HYBRID ANALYSIS OF OVERHEAD POWER LINE CONDUCTORS CONFIGURATION USING INNOVATIVE ON-LINE MEASUREMENTS

(HYBRYDOWA ANALIZA PRZEWODÓW NAPOWIETRZNYCH ELEKTROENERGETYCZNYCH LINII PRZESYŁOWYCH WYKORZYSTUJĄCA INNOWACYJNE TECHNIKI POMIAROWE ON-LINE)

Janusz Orkisz, Sławomir Milewski, Witod Cecot
Institute for Computational Civil Engineering
Cracow University of Technology

1. INTRODUCTION

1. INTRODUCTION

1.1 Research subject

Today talk is about energy **transmission** by overhead power lines.
Everybody needs this energy. Are there any **obstacles** in energy transmission?

troubles - **limited** level of energy supply

reality - **ageing** (40 years) infrastructure

- **only two** allowed transmission **safety** thresholds: summer (high temperature) and winter (ice)

change proposed - **S**ystem of **D**ynamic **P**ower **F**low **C**ontrol **T**ransmission using innovative on-line (SDZP) measurements and analysis

effect - estimated gain
SDZP < 15%
graphene 100% ÷ 200%

consortium - Universities 5, Polish Academy of Sciences, Companies 2, Network operators 3 (TAURON, PSG, PSE)

sponsorship - **E**cologic **C**oncepts **G**enerator (GEKON)

our task - **Measurements** aided **numerical analysis** of large 3D displacements of extensible cables in overhead power **transmission lines** searched are solutions:
reliable, precise, fast

CONTENTS

1.2 Main objectives of the research program

SDZP project

- Provide ways and tools for the **optimal** dynamic **management** of **safe** overhead power transmission

Our research

- Using innovative **on-line measurements** develop reliable and efficient tools of **3D on-line analysis** of conductors behaviour in overhead power **transmission lines**.

- Examine various **mechanical** models, their **mathematical formulations** (strong, weak, hybrid mixed), and discrete solution methods (FEM, MFDM, PBA) in order to **find** the **best** solution approach.

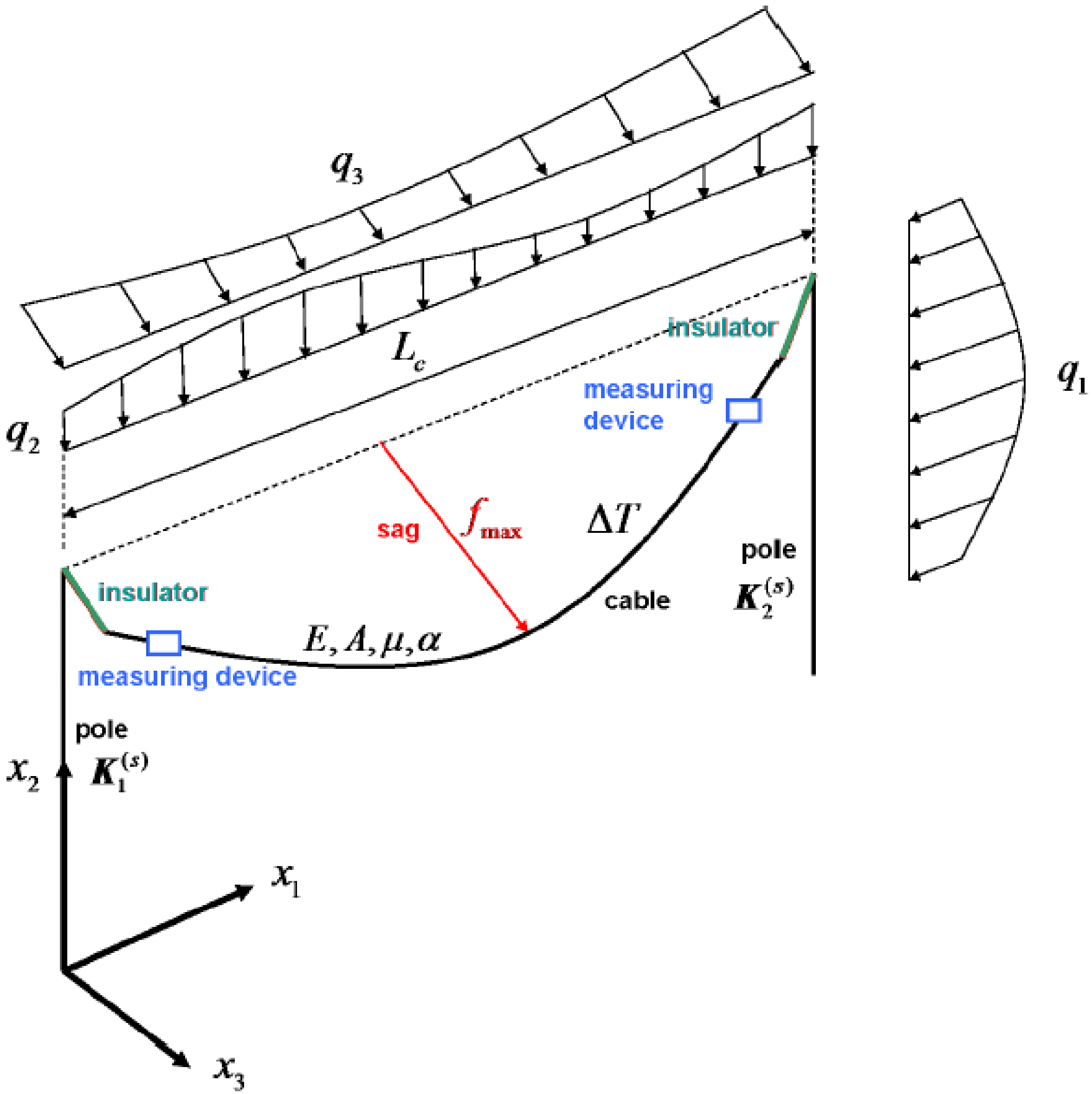
1.3 Categories of engineering tasks involved

I. Evaluation of the **actual**, and the **maximum current safety** of overhead power transmission lines based on technical data, and all **on-line measurements**

II. **Prediction** of overhead power transmission lines behaviour based on technical data and weather forecast (6-72 h only) while **on-line data** are **not available**

III. **Verification** of weather forecast **data** against measured on-line data, and **evaluation of prediction quality** of overhead power transmission lines behaviour

Cable deflection model



2.7 Boundary value problem type A - strong formulation

Find displacement components (in total Lagrangian description):

$u_1(X,t), u_2(X,t), u_3(X,t), \qquad X \in [0, L], \qquad L = L(\beta, t)$

$$\begin{cases} \rho \dfrac{\partial^2 u_i}{\partial t^2} - F_i^{'} = p_i & \textbf{linear momentum} \\ F_i = AE \dfrac{\varepsilon - \alpha \triangle T}{\varepsilon + 1} (\delta_{1i} + u_i^{'}) & \textbf{constitutive relation} \\ \varepsilon = \sqrt{(1 + u_1^{'})^2 + (u_2^{'})^2 + (u_3^{'})^2} - 1 & \textbf{strain definition} \\ \boldsymbol{F} + \boldsymbol{K}^s (\boldsymbol{u} - \hat{\boldsymbol{u}}) = 0 \ \ \textbf{(elastic supports)} & \textbf{b.c. for } X = 0, L \\ +initial \ \ conditions & \end{cases}$$

$i = 1, 2, 3$
$L - unloaded\ cable\ length$
$F_i - axial\ force\ components$
$\boldsymbol{K}^s - elastic\ support\ stiffness\ matrix$
$\hat{u} - unloaded\ support\ position$

deflection curve $\gamma : \begin{cases} x = X + u_1(X) \\ y = u_2(X) \\ z = u_3(X) \end{cases}$

2.8 Boundary value problem type A - weak formulation

$\boldsymbol{u} \in H^1[0,L]$

$$\int_0^L \rho \boldsymbol{v} \cdot \ddot{\boldsymbol{u}} + \int_0^L \boldsymbol{v}' \cdot \boldsymbol{F} \, \mathrm{d}X - \int_0^L \boldsymbol{v} \cdot \boldsymbol{p} \, \mathrm{d}X + \sum_{k=1}^{2} \boldsymbol{v}_k^T \boldsymbol{K}_k^{(s)} (\boldsymbol{u}_k - \hat{\boldsymbol{u}}_k) = 0$$

$\forall \boldsymbol{v} \in H_0^1[0,L]$

Newton-Raphson linearization for static case $\boldsymbol{u}^{(n+1)} = \boldsymbol{u}^{(n)} + \psi$

$$\int_0^L (\boldsymbol{v}')^T \frac{\partial \boldsymbol{F}}{\partial \boldsymbol{u}'} \psi' \, \mathrm{d}X - \int_0^L \boldsymbol{v}^T \frac{\partial \boldsymbol{p}}{\partial \boldsymbol{u}'} \psi' \, \mathrm{d}X +$$

$$+ \int_0^L \boldsymbol{v}' \cdot \boldsymbol{F} \, \mathrm{d}X - \int_0^L \boldsymbol{v} \cdot \boldsymbol{p} \, \mathrm{d}X + \sum_{k=1}^{2} \boldsymbol{v}_k^T \boldsymbol{K}_k^{(s)} (\boldsymbol{u}_k - \hat{\boldsymbol{u}}_k) = 0$$

$\forall \boldsymbol{v} \in H_0^1[0,L]$

2.9 Exact analytical 3D solution – **verification** of numerical model

$$p_1 = 0; \;\; p_2 = \mu = const, \;\; p_3 = const, \;\; u_1(0) = u_2(0) = u_3(0) = 0$$

$$u_1 = \frac{Ct}{p_0}\log\left(\frac{p_0X + D + \sqrt{C^2 + (p_0X + D)^2}}{D + \sqrt{C^2 + D^2}}\right) + \left(\frac{C}{AE} - 1\right)X$$

$$u_2 = \frac{p_2 t}{p_0^2}\left(\sqrt{C^2 + (p_0X + D)^2} - \sqrt{C^2 + D^2}\right) + \frac{p_0X + 2D}{2AEp_0}p_2X$$

$$u_3 = \frac{p_3 t}{p_0^2}\left(\sqrt{C^2 + (p_0X + D)^2} - \sqrt{C^2 + D^2}\right) + \frac{p_0X + 2D}{2AEp_0}p_3X$$

$$p_0 = \sqrt{p_2^2 + p_3^2}.$$

C & D are constants that may be found from two boundary conditions $u_1(L) = c, \;\; \sqrt{u_2^2(L) + u_3^2(L)} = d.$

