5.4. The Resonik method － A new way of measuring rigid body inertia properties （剛体特性の完全同時全自動高精度同定法システム）

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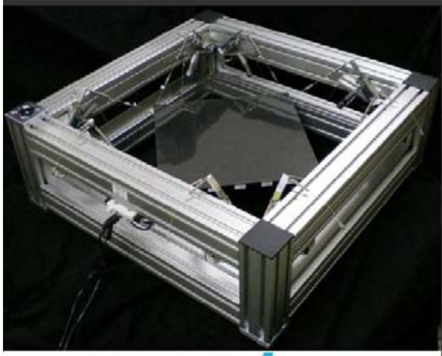

The Resonik method – A new way of measuring rigid body inertia properties

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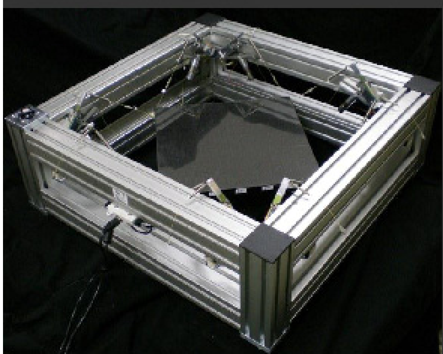
Outline

- Importance of rigid body properties
- Current identification methods
- New proposal: Resonik method
- Results:
  - Manual testing procedure
  - Measurement robot
- Conclusions

Importance of rigid body properties



The Resonik method – A new way of measuring rigid body inertia properties

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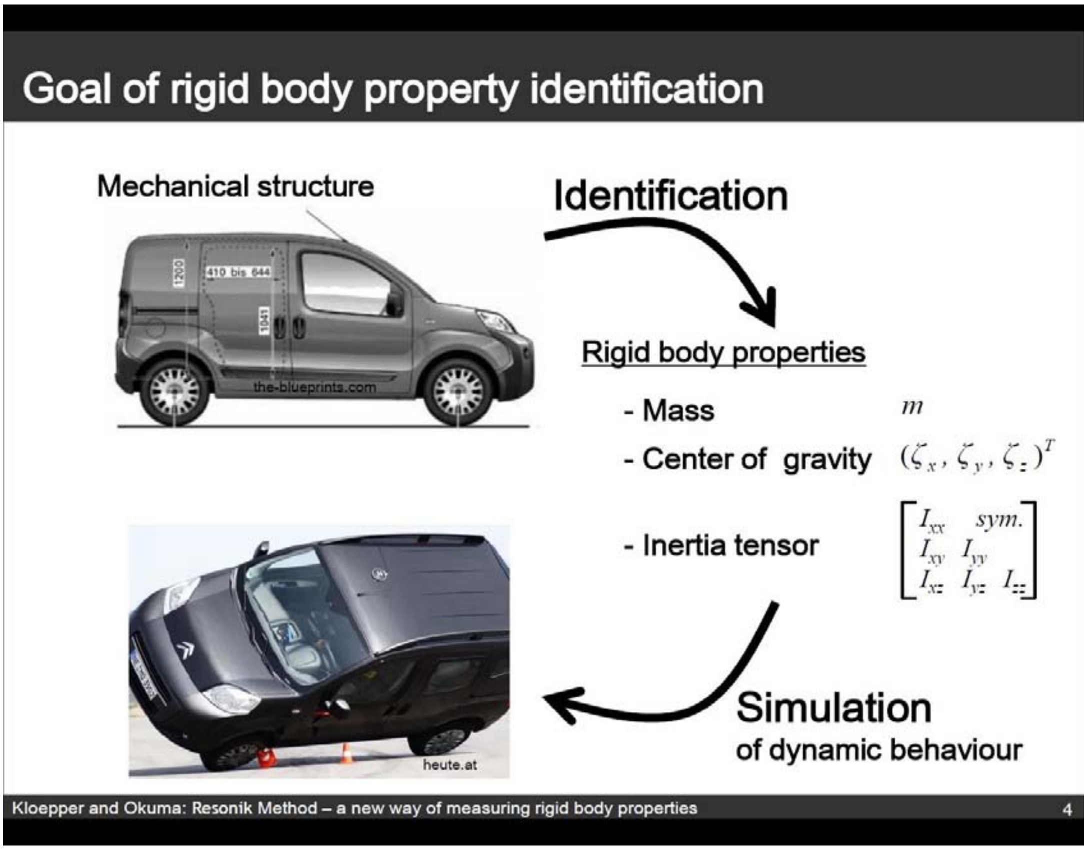
Goal of rigid body property identification
Mechanical structure
the-blueprints.com
Identification
Rigid body properties
- Mass m
- Center of gravity $(\zeta_x, \zeta_y, \zeta_z)^T$
- Inertia tensor $\begin{bmatrix} I_{xx} & & sym. \\ I_{xy} & I_{yy} & \\ I_{xz} & I_{yz} & I_{zz} \end{bmatrix}$
heute.at
Simulation
of dynamic behaviour
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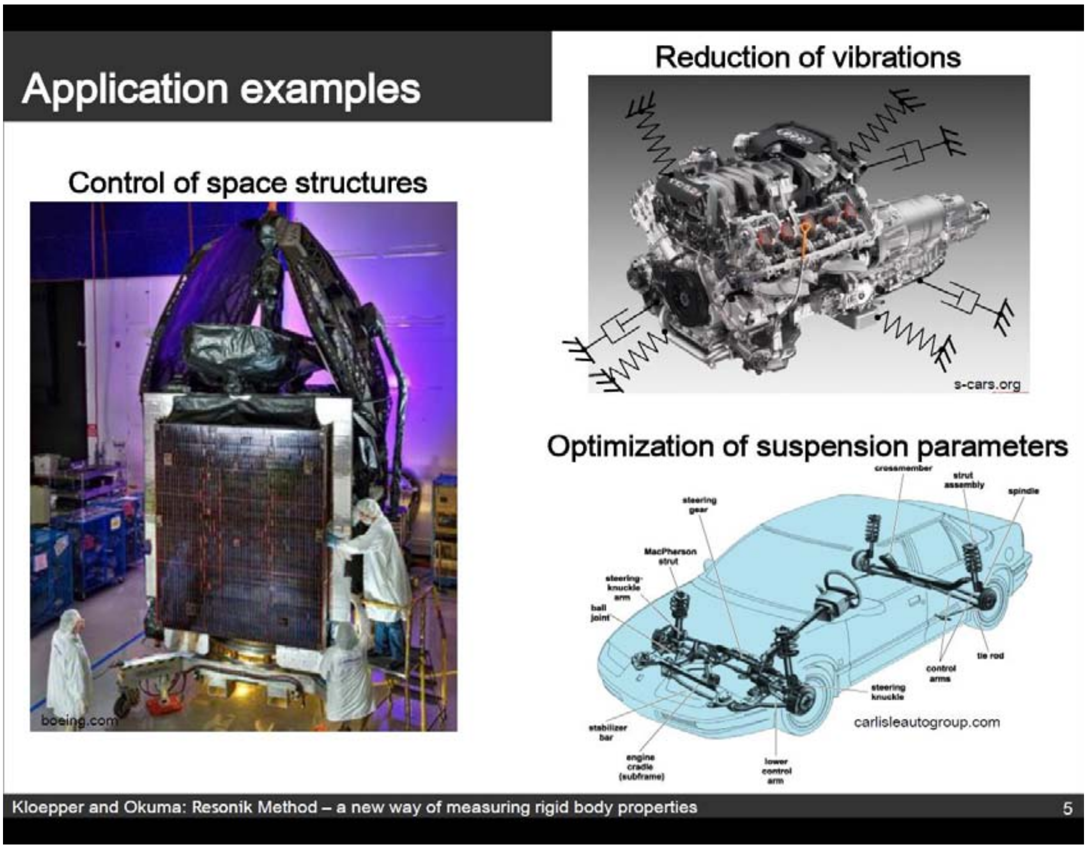
Application examples
Control of space structures
boeing.com
Reduction of vibrations
s-cars.org
Optimization of suspension parameters
carlisleautogroup.com
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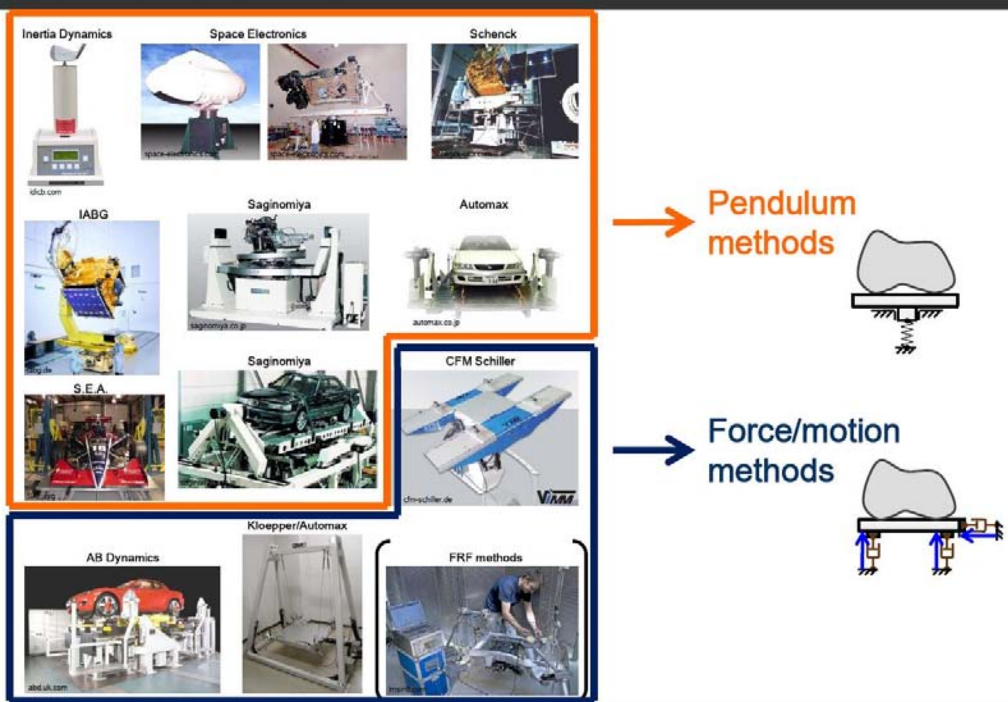
Current identification methods

