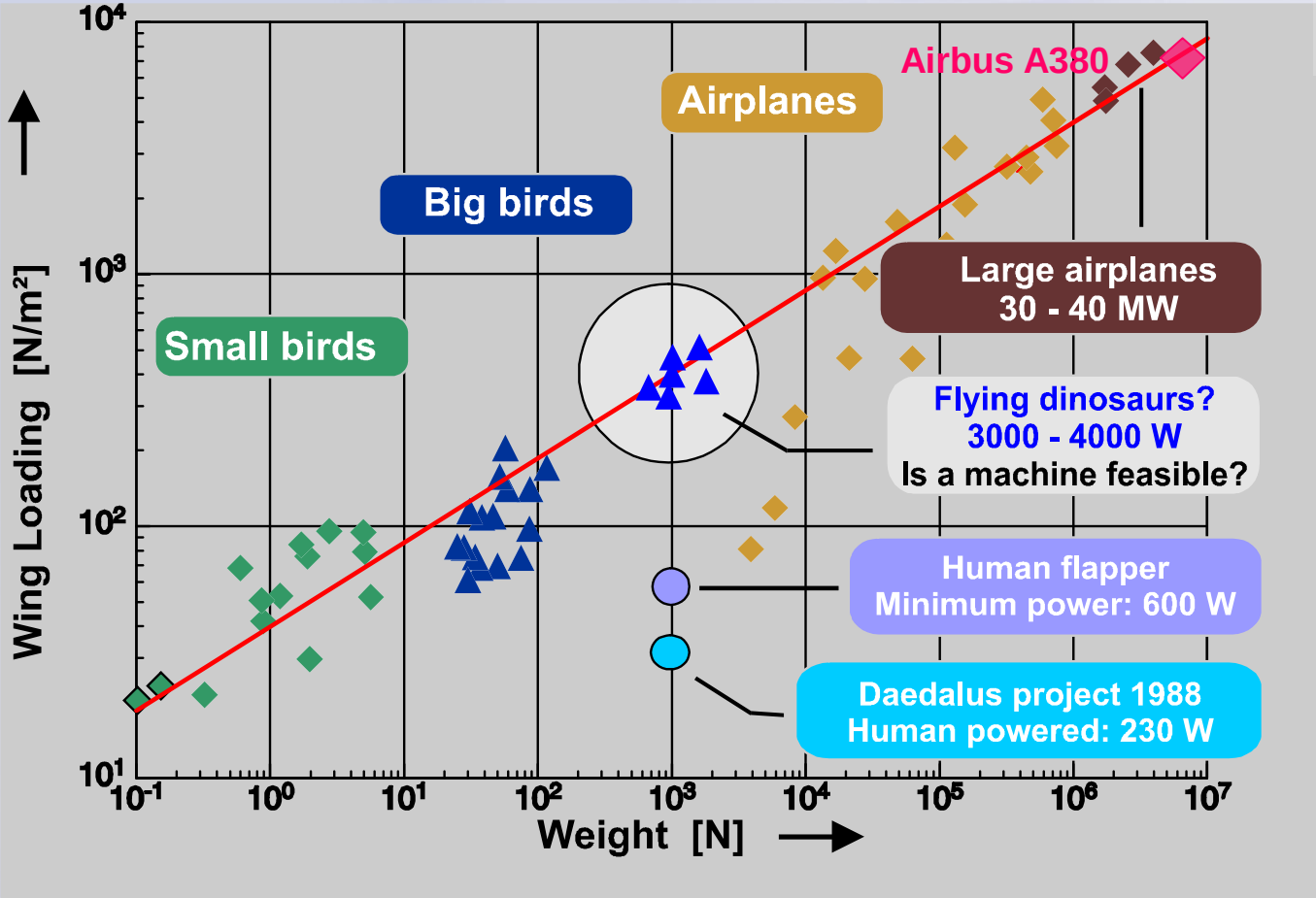

„Normal Flyers“

The high efficiency of the flapping-flight mechanism (bending-/torsional motion) in combination with fuel cells opens the view to an attractive alternative source of thrust generation.

Benefits come from reduced

- consumption of fossil fuel,
- environmental noise by encapsulated power generators,
- air pollution.

A great step would be a full size airplane (single or two seater).

The Technical Perspective of Our Research

In the long run: A renaissance of nature‘s greatest patent in animal flight?

Send W. Flapping-Wing Thrust in Compressible Flow, ICAS 2006-3.10.4, 25th ICAS Congress Hamburg, 3-6 Sep 2006.

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Player C: Player D:

„State-of-the-art“
But:
That‘s not yet the way nature does.

After a long period of tests and „near“ take-offs a historic event took place in 2006:

On July 8th, 2006, the airplane successfully took off, flying 2 or 3 meters above the runway.

The date marks a turn. To the author‘s knowledge, for the first time in history an airplane driven by a flapping-flight engine was able to lift off.

Along the Lines of Nature – Flapping Flight Remains a Challenge

Full-scale piloted ornithoper J.D. DeLaurier
University of Toronto, Canada

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- **Experimental research on flapping-flight components is carried out with a test stand in which the models move relative to the air at rest.**

  Comment. Wind tunnels do not permit the immediate reaction to rapid changes in velocity due to increase and decrease of thrust.

- **The test stand provides, among others, the measurement of velocity, lift and drag. The centre of gravity (c.g.) is free to react to the wings' flapping motion.**

  Comment. The flight of a model without constraint to its c.g. is quite different from the motion in which the fuselage of a model is fixed to a balance.

- **A major goal. Verifying the theoretically predicted high aerodynamic efficiency of flapping flight. It can be checked and validated if the electromechanical efficiency for the drive is known. Special tools have been developed and applied.**

- **The thrust of a model in "free" flight is determined by a mathematical procedure in which the momentum equation is solved on the basis of the acquired velocity data.**

Thrust Measurement for Flapping-Flight Components

Summary