2.10 Large deflections of inextensible catenary curve

MATHEMATICAL MODEL

differential equation:

$$a\frac{d^2y}{dx^2} = \sqrt{1+\left(\frac{dy}{dx}\right)^2} \quad \text{in } (0, L)$$

with kinematic boundary conditions

$$y(0) = H_0, \; y(L) = H_L$$

analytical solution

$$y = a\cosh\left(\frac{x-C}{a}\right) + D, \qquad x \in [0, L]$$

conditions for the Newton – Raphson procedure

$$\begin{cases} y(0) - H_0 = 0 \\ y(L) - H_L = 0 \\ \Delta L(T) - L_0(1+\alpha T) = 0 \end{cases}$$

where

$$\Delta L_0 = \frac{\Delta L(T_c)}{1+\alpha T_c}$$

$$\Delta L(T_c) = a\left[\sinh\left(\frac{C}{a}\right) - \sinh\left(\frac{C-L}{a}\right)\right]$$

3. Experimental measurements involved

Routine test

surveying measurements of selected cables deflections

use: theoretical model calibration and validation

On-line

Measuring device	Location	Measured quantity
Register	Selected **conductors**	Current intensity I
	close to towers	Conductor temperature T
		Conductor inclination γ and rotation ω angles
Base stations	Selected **towers** close to register	Meteorological data (temp., wind, …
Meteorological station	Nodes of network used for collection meteo data, recalculated to **arbitrary** chosen **point**	Meteo data as for base station and more, no information about conductors as above (I, T, γ , ω)

3. Experimental measurements involved - continued

Use of **on-line** measured data

Metrological data
(**temperature**, wind, …) $\Rightarrow$ power line structure **loading**

conductor inclination $\Rightarrow$ (i) **comparison** of measured
and rotation **angles** γ , ω and calculated results
(ii) **hybrid** theoretical –
experimental **approach**

4. MODELS CALIBRATION AND VALIDATION

4.1 Formulation

Calibration

Evaluation of the model **free** parameter
(here initial cable tension N_0 or initial cable length L_0)
based on surveyors **measurements** of cable **deflection**

Solution approach

(i) **Minimization** of averaged L_2 norm of difference between **measured** cable deflections x_i^E, y_i^E, z_i^E and those calculated upon **theoretical** model, number of measured points of cable

$$\min_{u_1(L_0),u_2(L_0),u_3(L_0)} I$$

$$I^2 = \frac{1}{m}\sum_{i=1}^{m}\left[\left(X_i + u_1(X_i) - x_i^E\right)^2 + \left(u_2(X_i) - y_i^E\right)^2 + \left(u_3(X_i) - z_i^E\right)^2\right]$$

$i = 1, 2, \ldots, m$ - number of measured points of cable

(ii) Theoretical and experimental cable **SAG equality**

Validation

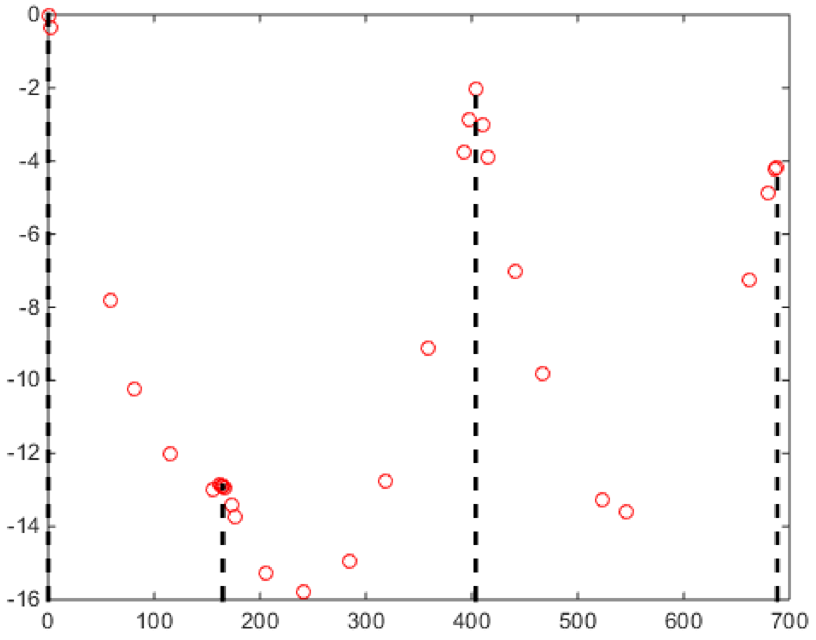
Verification of the model **quality** is done when using in a similar way as above a **new** set of measured cable deflections

We use the **same formula** for I as before but this time values u_1, u_2, u_3 are considered as known from the already **calibrated** theoretical model.
Then we may directly determine I value characterizing model quality

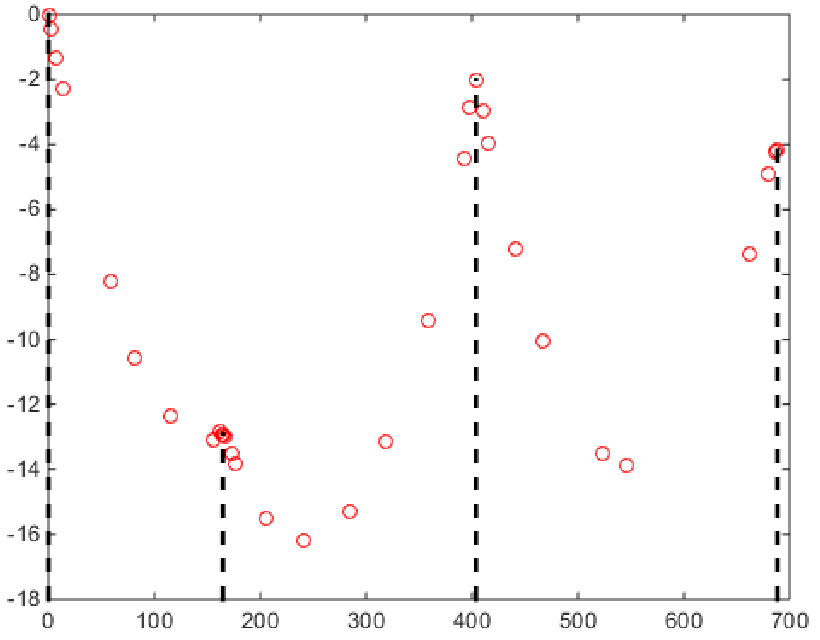
4.2 Results of cable deflections measurements

TAURON POWER TRANSMISSION LINE IN GLIWICE

CALIBRATION DATA (17.03)



VALIDATION DATA (04.04)

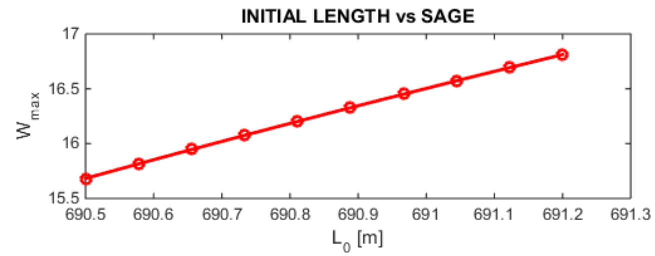


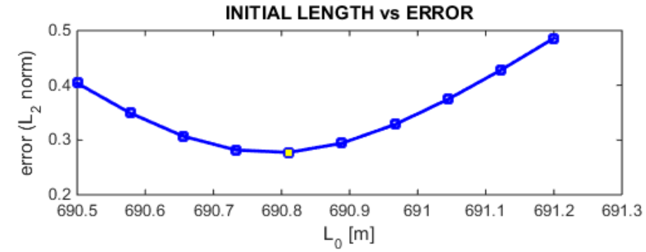
4.3 Results of calibration and validation in Gliwice power line

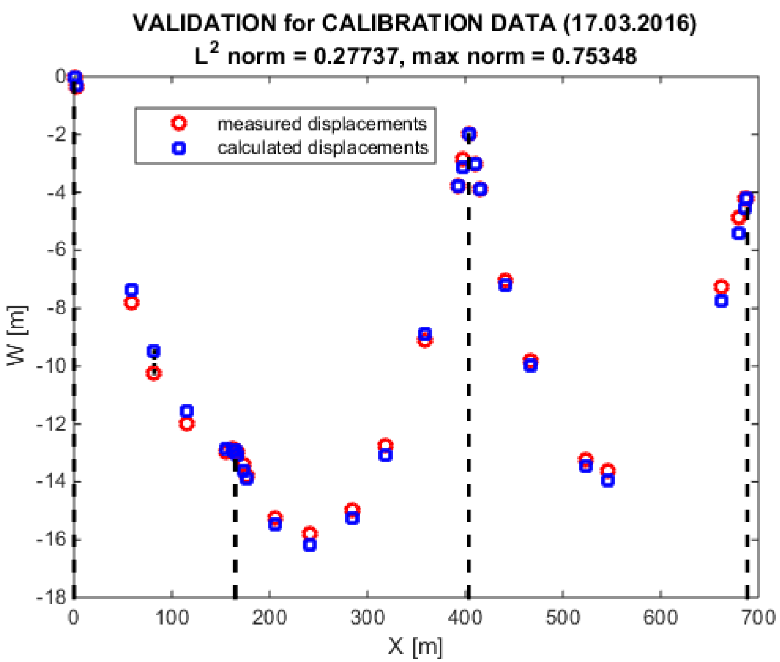
distances between poles: 164.9199 238.8068 284.8194
total = 688.5461

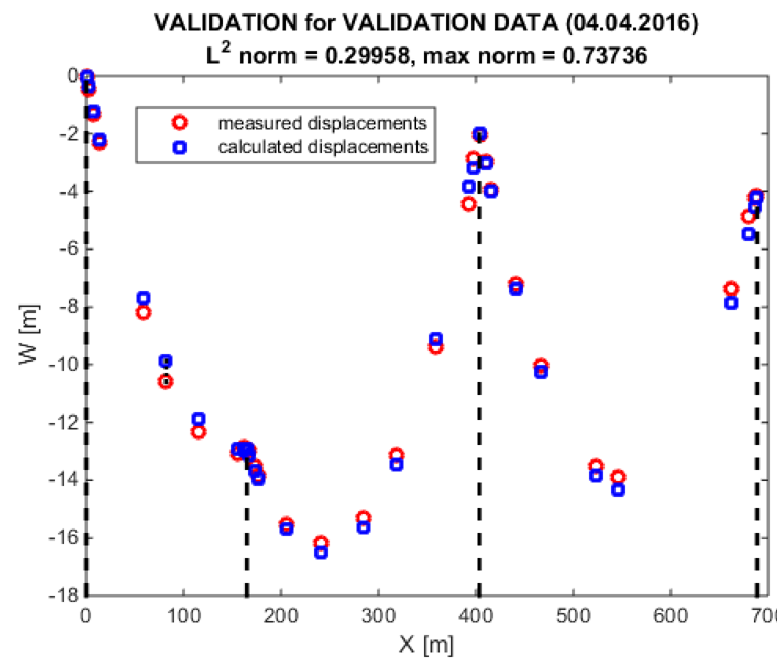
found length = **165.6749 239.5618 285.5744**,
total = 690.8111