Commercial solutions



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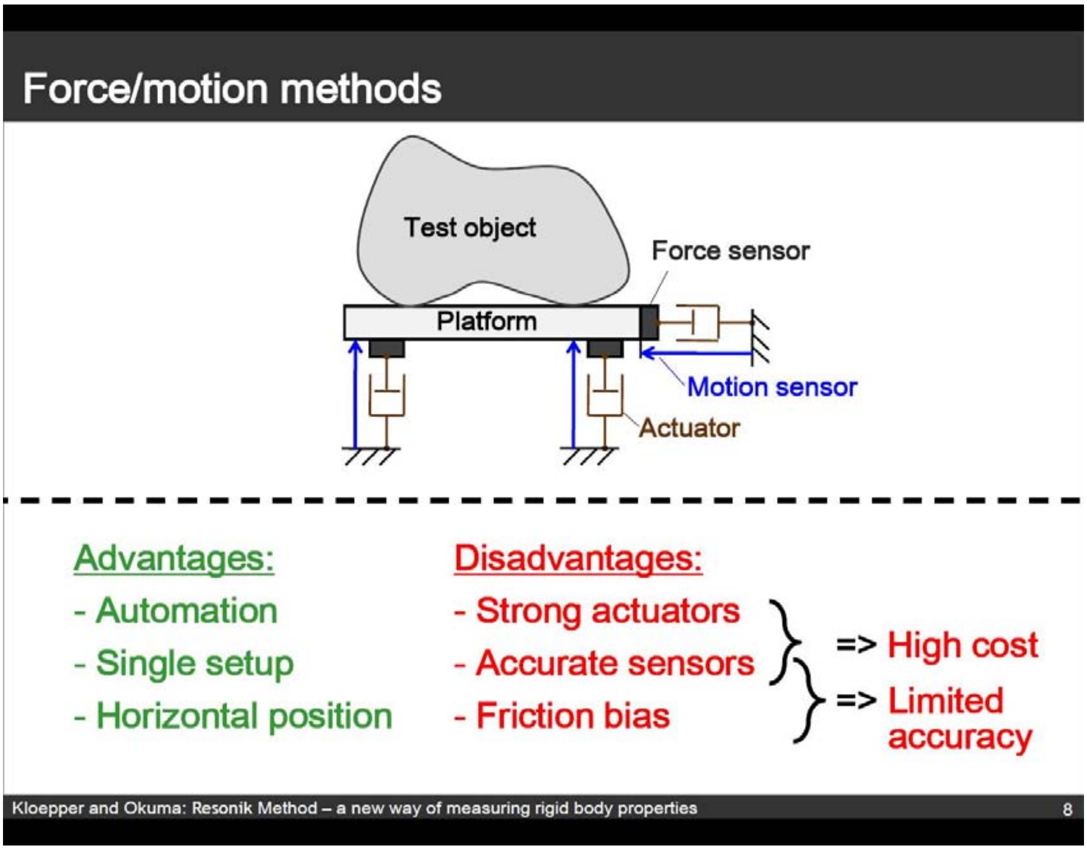
Force/motion methods
Test object
Force sensor
Platform
Motion sensor
Actuator
Advantages:
- Automation
- Single setup
- Horizontal position
Disadvantages:
- Strong actuators
- Accurate sensors
- Friction bias
=> High cost
=> Limited accuracy
Kloepper and Okuma: Resonik Method – a new way of measuring rigid body properties
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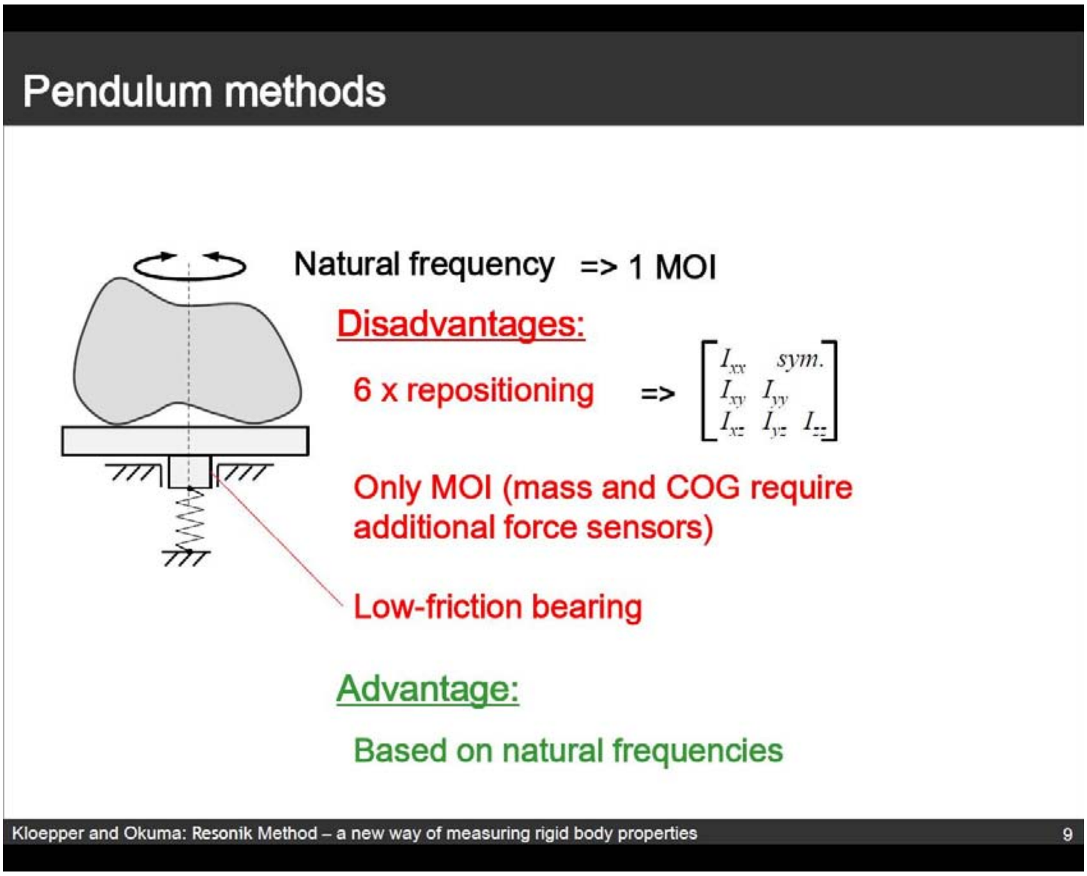
Pendulum methods
Natural frequency => 1 MOI
Disadvantages:
6 x repositioning =>
$\begin{bmatrix} I_{xx} & & sym. \\ I_{xy} & I_{yy} & \\ I_{xz} & I_{yz} & I_{zz} \end{bmatrix}$
Only MOI (mass and COG require additional force sensors)
Low-friction bearing
Advantage:
Based on natural frequencies
Kloepper and Okuma: Resonik Method – a new way of measuring rigid body properties
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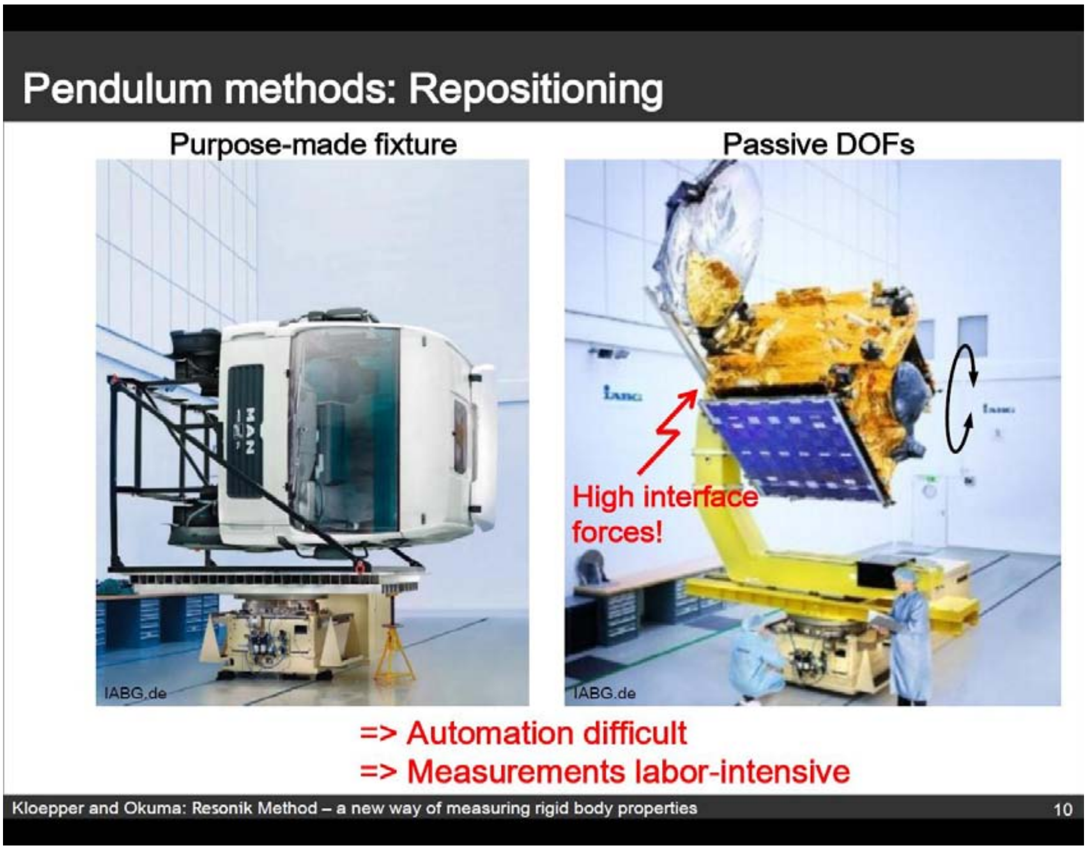
Pendulum methods: Repositioning
Purpose-made fixture
Passive DOFs
IABG.de
IABG.de
High interface forces!
=> Automation difficult
=> Measurements labor-intensive