ALL MEASUREMENTS DATA
ARE USED AT ONCE





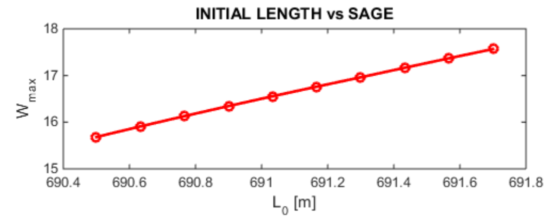


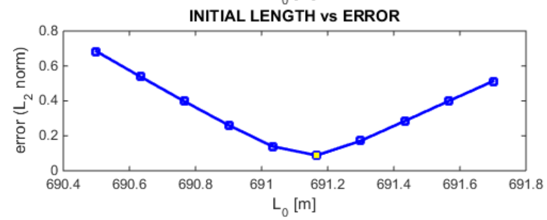


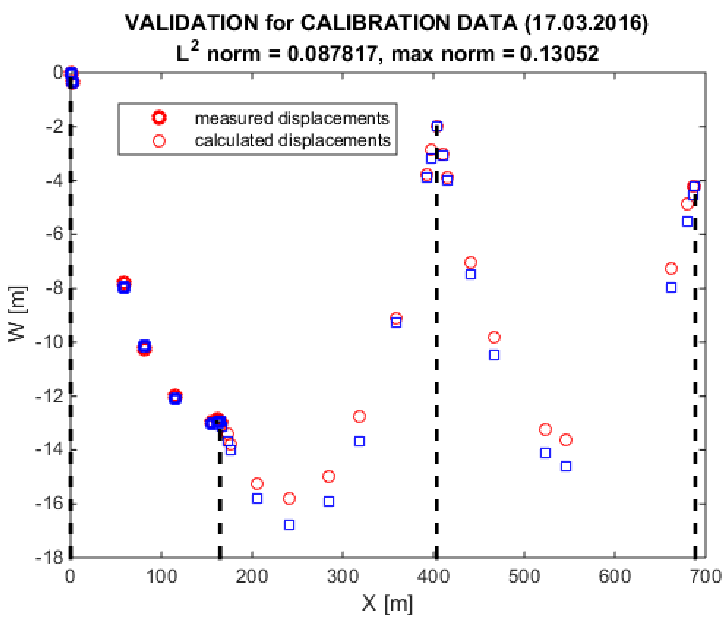
4.3 Results of calibration and validation in Gliwice – cont.

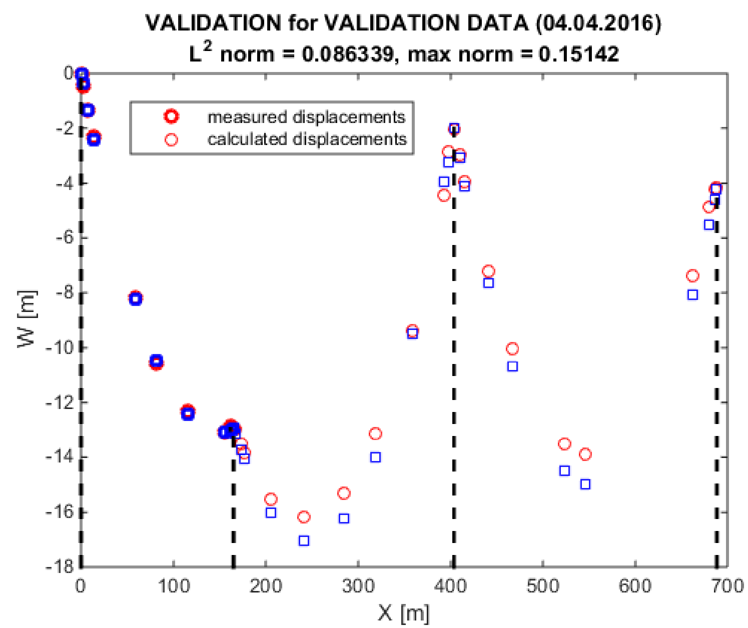
found length = **165.7934** 239.6803 285.6929,
total = 691.1667

ONLY LEFT SPAN MEASUREMENTS ARE USED





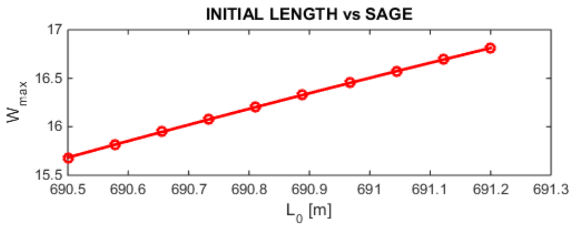


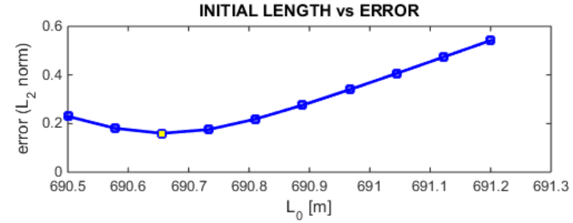


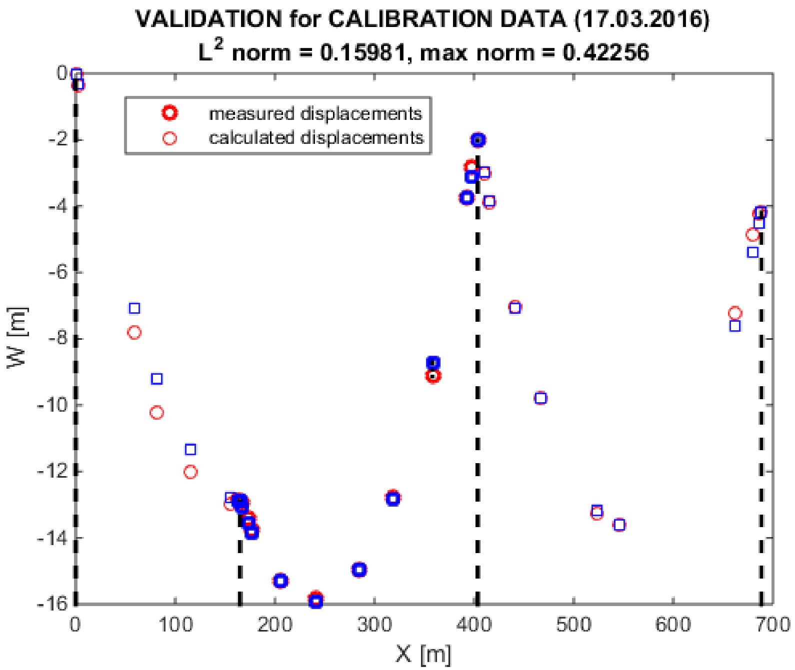
4.3 Results of calibration and validation in Gliwice power line – cont.

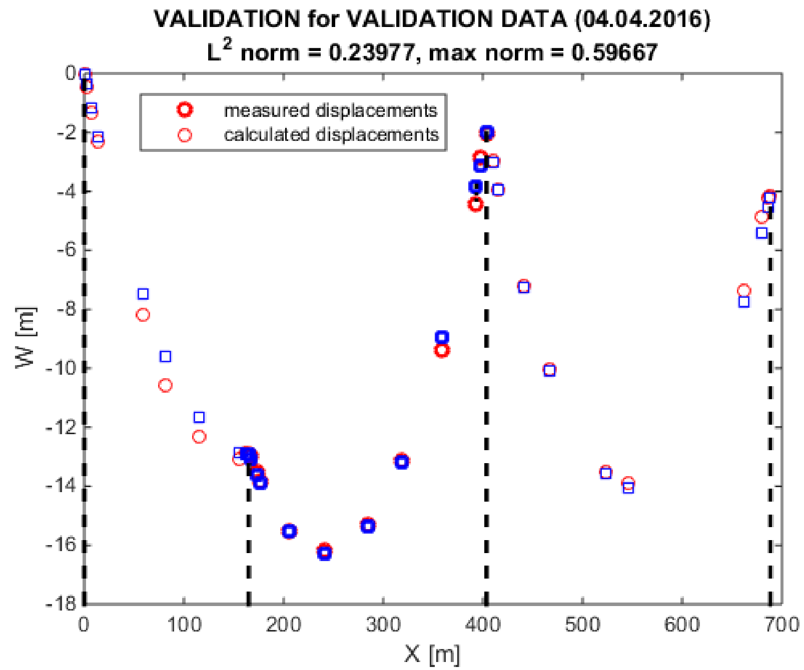
found length = 165.6231 **239.51** 285.5226,
total = 690.6556

ONLY MIDDLE SPAN MEASUREMENTS ARE USED





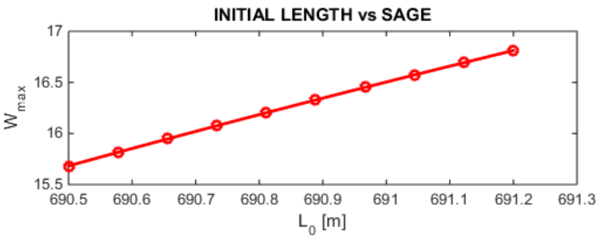


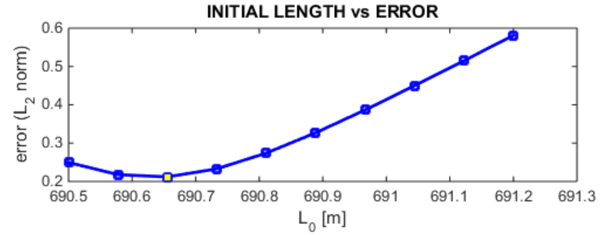


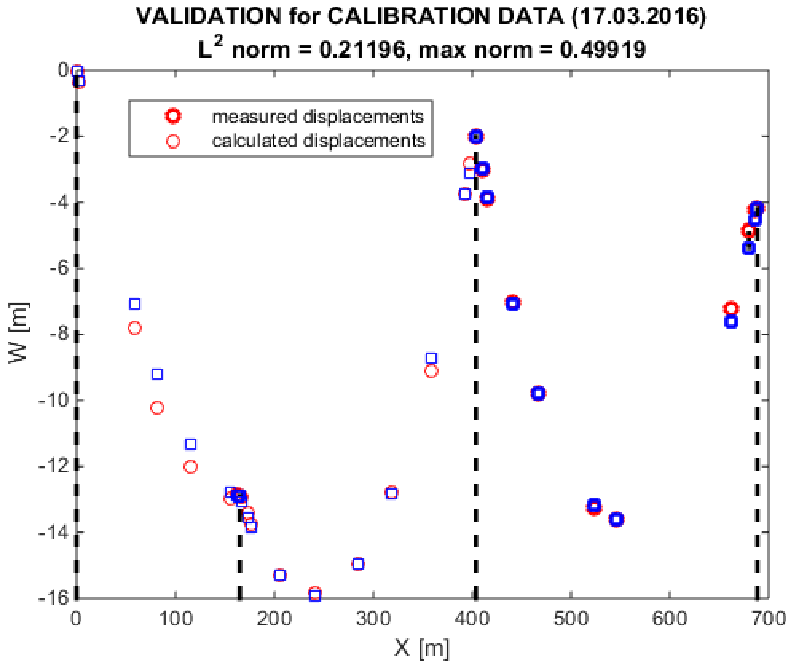
4.3 Results of calibration and validation in Gliwice power line – cont.