Kloepper and Okuma: Resonik Method – a new way of measuring rigid body properties
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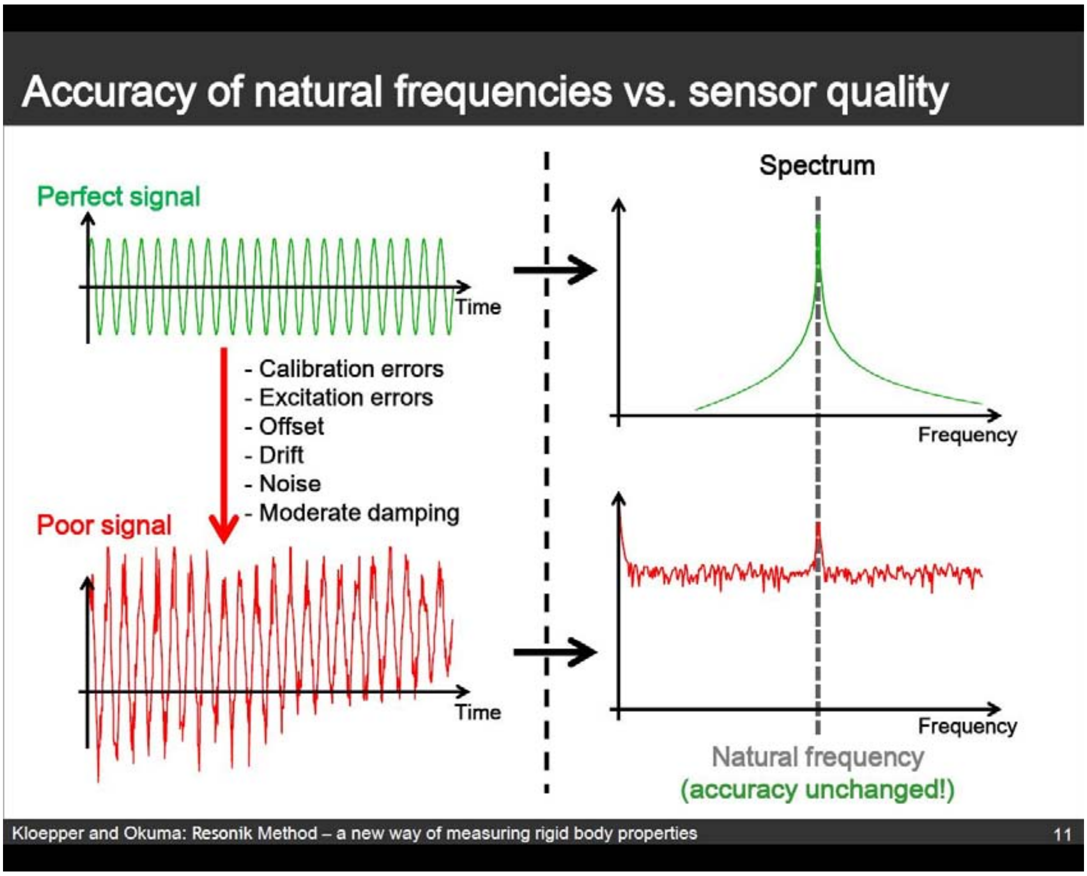
Accuracy of natural frequencies vs. sensor quality
Perfect signal
Time
Spectrum
Frequency
- Calibration errors
- Excitation errors
- Offset
- Drift
- Noise
- Moderate damping
Poor signal
Time
Frequency
Natural frequency
(accuracy unchanged!)
Kloepper and Okuma: Resonik Method – a new way of measuring rigid body properties
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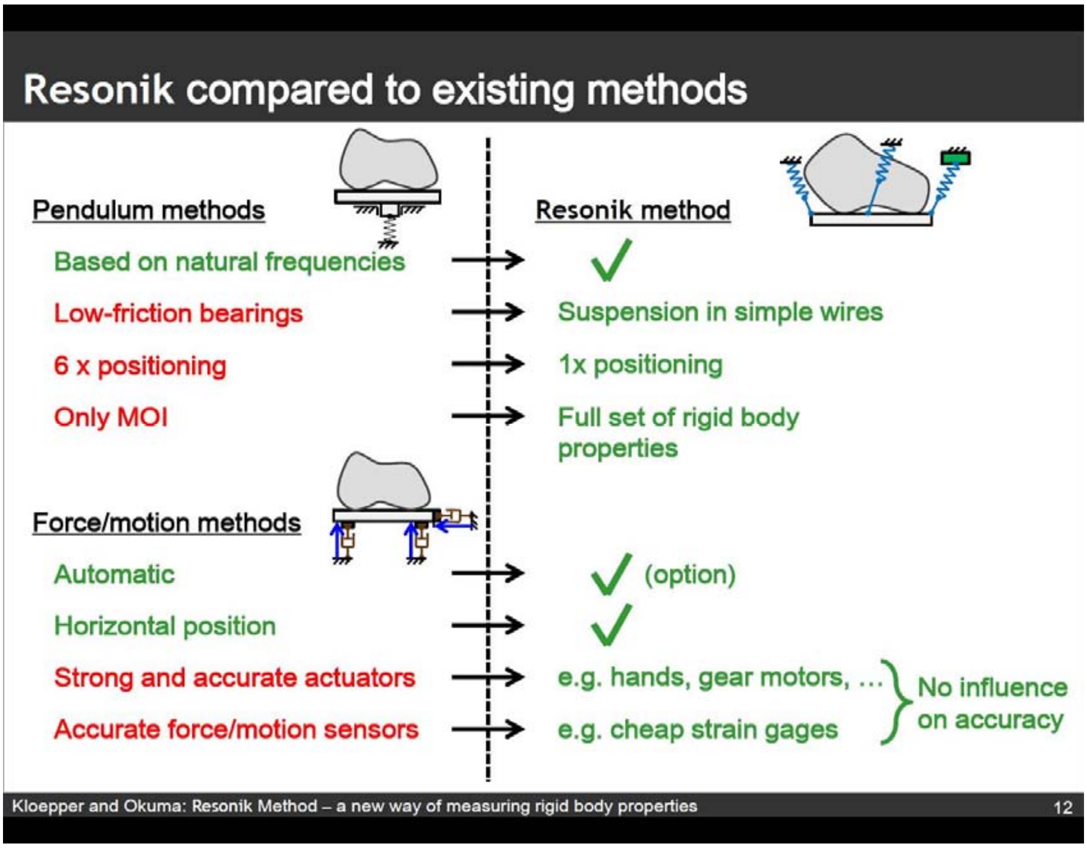
Resonik compared to existing methods
Pendulum methods
Based on natural frequencies
Low-friction bearings
6 x positioning
Only MOI
Resonik method
Suspension in simple wires
1x positioning
Full set of rigid body properties
Force/motion methods
Automatic
Horizontal position
Strong and accurate actuators
Accurate force/motion sensors
(option)
e.g. hands, gear motors, …
e.g. cheap strain gages
No influence on accuracy
Kloepper and Okuma: Resonik Method – a new way of measuring rigid body properties
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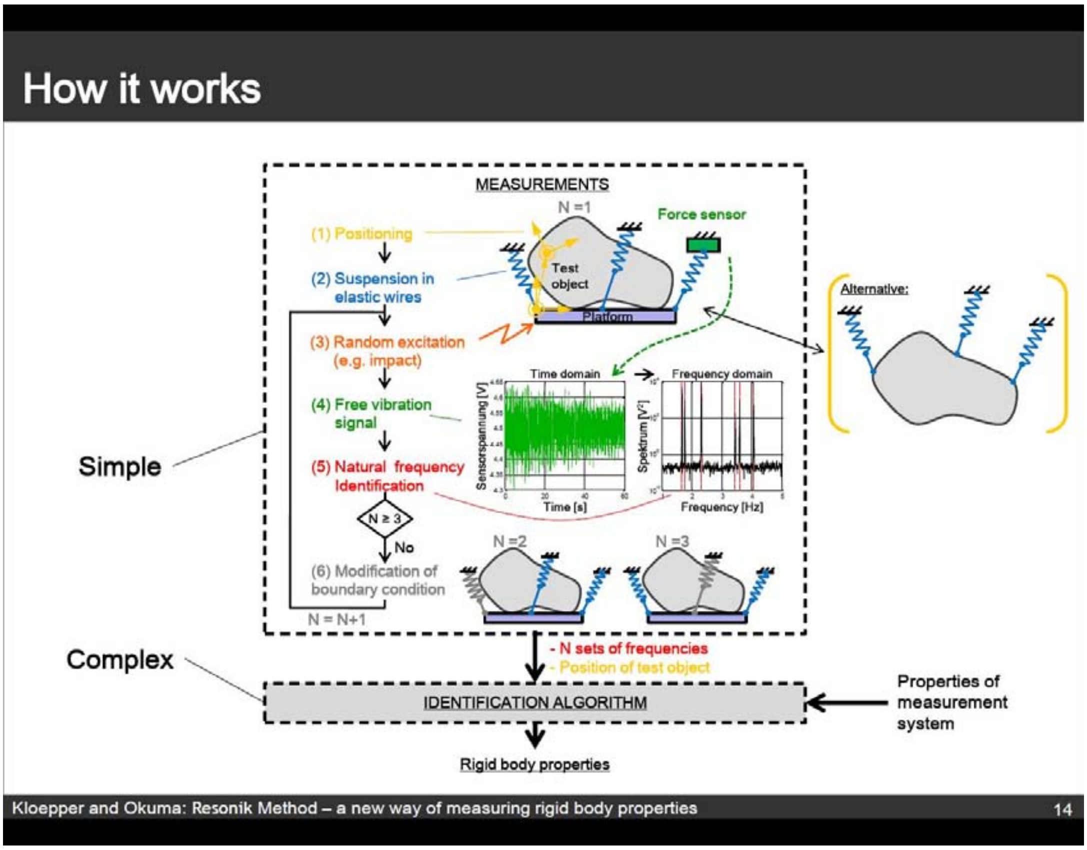
Resonik method:
How it works


How it works
MEASUREMENTS
N =1
(1) Positioning
(2) Suspension in elastic wires
(3) Random excitation (e.g. impact)
(4) Free vibration signal
(5) Natural frequency Identification
N ≥ 3
No
(6) Modification of boundary condition
N = N+1
Force sensor
Test object
Platform
Time domain
Frequency domain
Sensorspannung [V]
Time [s]
Spektrum [V²]
Frequency [Hz]
Alternative:
N =2
N =3
Simple
Complex
- N sets of frequencies
- Position of test object
IDENTIFICATION ALGORITHM
Properties of measurement system
Rigid body properties
Kloepper and Okuma: Resonik Method – a new way of measuring rigid body properties
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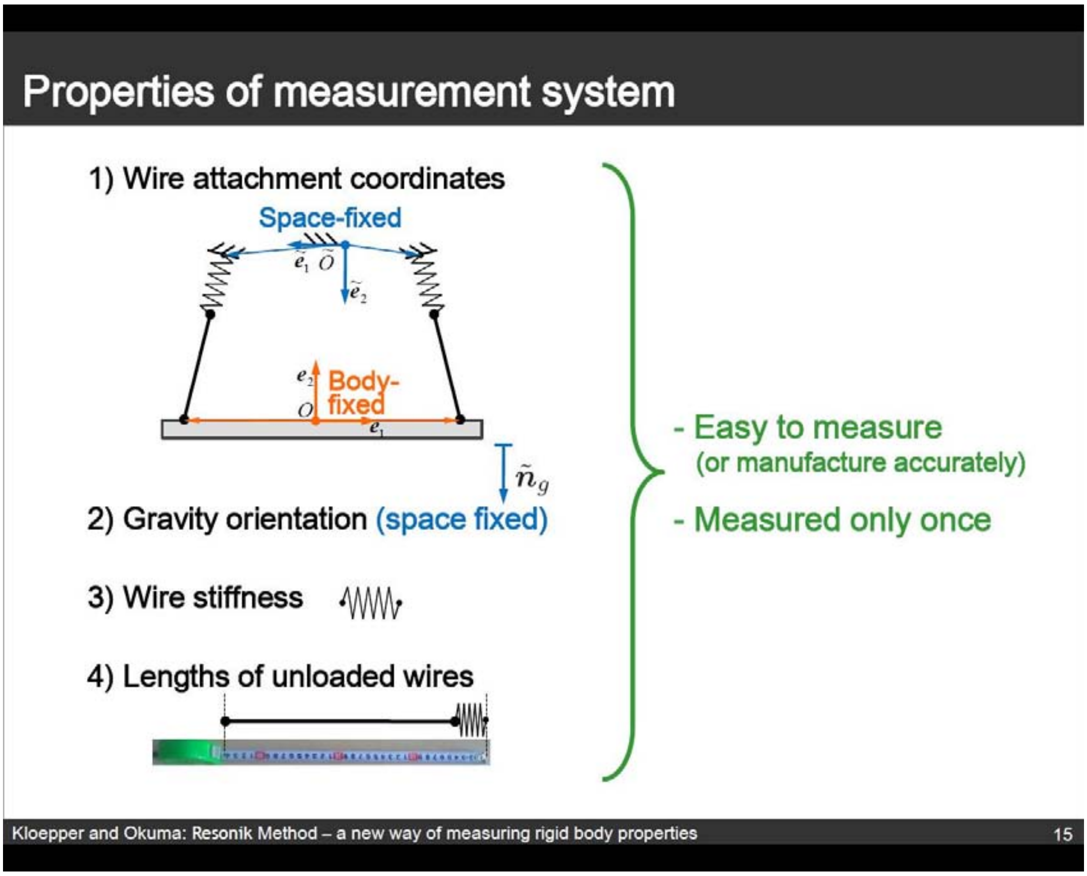
Properties of measurement system
1) Wire attachment coordinates
Space-fixed
Body-fixed
2) Gravity orientation (space fixed)
3) Wire stiffness
4) Lengths of unloaded wires
- Easy to measure
(or manufacture accurately)
- Measured only once
Kloepper and Okuma: Resonik Method – a new way of measuring rigid body properties
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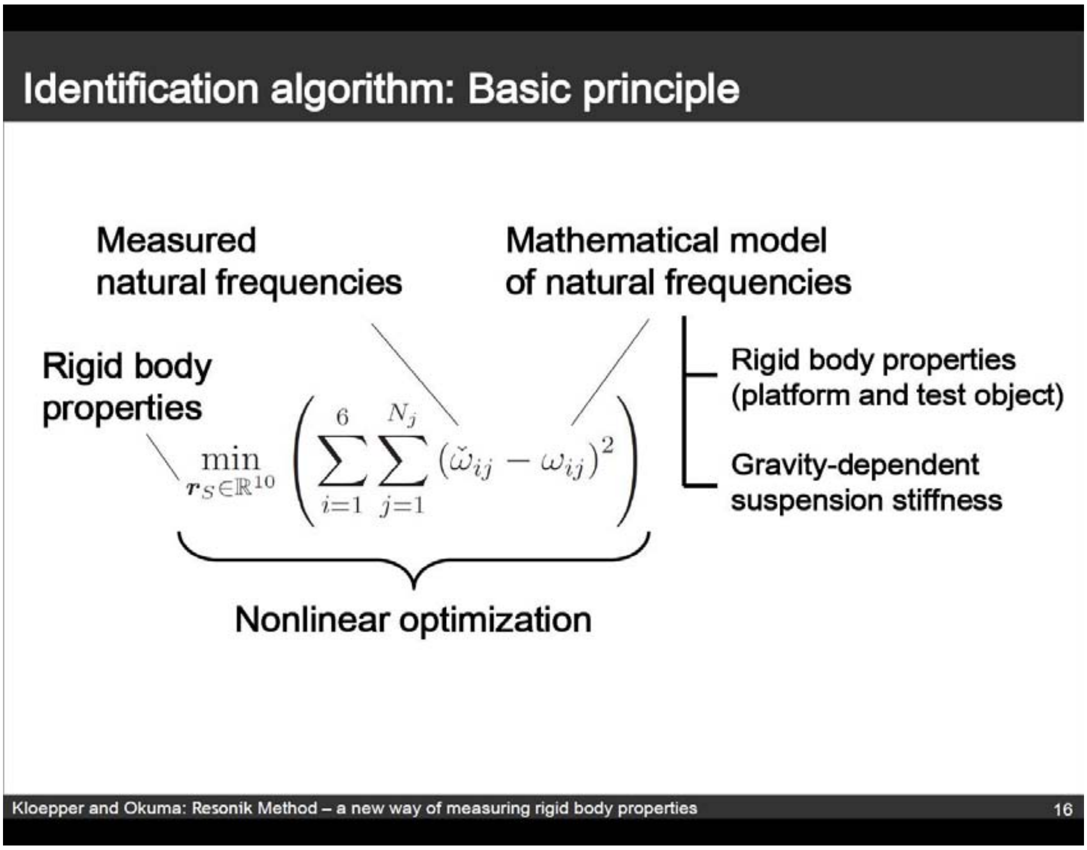
Identification algorithm: Basic principle
Measured natural frequencies
Mathematical model of natural frequencies
Rigid body properties
$\min_{\boldsymbol{r}_S \in \mathbb{R}^{10}} \left(\sum_{i=1}^{6} \sum_{j=1}^{N_j} (\breve{\omega}_{ij} - \omega_{ij})^2 \right)$
Rigid body properties (platform and test object)
Gravity-dependent suspension stiffness
Nonlinear optimization
Kloepper and Okuma: Resonik Method – a new way of measuring rigid body properties
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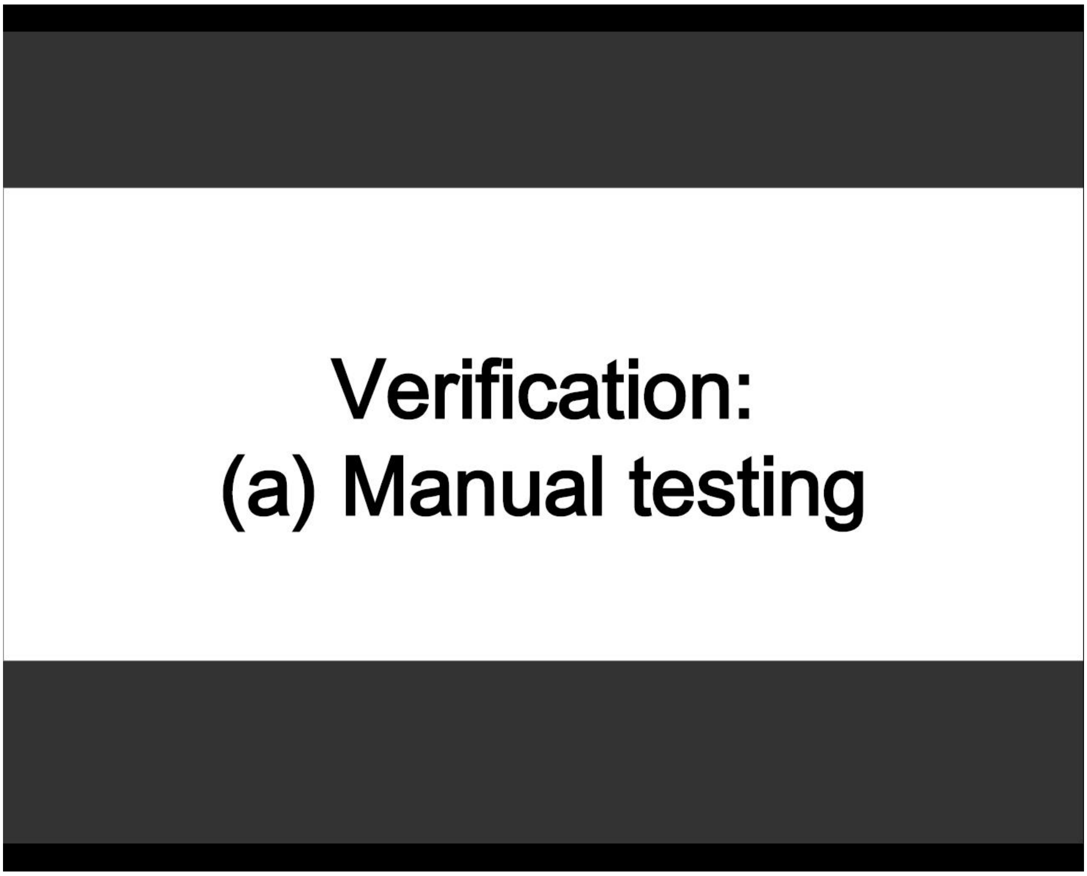
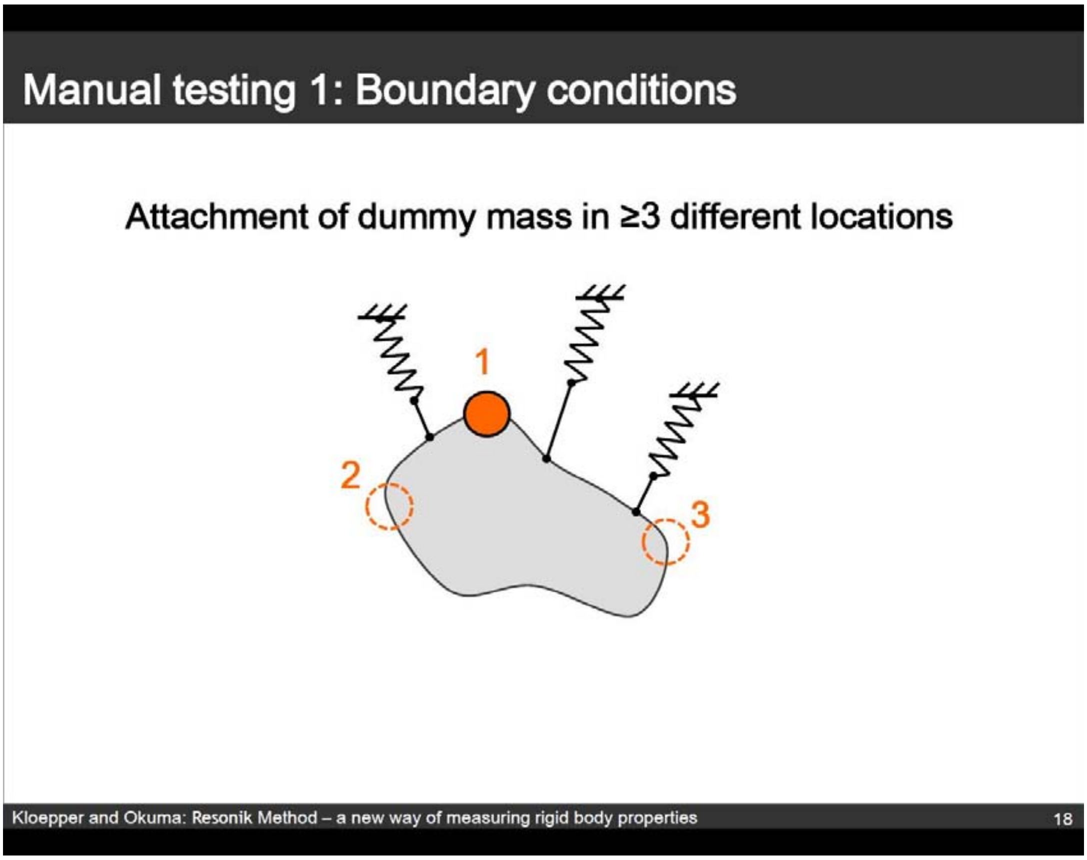