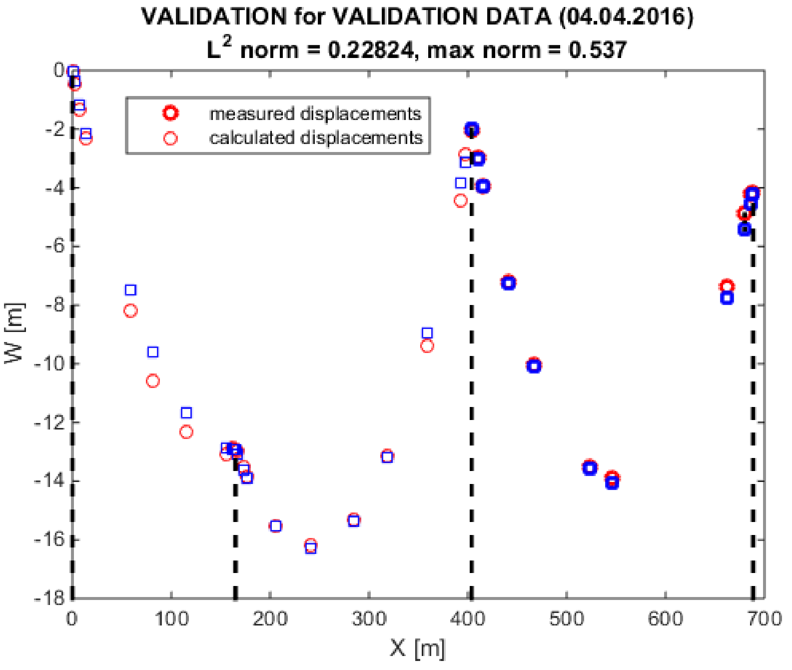
found length = 165.6231 239.51 **285.5226**,
total = 690.6556

ONLY RIGHT SPAN MEASUREMENTS ARE USED

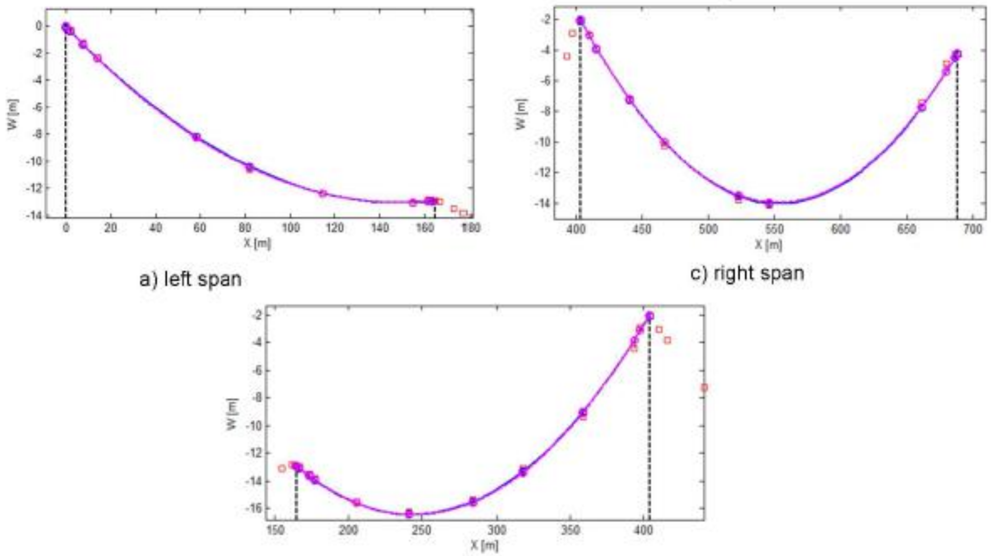








4.4 Comparison of errors of calibrated extensible and inextensible cable models



a) left span

c) right span

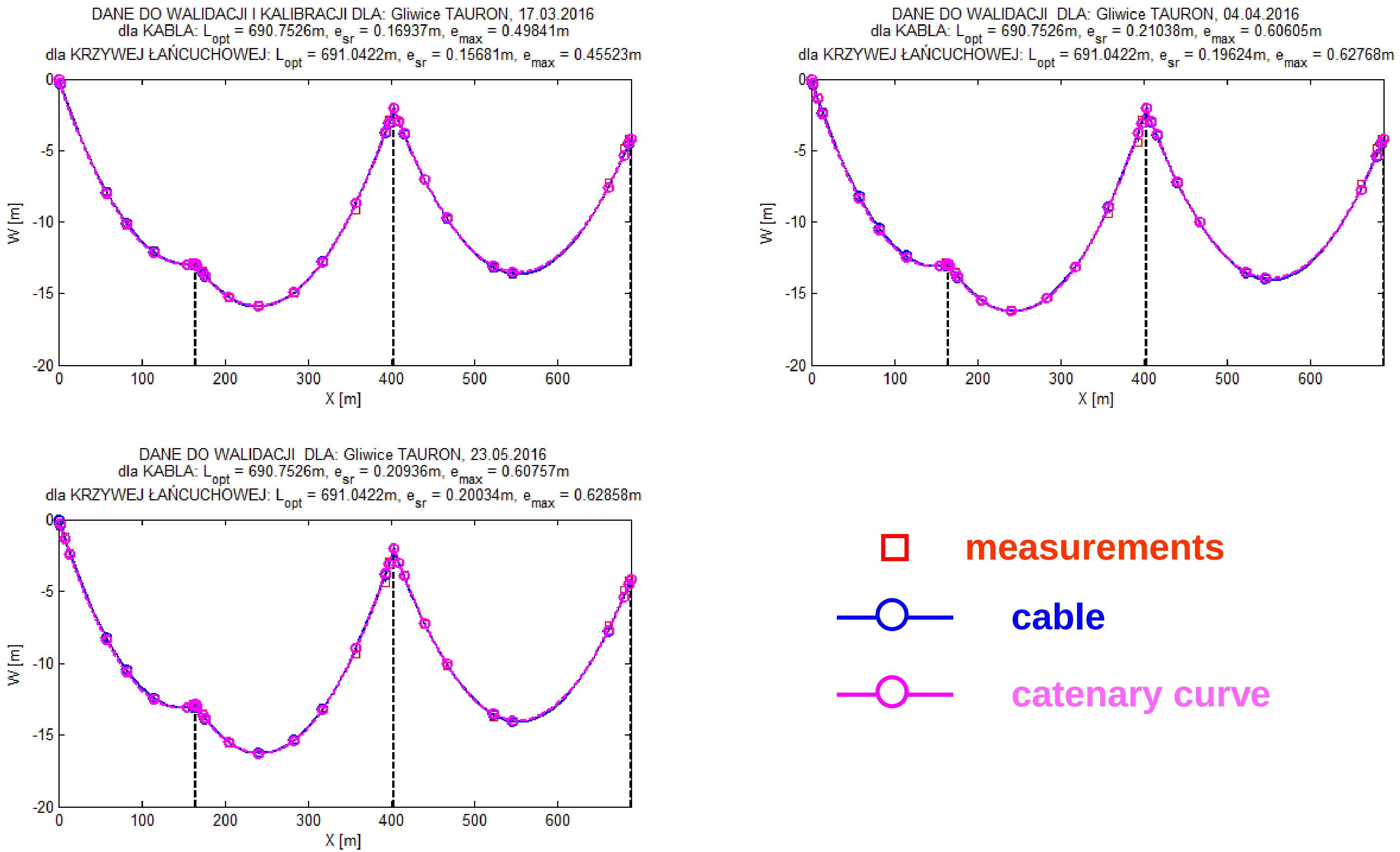
b) middle span

Figure 12: The measured data (red squares) and cable deformations computed by extensible (pink curve) as well as inextensible (blue curve) models after calibration

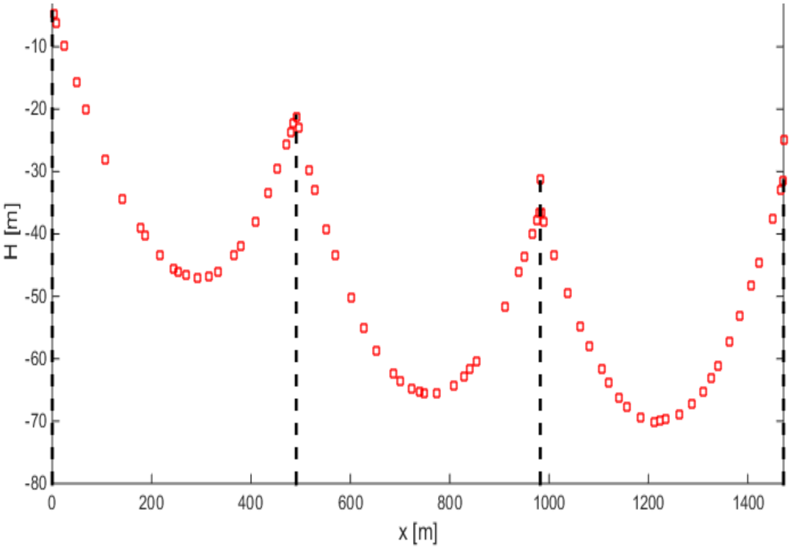
span / location		Gliwice, Poland, *110kV*			Częstochowa, Poland, *220kV*		
		span length	cable	catenary	span length	cable	catenary
left span	mean norm	164.92m	0.057m	0.0464m	491.11m	no data	no data
	max norm		0.194m	0.151m		no data	no data
middle span	mean norm	238.81m	0.145m	0.148m	491.19m	0.241m	0.316m
	max norm		0.593m	0.596m		0.826m	1.005m
right span	mean norm	284.20m	0.142m	0.138m	489.56m	0.357m	0.361m
	max norm		0.534m	0.496m		1.202m	1.057m

Table 1: Norms of errors after calibration

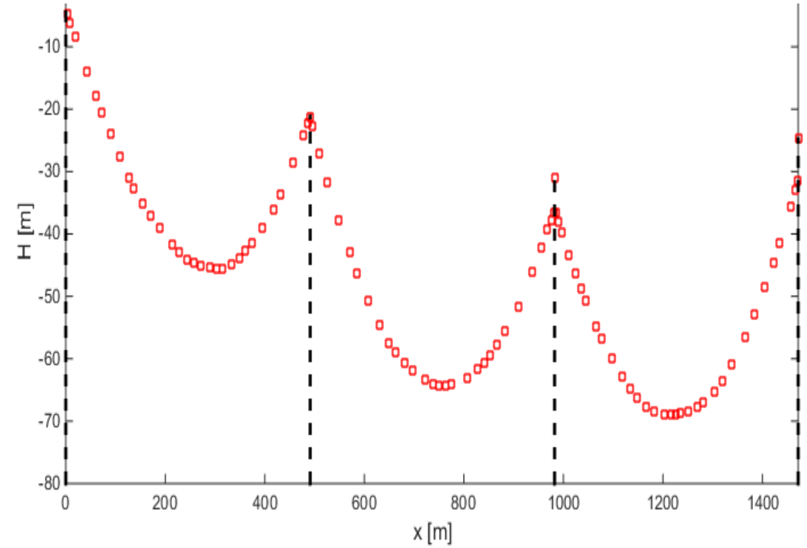
MEASUREMENTS + CABLE + CATENARY CURVE



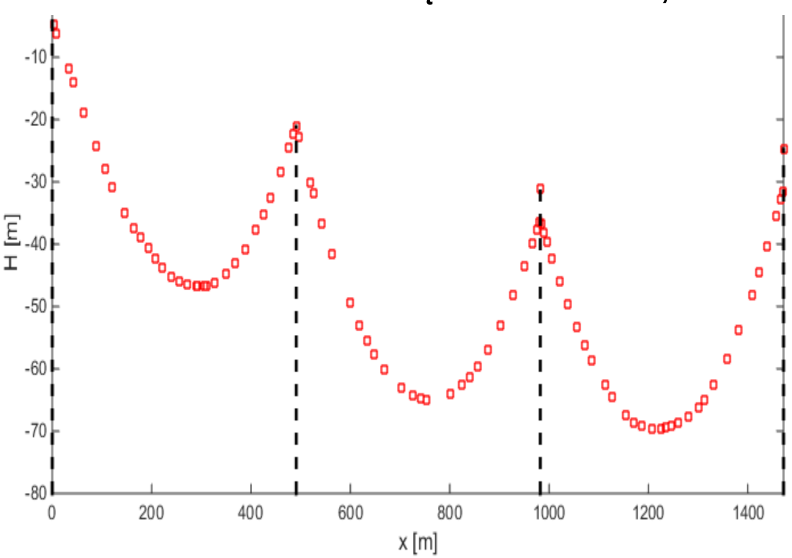
VALIDATION DATA FOR: Częstochowa-PSE, 21.05.2016



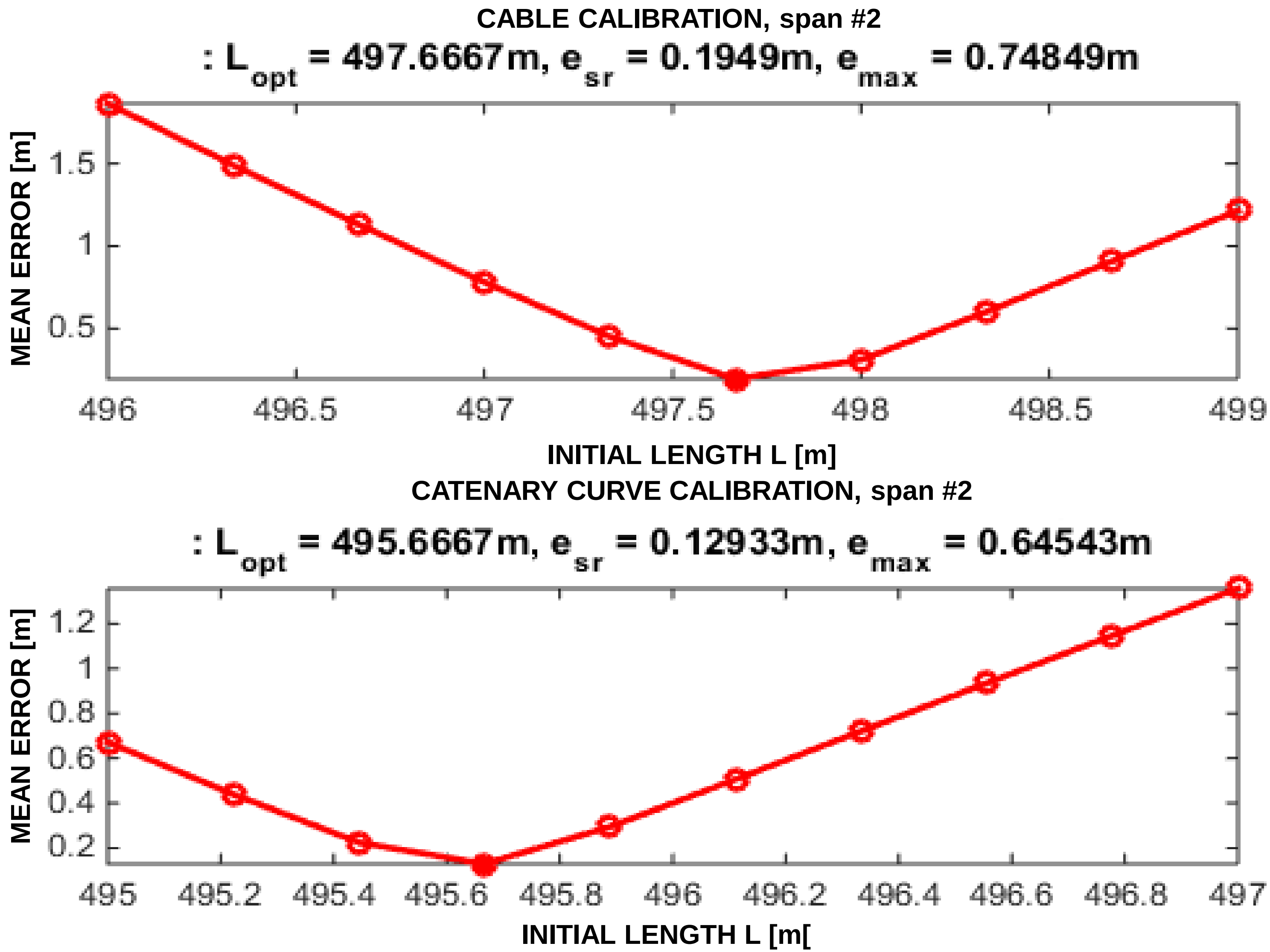
VALIDATION DATA FOR: Częstochowa-PSE, 25.05.2016

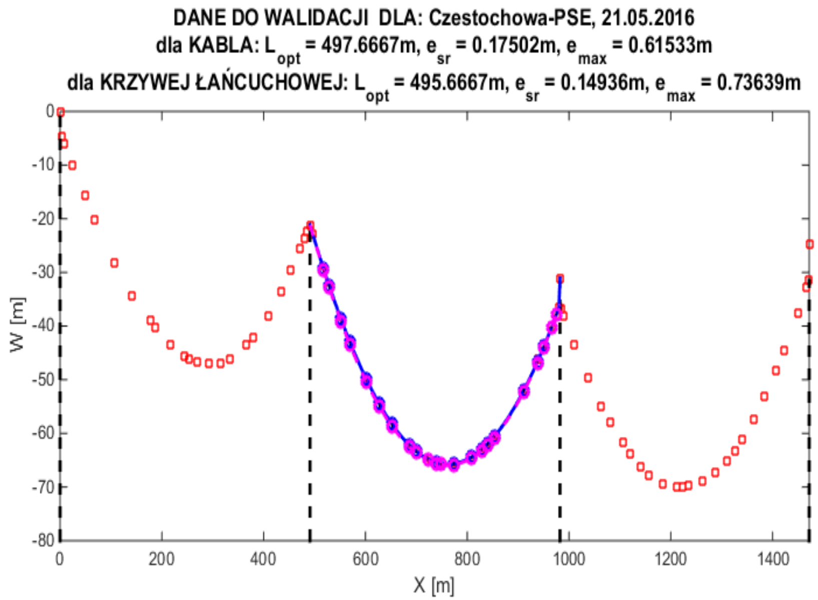


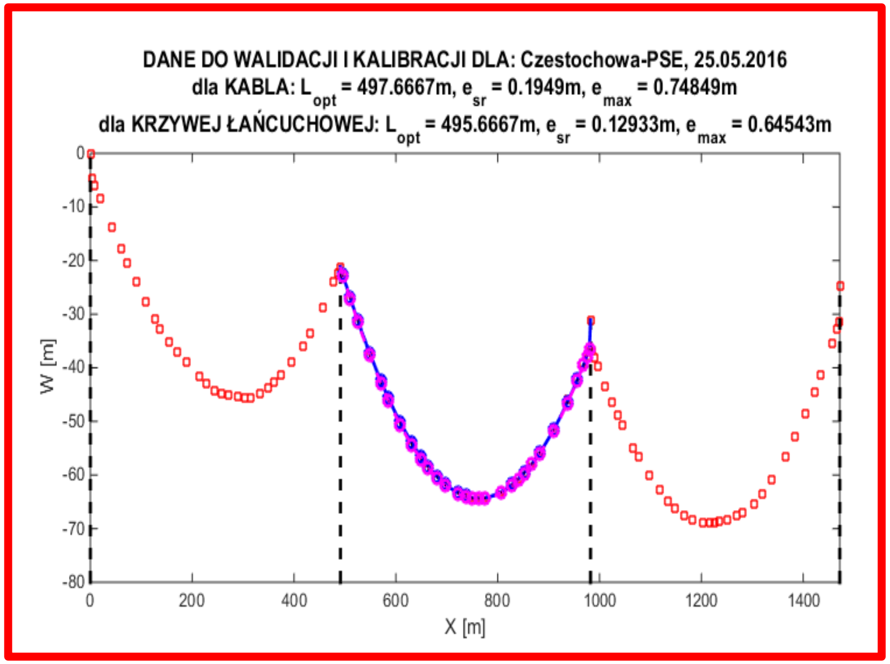
VALIDATION DATA FOR: Częstochowa-PSE, 31.05.2016