Verification:
(a) Manual testing


Manual testing 1: Boundary conditions
Attachment of dummy mass in ≥3 different locations
1
2
3
Kloepper and Okuma: Resonik Method – a new way of measuring rigid body properties
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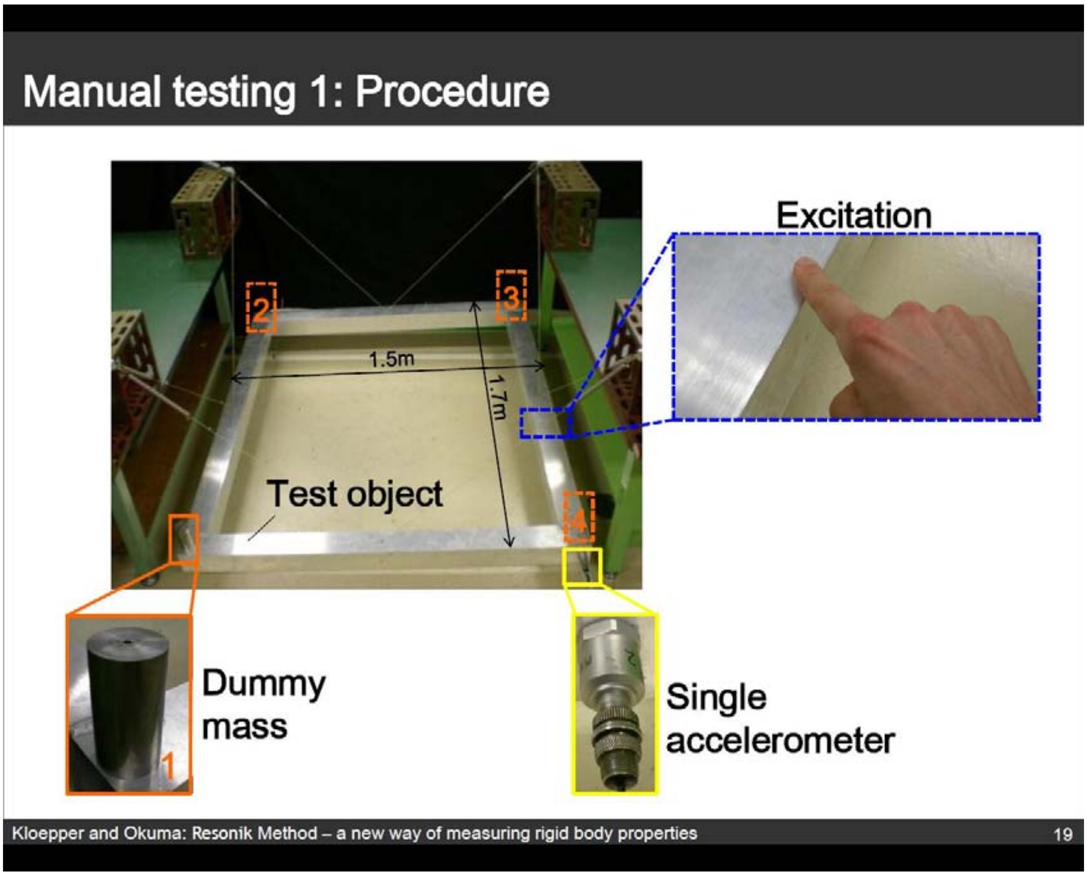
Manual testing 1: Procedure
Excitation
2
3
1.5m
1.7m
Test object
4
1
Dummy mass
Single accelerometer
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Manual testing 1: Identification errors

Parameter	Unit	True value	Errors	
m	kg	15.52	0.0500	(0.32%)
I_{11}	kgm^2	5.301	0.0274	(0.51%)
I_{22}	kgm^2	6.462	0.0483	(0.74%)
I_{33}	kgm^2	11.72	-0.0988	(0.84%)
I_{12}	kgm^2	0	0.0037	
I_{13}	kgm^2	0	-0.0479	
I_{23}	kgm^2	0	0.0299	
$e_1^T \zeta_G$	mm	850	3.1	
$e_2^T \zeta_G$	mm	750	-3.0	
$e_3^T \zeta_G$	mm	-50	-1.3	

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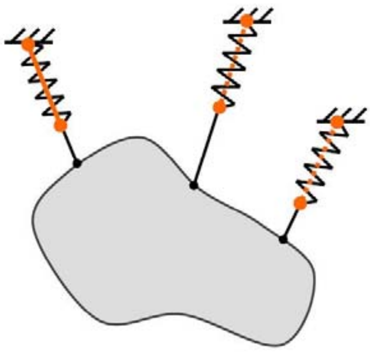
Manual testing 2: Boundary conditions

Rigidification of one wire at a time



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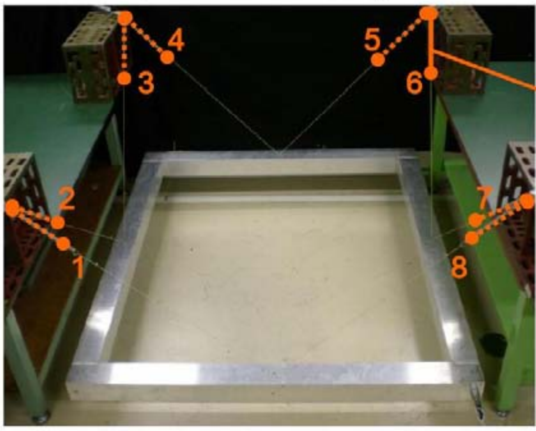
Manual testing 2: Procedure

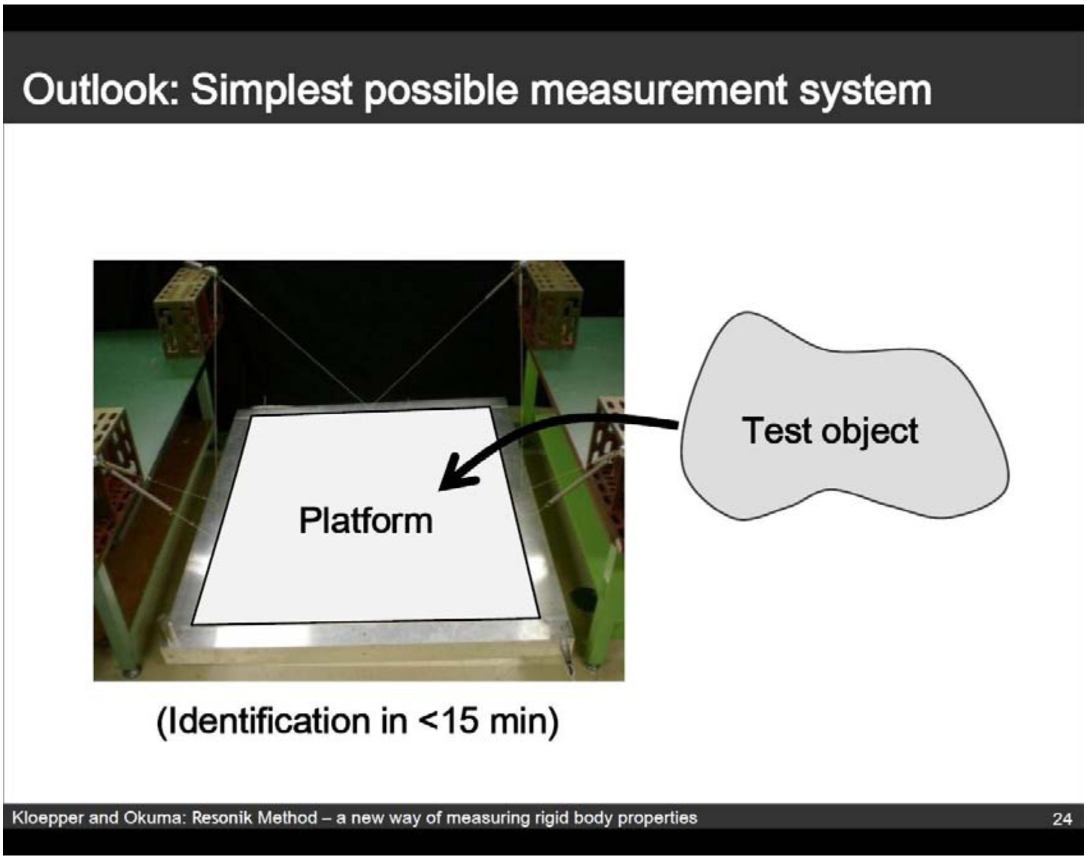
Suspended test object



Rigidification

Manual testing 2: Identification errors

Parameter	Unit	True value	Errors	
m	kg	15.52	-0.0402	(0.26%)
I_{11}	kgm^2	5.301	0.0116	(0.21%)
I_{22}	kgm^2	6.463	0.0033	(0.05%)
I_{33}	kgm^2	11.72	-0.0631	(0.54%)
I_{12}	kgm^2	0	0.0413	
I_{13}	kgm^2	0	0.0022	
I_{23}	kgm^2	0	-0.0073	
$e_1^T \zeta_G$	mm	850	0.7	
$e_2^T \zeta_G$	mm	750	0.4	
$e_3^T \zeta_G$	mm	-50	-2.8	


Outlook: Simplest possible measurement system
Platform
Test object
(Identification in <15 min)
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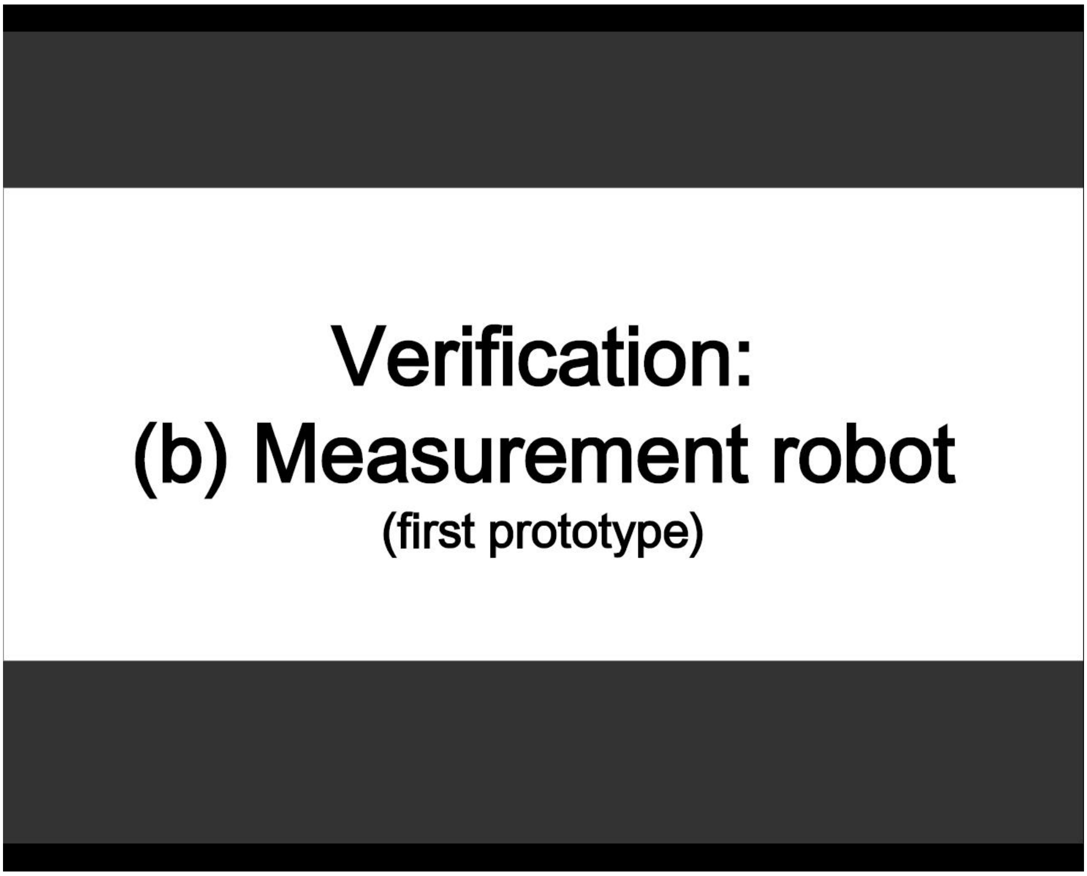
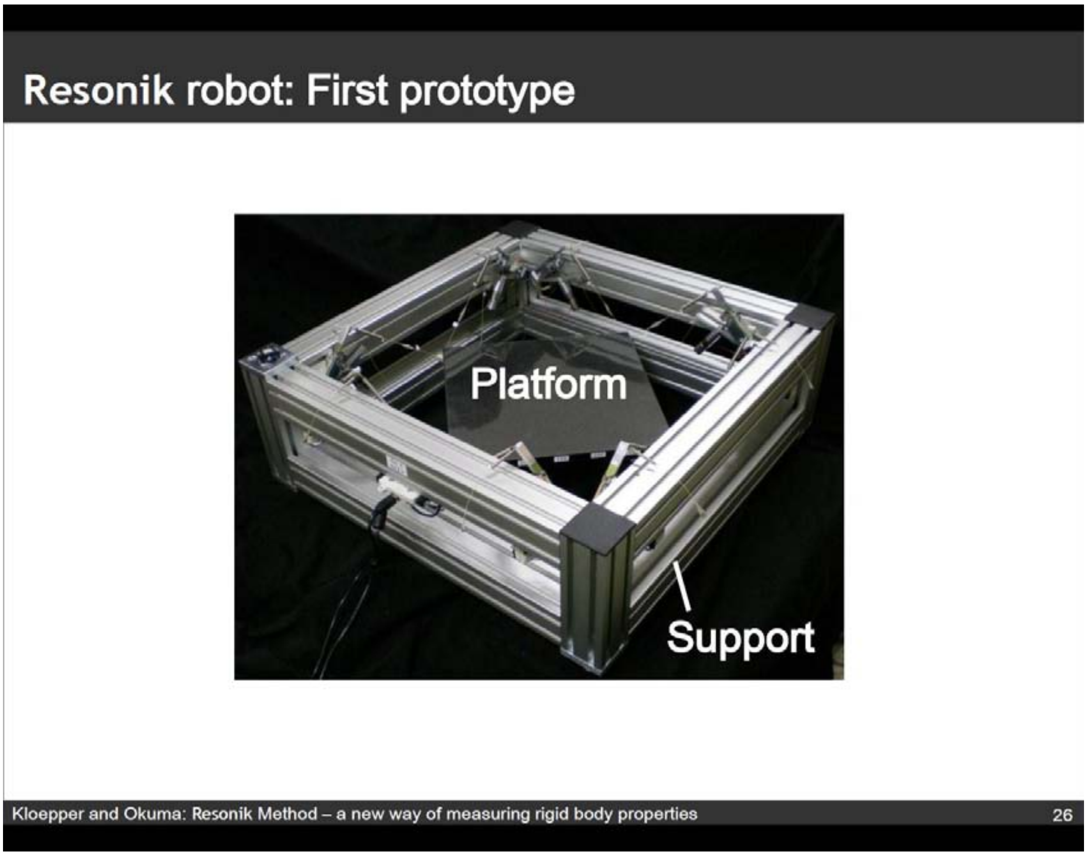

Verification:
(b) Measurement robot
(first prototype)


Resonik robot: First prototype
Platform
Support
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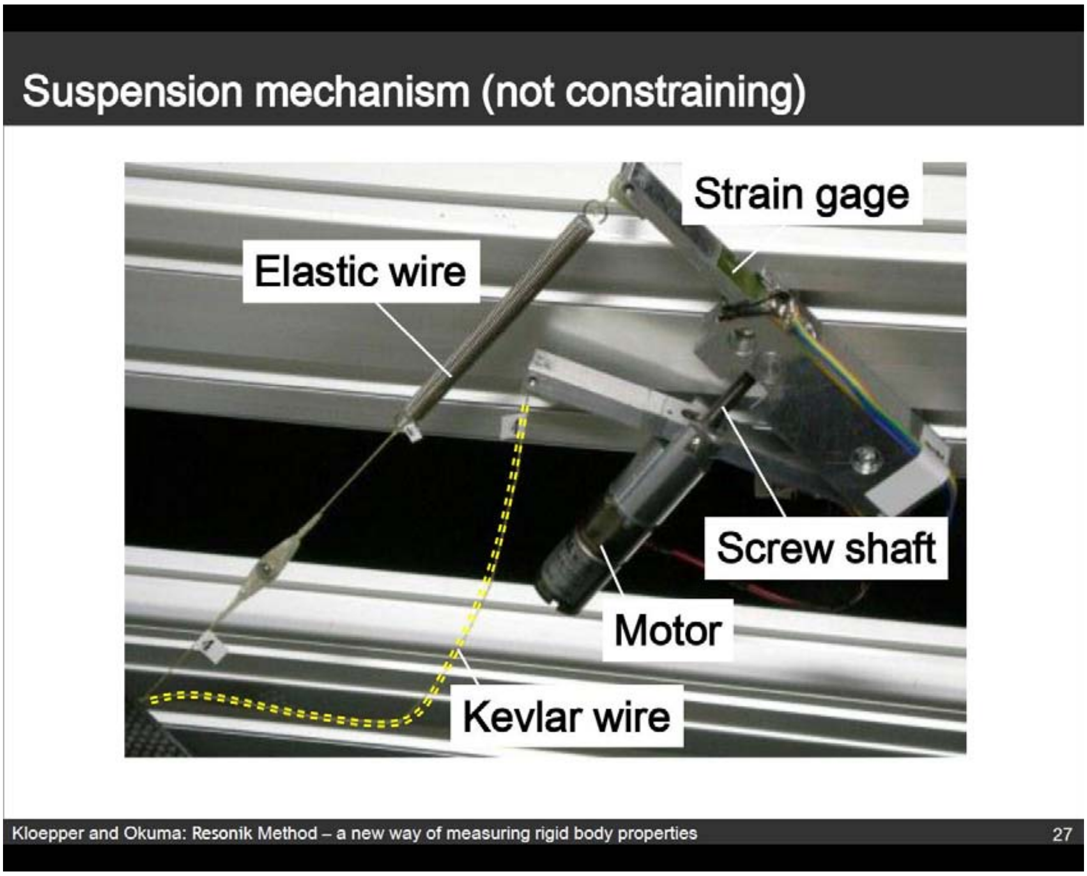
Suspension mechanism (not constraining)
Strain gage
Elastic wire
Screw shaft
Motor
Kevlar wire
Kloepper and Okuma: Resonik Method – a new way of measuring rigid body properties
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Suspension mechanism (constraining)