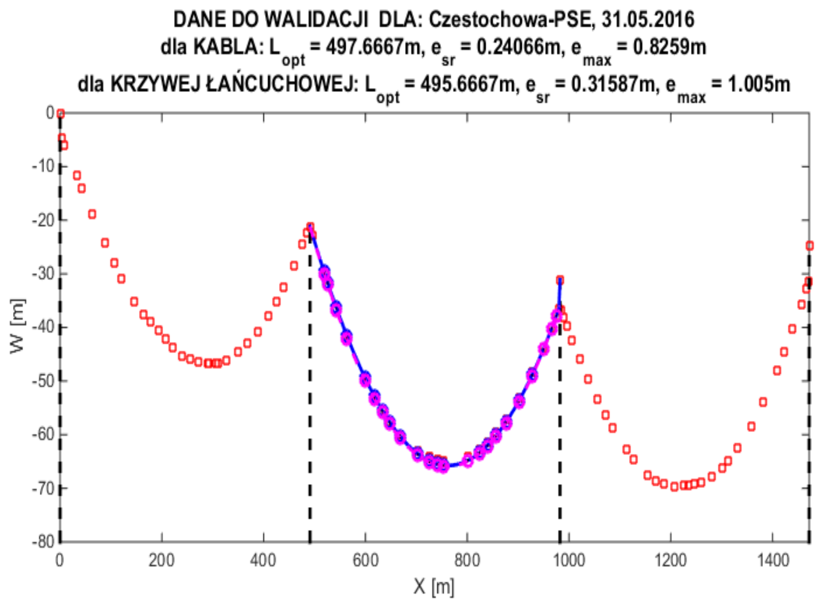


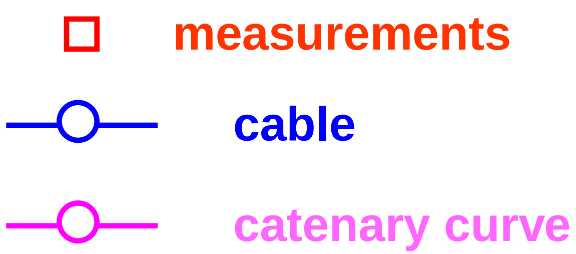
1. PSE S.A. 220kV Joachimów – Huta Częstochowa (double line)


CABLE CALIBRATION, span #2
: L_{opt} = 497.6667m, e_{sr} = 0.1949m, e_{max} = 0.74849m
MEAN ERROR [m]
1.5
1
0.5
496
496.5
497
497.5
498
498.5
499
INITIAL LENGTH L [m]
CATENARY CURVE CALIBRATION, span #2
: L_{opt} = 495.6667m, e_{sr} = 0.12933m, e_{max} = 0.64543m
MEAN ERROR [m]
1.2
1
0.8
0.6
0.4
0.2
495
495.2
495.4
495.6
495.8
496
496.2
496.4
496.6
496.8
497
INITIAL LENGTH L [m[


DANE DO WALIDACJI DLA: Czestochowa-PSE, 21.05.2016
dla KABLA: L_{opt} = 497.6667m, e_{sr} = 0.17502m, e_{max} = 0.61533m
dla KRZYWEJ ŁAŃCUCHOWEJ: L_{opt} = 495.6667m, e_{sr} = 0.14936m, e_{max} = 0.73639m
W [m]
X [m]


DANE DO WALIDACJI I KALIBRACJI DLA: Czestochowa-PSE, 25.05.2016
dla KABLA: L_{opt} = 497.6667m, e_{sr} = 0.1949m, e_{max} = 0.74849m
dla KRZYWEJ ŁAŃCUCHOWEJ: L_{opt} = 495.6667m, e_{sr} = 0.12933m, e_{max} = 0.64543m
W [m]
X [m]


DANE DO WALIDACJI DLA: Czestochowa-PSE, 31.05.2016
dla KABLA: L_{opt} = 497.6667m, e_{sr} = 0.24066m, e_{max} = 0.8259m
dla KRZYWEJ ŁAŃCUCHOWEJ: L_{opt} = 495.6667m, e_{sr} = 0.31587m, e_{max} = 1.005m
W [m]
X [m]


measurements
cable
catenary curve

4.5 Comparison of calibrated catenary and extensible cable deflections (Gliwice power line)

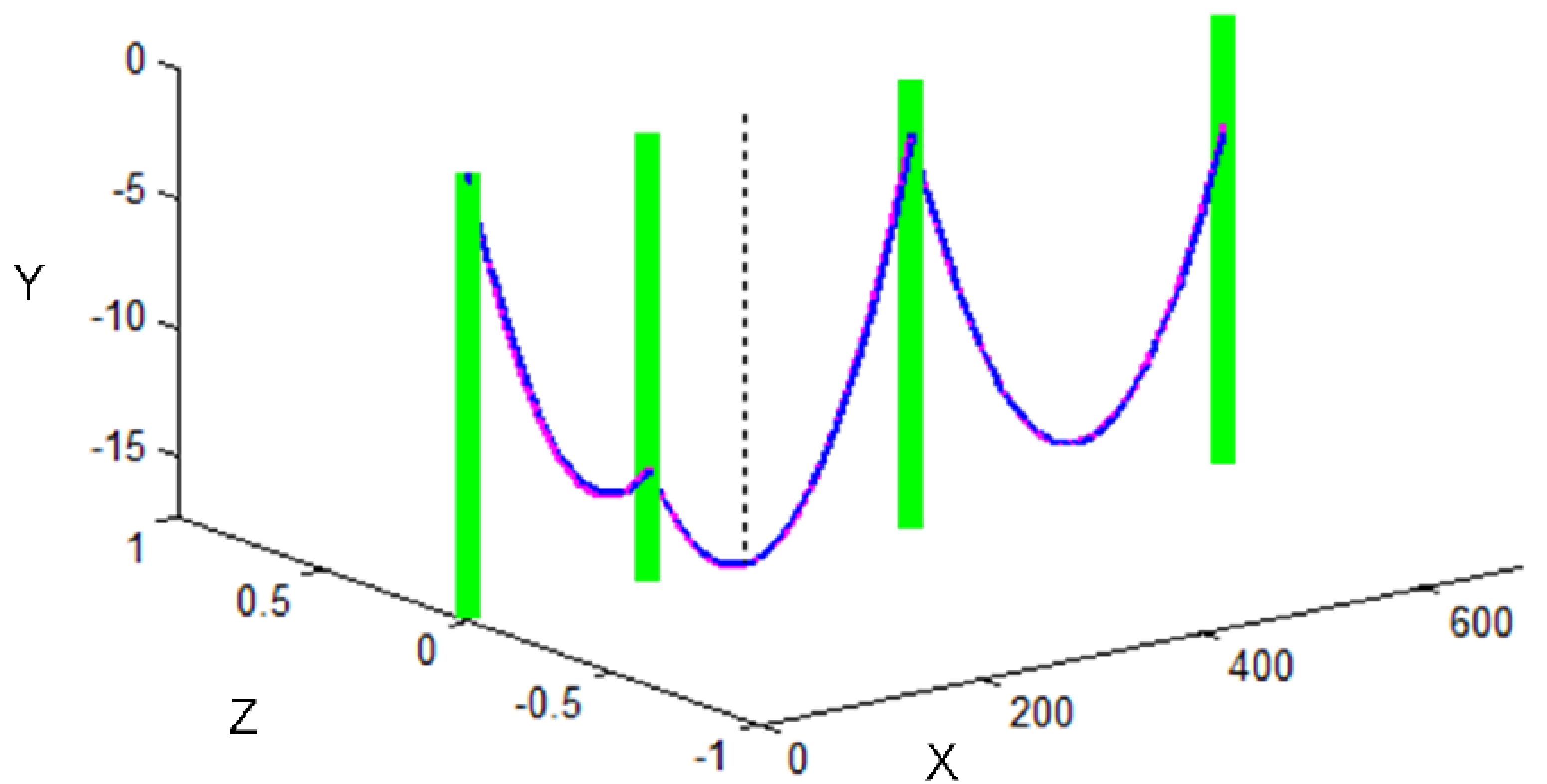
$Sag_{catenary} = 17.45m$

$Sag_{cable} = 17.36m$

Air temperature

80°C

Solution difference norms:
mean norm = 10cm, max. norm = 24cm



5. HYBRID THEORETICAL – EXPERIMENTAL ANALYSIS OF OVERHEAD POWER TRANSMISSION LINES

Constrained nonlinear optimization problem

5.1 Types of **on-line measured data**, and ways of their use

data types

= **weather conditions**, electric **current** induced data $\Rightarrow$ conductors loadings

= **angles** of conductor **inclination** and **rotation**

chosen **ways** of **use** of measured angles

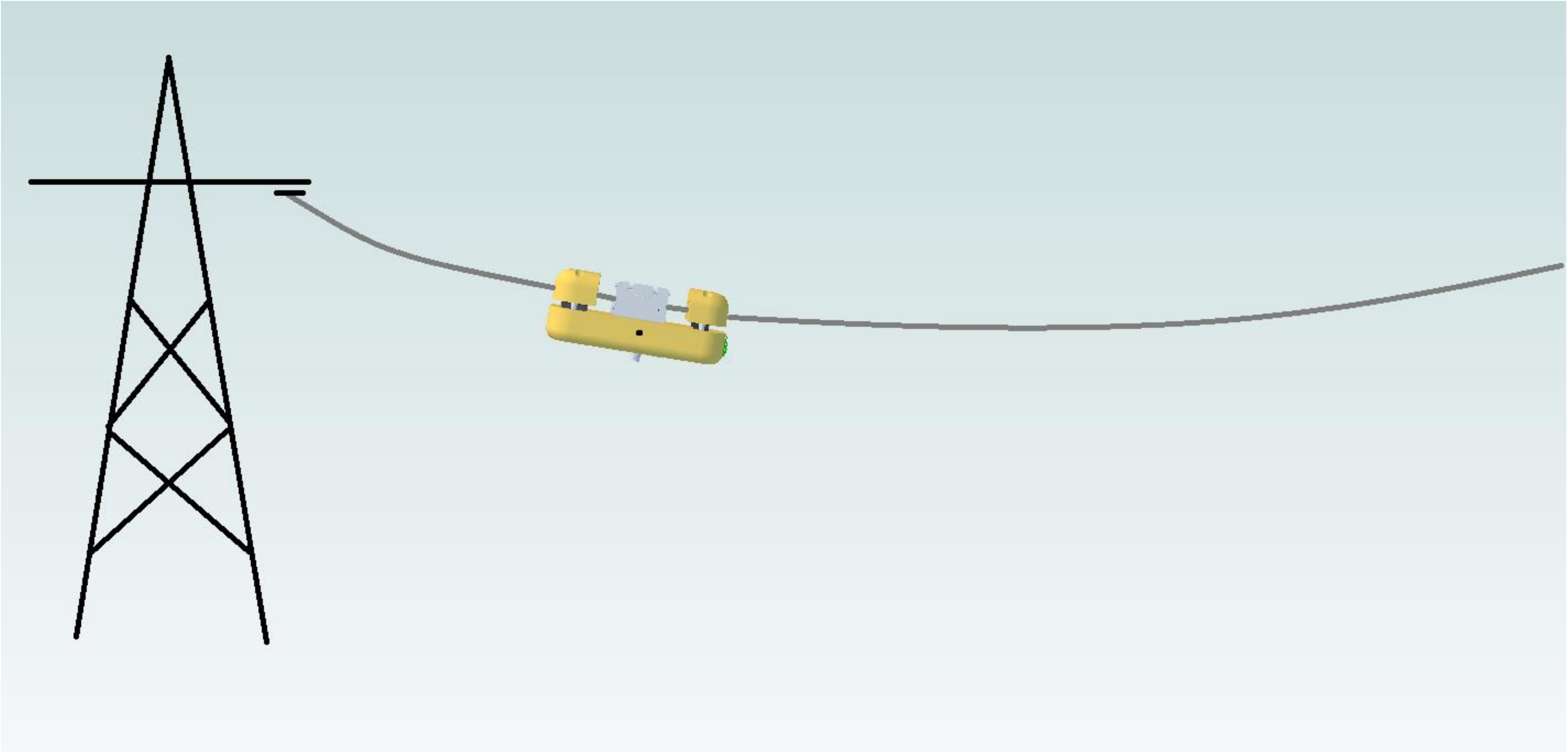
= **comparison** of **measured** and **calculated data** itself

= cable deflections analysis including measured data

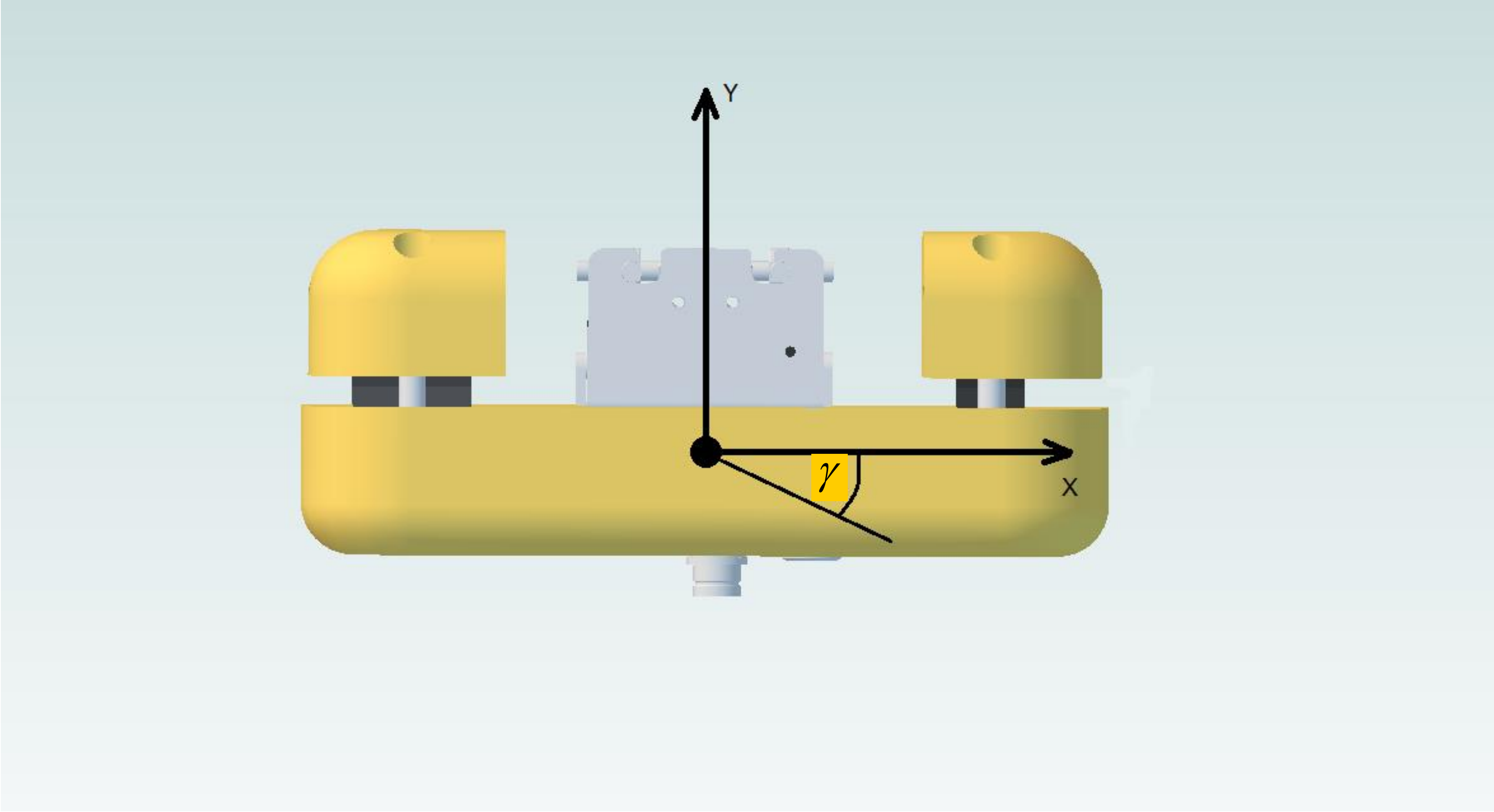
- Approach I: including angle measurements into common **simultaneous hybrid theoretical-experimental-numerical solution** approach

- Approach II: use of measured cable **inclination** and **rotation angles** to appropriate modification of initial data and solution of cable deflections b.v.problem mentioned above

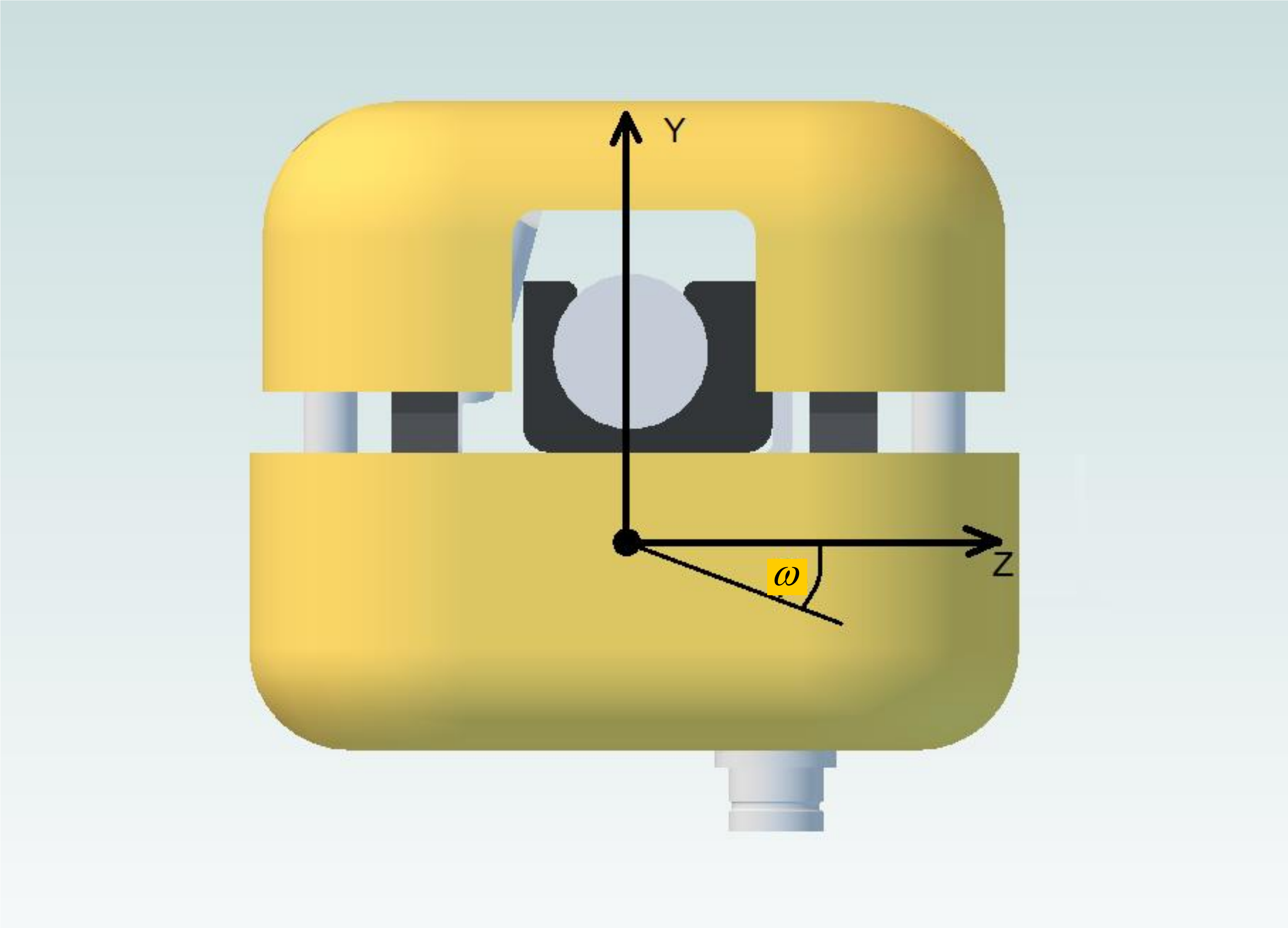
5.2 Measurement of cable inclination angles by EC Systems