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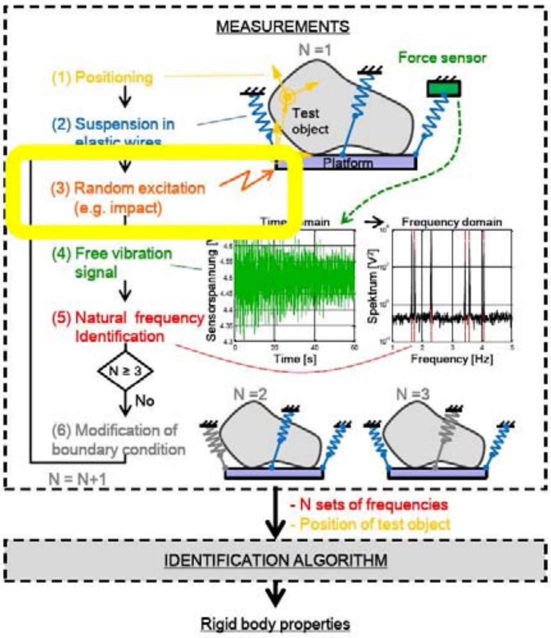
Resonik robot: Excitation



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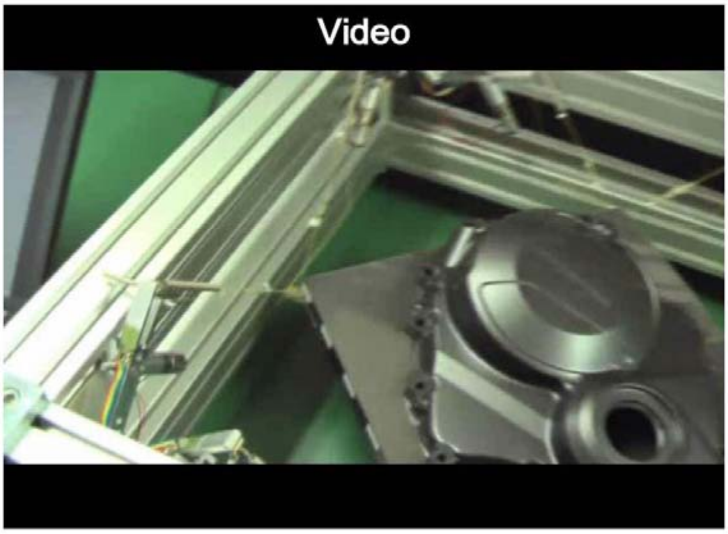
Resonik robot: Excitation



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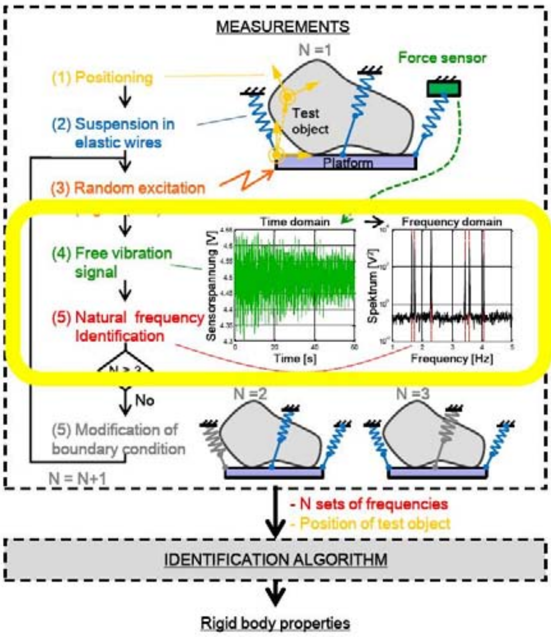
Resonik robot: Identification of natural frequencies



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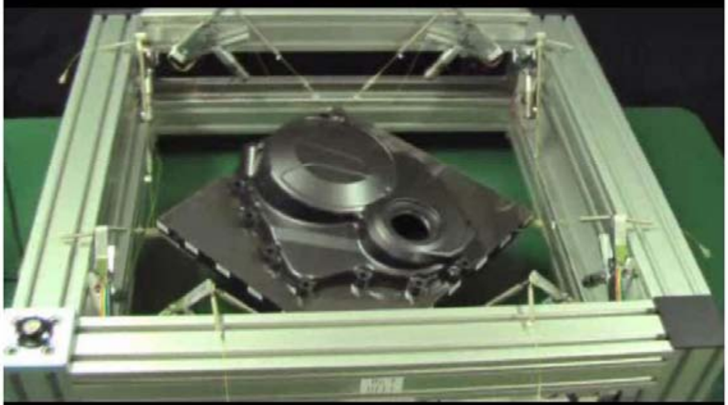
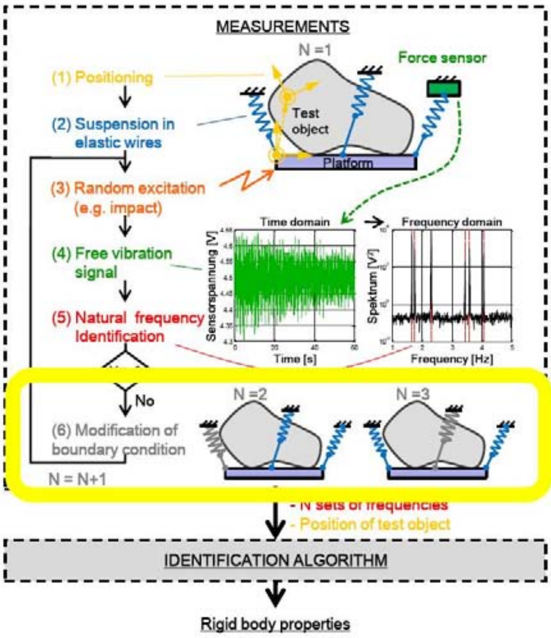
Resonik robot: Identification of natural frequencies

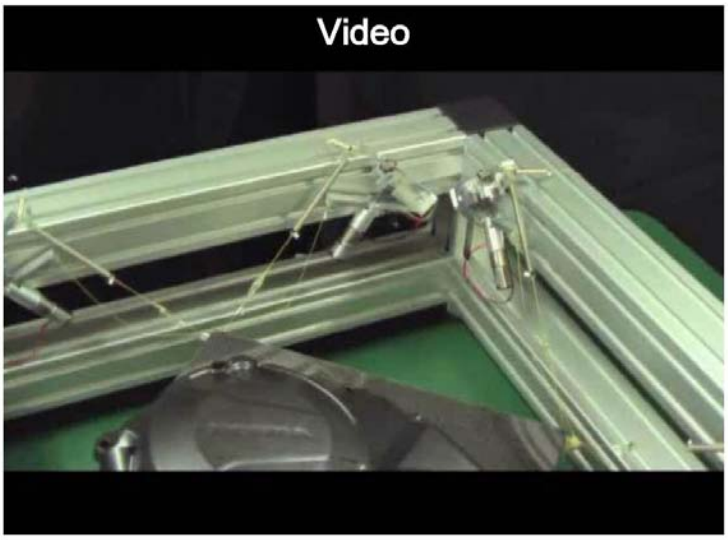
Video



Resonik robot: Boundary conditions



Resonik robot: Boundary conditions



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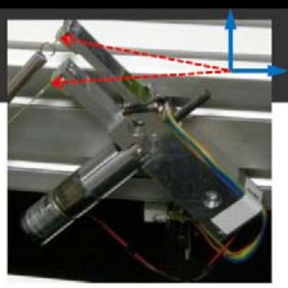
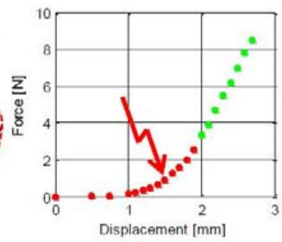
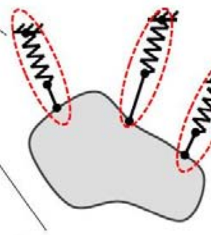
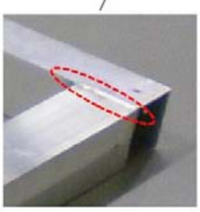
Room for improvement

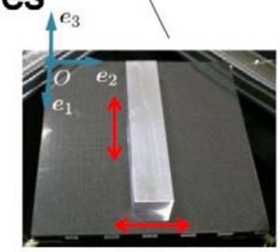


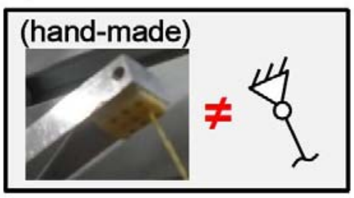
- Manufacturing tolerances
- Nonlinearity of twisted Kevlar wires
- Wire arrangement
- Suspension point design
- Test object positioning
- "True" values











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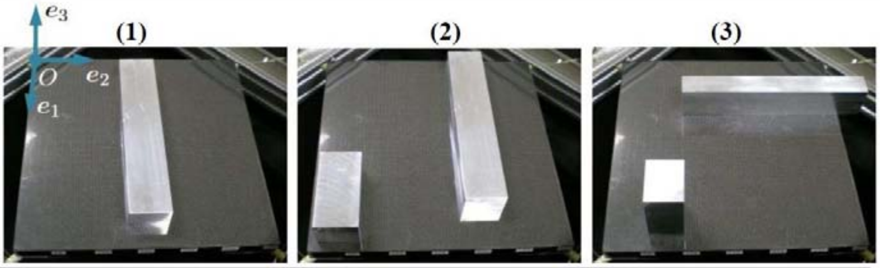
Resonik robot: Identification errors (results A)



Parameter	Unit	Platform	(1) True	(1) Error	(2) True	(2) Error	(3) True	(3) Error
m	g	569.6	1000	1.354	1535	1.136	1535	0.640
I_{11}	gm^2	5.679	0.283	0.029	10.55	-0.015	13.48	-0.023
I_{22}	gm^2	5.689	5.286	0.007	10.42	0.031	12.35	-0.159
I_{33}	gm^2	11.12	5.419	0.101	20.66	-0.137	24.09	-0.259
I_{12}	gm^2	0.002	0.000	0.009	6.816	-0.051	9.099	-0.138
I_{13}	gm^2	-0.031	0.000	0.016	-0.200	-0.051	-1.568	-0.032
I_{23}	gm^2	0.022	0.000	-0.026	0.296	0.003	1.263	0.049
$\boldsymbol{e}_1^T\boldsymbol{\zeta}_G$	mm	154.4	155.0	-0.014	175.0	0.093	157.7	0.117
$\boldsymbol{e}_2^T\boldsymbol{\zeta}_G$	mm	152.8	155.0	-0.090	145.7	0.148	164.4	-0.120
$\boldsymbol{e}_3^T\boldsymbol{\zeta}_G$	mm	-11.35	15.30	-1.261	17.04	-2.037	34.01	-1.998

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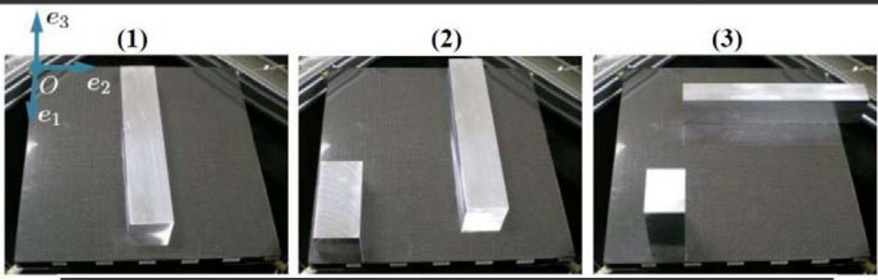
Resonik robot: Repeatability (Δ results A-B)



Parameter	Unit	(1) True	(1) Δ	(2) True	(2) Δ	(3) True	(3) Δ
m	g	1000	-0.718	1535	0.726	1535	0.935
I_{11}	gm^2	0.283	-0.004	10.55	0.005	13.48	-0.005
I_{22}	gm^2	5.286	-0.003	10.42	-0.008	12.35	0.020
I_{33}	gm^2	5.419	-0.011	20.66	0.029	24.09	0.021
I_{12}	gm^2	0.000	-0.000	6.816	-0.003	9.099	0.006
I_{13}	gm^2	0.000	0.000	-0.200	0.013	-1.568	0.014
I_{23}	gm^2	0.000	-0.001	0.296	0.007	1.263	0.002
$\boldsymbol{e}_1^T\boldsymbol{\zeta}_G$	mm	155.0	-0.009	175.0	-0.013	157.7	-0.129
$\boldsymbol{e}_2^T\boldsymbol{\zeta}_G$	mm	155.0	-0.034	145.7	-0.003	164.4	-0.073
$\boldsymbol{e}_3^T\boldsymbol{\zeta}_G$	mm	15.30	-0.017	17.04	0.087	34.01	0.043

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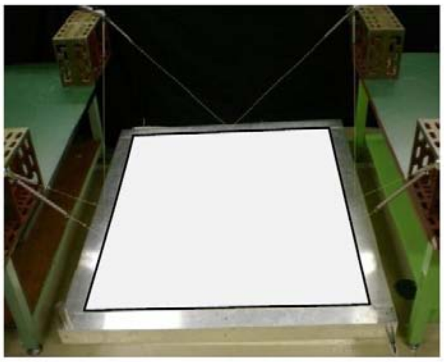
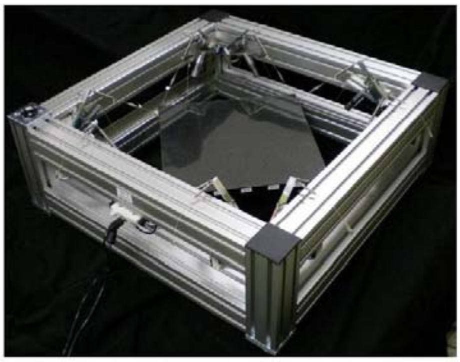
Conclusions

Distinctive features of Resonik method 1/4





Outstanding balance between:
- Accuracy
- Convenience
- Low-cost hardware/ simple manufacturing

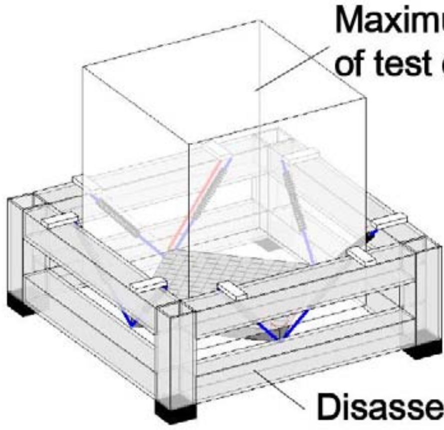
Distinctive features of Resonik method 2/4

- Customization easy

(through modification of support and platform)

Distinctive features of Resonik method 3/4

- Lightweight/mobile




Distinctive features of Resonik method 4/4
- Improvised Resonik method will work for large structures
nasa.cov
(current methods: excessive cost)
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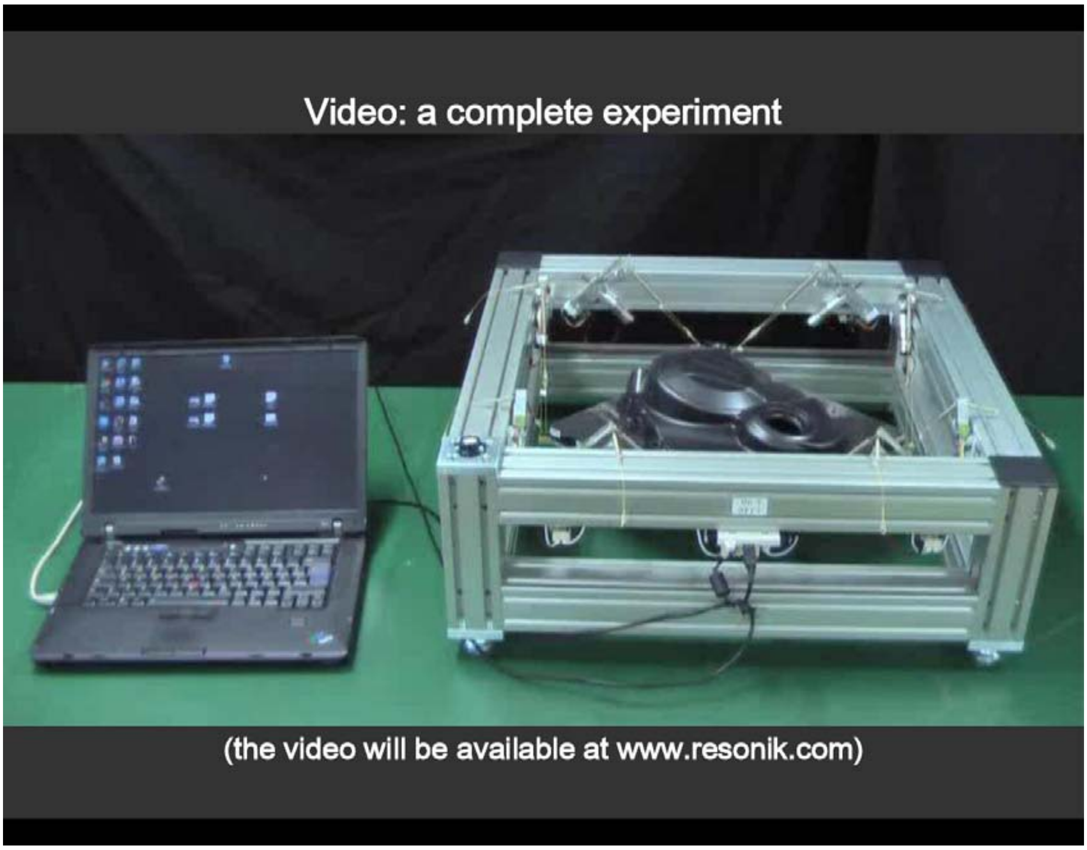
Thank you very much!
kloepper.r.aa@m.titech.ac.jp
mokuma@mech.titech.ac.jp


Video: a complete experiment
(the video will be available at www.resonik.com)

質疑応答

質問者①

フレーム全体が剛体ではないことはどのように影響しますか。

発表者

大事なポイントです。計測する周波数が低ければ剛性は問題ないです。このシステムでは 3.5Hz まで使っているのですが、低い周波数を使っているので大丈夫です。フレームは硬く作ることはできますが、なるべく軽く作りたいです。そこでサポートポイントを柔らかくして剛性を計測してモデルに入れれば大丈夫なはずです。

質問者②

素晴らしいアイディアだと思います。ただ、質量の計測誤差が 0.3%で、JAXA の設備と比較してまだあまりよくないという印象です。この方法の精度に影響する一番大きいポイントはどこにあるのでしょうか。例えば大きい衛星の場合、座標値の計測精度が影響するのですが、その辺の検討はされていますでしょうか。

発表者

シミュレーションを使って検討しています。シミュレーションから分かることは、どの誤差要因も誤差に対する感度はあまり高くありません。なので、しっかりつくればいくらでも精度が出ます。誤差要因は、例えば、吊るすポイントの座標がありますが、これは私が手でつくったものなので良くないです。また、ケプラーワイヤーは非常に非線形です。力が強いところの剛性は一定ですが、非線形な領域で使っていたことが分かっています。今後はケプラーワイヤーは使わないようにします。他にはワイヤーのコンフィギュレーションが影響します。シミュレーションで最適化してもっと良くできないかと思っています。吊るすポイントはピン固定になっているか、ケプラーの改善、構造の位置は合っているか、構造の剛体特性などです。

精度が悪いとは、全然、思っていません。以前、FRF 法でシステムを作りましたが、一日中頑張っても、今回の方法の精度は一回も出なかったです。以前のシステムは automaz という会社がコマーシャルしていますが、そのシステムよりも、適当に吊るした供試体、ひもとばね、センサー1 個しか必要ない今回の方法の方がずっといい結果が出ました。ガスベアリングを使った装置は理論的な精度は 100%と言っていますが、精度を出すことは簡単ではないです。方向や位置の調整は困難で、実際にはだいぶ精度が落ちます。