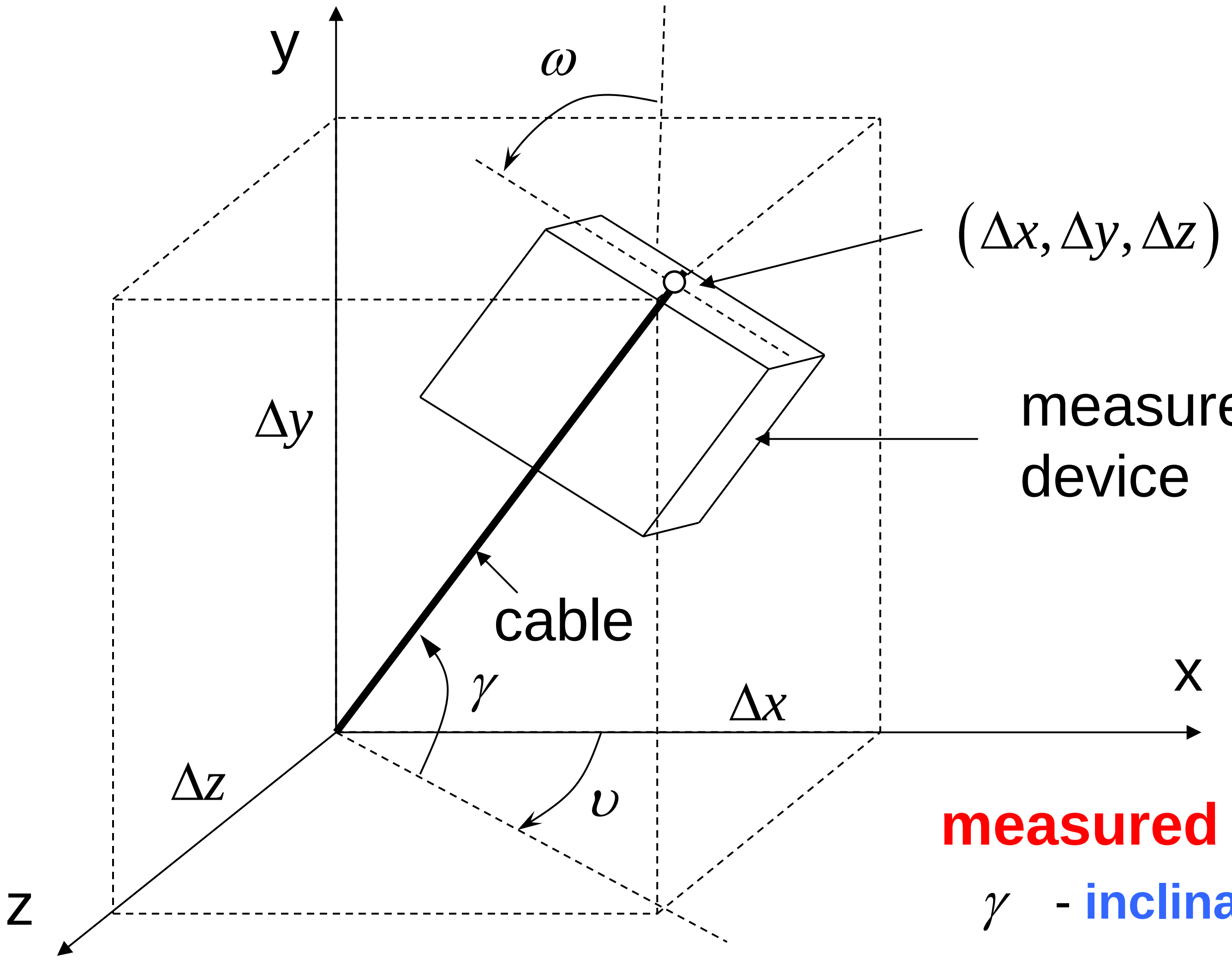
Cable inclination measurement



Cable rotation measurement



On-line measured angles



measured

γ - **inclination** angle

$$tg\gamma = \frac{\Delta y}{\sqrt{(\Delta x)^2 + (\Delta z)^2}}$$

ω - **rotation** angle

5.3 **Hybrid solution approach** I using the physically based approximation (PBA) for **simultaneous** analysis of **theory** and all **experimental** data

General formulation

find the **stationary point** of the functional

$$\phi(u,\lambda) = \lambda \phi^T(u) + (1-\lambda)\phi^E(u) \qquad \lambda \in [0,1]$$

satisfying **equality** and **inequality constraints**

$$A(u) = b$$
$$B(u) < e$$

where ϕ^T and ϕ^E are dimensionless **theoretical** and **experimental** parts of the functional.

Formulation for conductors displacements $\boldsymbol{u}(X)$

Theoretical part - only variational form available

$$\delta\varphi^T = \frac{1}{C}\left\{ \int_0^L v' \cdot \mathbf{F}\, dX - \int_0^L v \cdot \mathbf{p}\, dX + \sum_k^2 v_k^T \cdot \mathbf{K}_k^{(s)} (u_k - \hat{u}_k) \right\}$$

C – parameter for dimensionless variational form

Experimental part – for measured inclination γ^E and rotation ω^E angles as well as displacements

$$\phi^E = \frac{1}{J+2K} \sum_{k=1}^{K} \left\{ \left[\frac{tg\gamma_k - tg\gamma_k^E}{e_{\gamma_k}} \right]^2 + \left[\frac{tg\omega_k - tg\omega_k^E}{e_{\omega_k}} \right]^2 \right\} + \sum_{j=1}^{J} \left(\frac{\left\| P_j - P_j^E \right\|}{e_{P_j}} \right)^2, \quad \left\| P_j - P_j^E \right\|^2 = \left(x_j - x_j^E\right)^2 + \left(y_j - y_j^E\right)^2 + \left(w_j - w_j^E\right)^2$$

Two steps **solution procedure**

(i) solve

$$\delta\varphi = \lambda\delta\varphi^T + (1-\lambda)\delta\varphi^E = 0 \quad \to \quad \boldsymbol{u}(X,\lambda)$$

(ii) find $\lambda_{\max}$ for $\boldsymbol{u}(X,\lambda)$, $\lambda \in [0,\ 1]$

satisfying **inequality constraints**

local error

$$\left|\frac{tg\gamma_k - tg\gamma_k^E}{e_{\gamma_k}}\right| \le 1 \quad , \quad \left|\frac{tg\omega_k - tg\omega_k^E}{e_{\omega_k}}\right| \le 1 \quad , \quad \frac{\left\|P_j - P_j^E\right\|^2}{e_{P_j}^2} \le 1 \ , \quad j = 1,2,\ldots,J, \quad k = 1,2,\ldots,K$$

global error

$$\sqrt{\Phi^E} < \frac{1}{m}, \quad m \ge 1, m \approx 2 \div 5$$

where

$$tg\gamma_i^T = \frac{1}{\Delta}\int_{\Delta} tg\gamma\, dX = \frac{1}{\Delta}\int_{\Delta} \frac{y'}{\sqrt{(x')^2 + (z')^2}}\, dX \approx \frac{\Delta y}{\sqrt{(\Delta x)^2 + (\Delta z)^2}}$$

$$tg\omega_i^T = \frac{1}{\Delta}\int_{\Delta} tg\omega\, dX = \qquad \approx h(\Delta x, \Delta y, \Delta z)$$

may be expressed in terms of unknown $\boldsymbol{u}$ quantities

e_{γ_k} , e_{ω_k} , e_{P_j} admissible **measurement tolerances**

5.4 Accounting for measurement data - approach II

Whenever $\left|\omega^E - \frac{1}{\Delta}\int_\Delta \omega(T^E, \hat{L}, \hat{q}, \hat{p})\, \mathrm{d}X\right| > e_\omega$

$$\left[T^E, \hat{L}, \hat{q}, \hat{p}\right] = \hat{\boldsymbol{Z}} \;\rightarrow\; \tilde{\boldsymbol{Z}} = \left[\tilde{T}, \tilde{L}, \tilde{q}, \tilde{p}\right]$$

$$J(\boldsymbol{Z}) = \alpha_\omega \left[\int_\Delta \omega(\boldsymbol{Z})\, \mathrm{d}X - \omega^E \Delta\right]^2 + \alpha_T (T - T^E)^2$$

α_ω, α_T − **appropriate weights**

$J(\tilde{\boldsymbol{Z}}) = \min_{\boldsymbol{Z}} J(\boldsymbol{Z})$ **subject to** $|\tilde{Z}_i - \hat{Z}_i| \leqslant e_z$

$$\boldsymbol{u} = \boldsymbol{u}(\tilde{T}, \tilde{L}, \tilde{q}, \tilde{p})$$

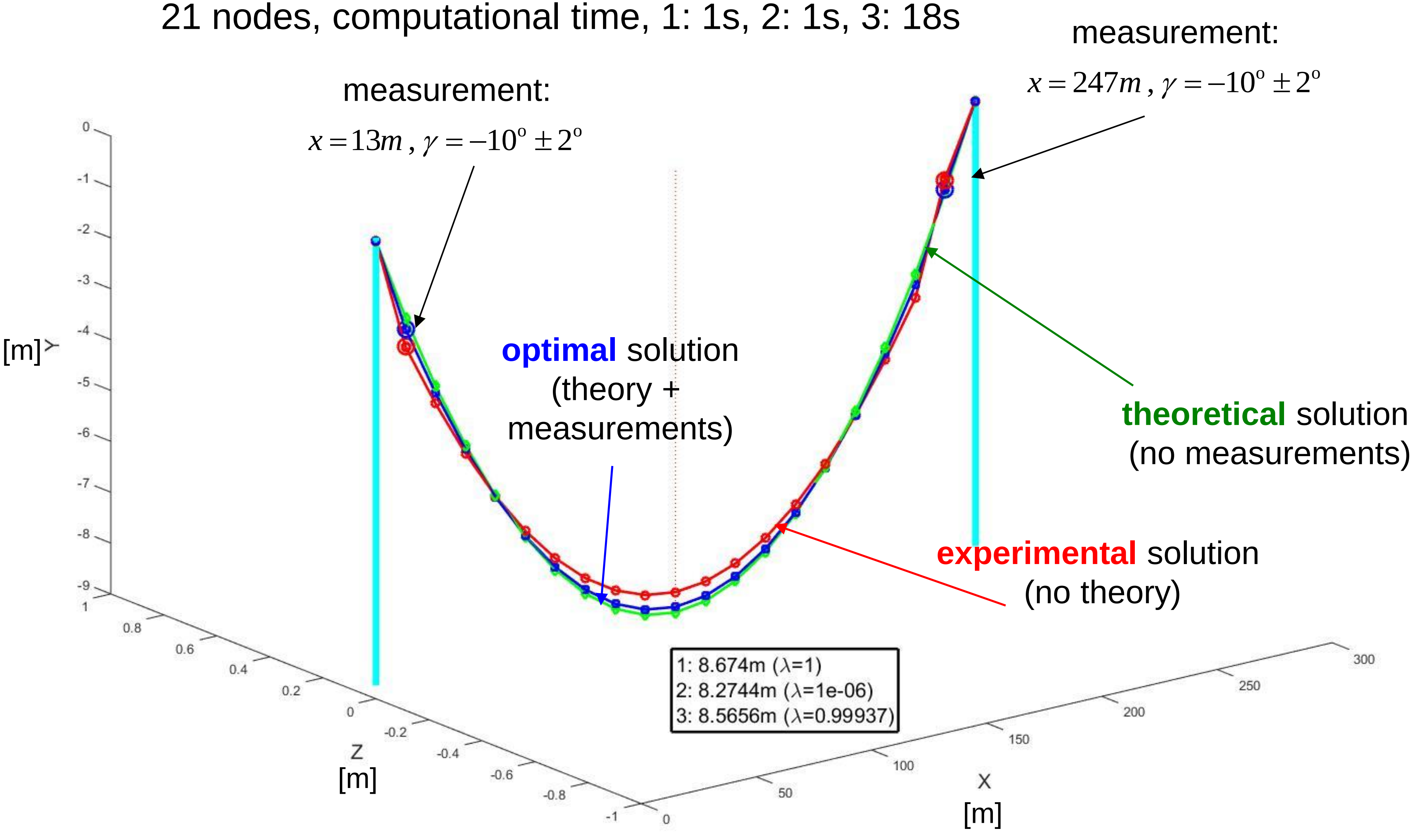
Other measured quantities, like angle γ or wind q may be also considered in $J(\boldsymbol{Z})$.

5.5 Approach comparisons

TEST DATA **#2** (EP) – **Approach I**

Influence of measurement data (MFDM)

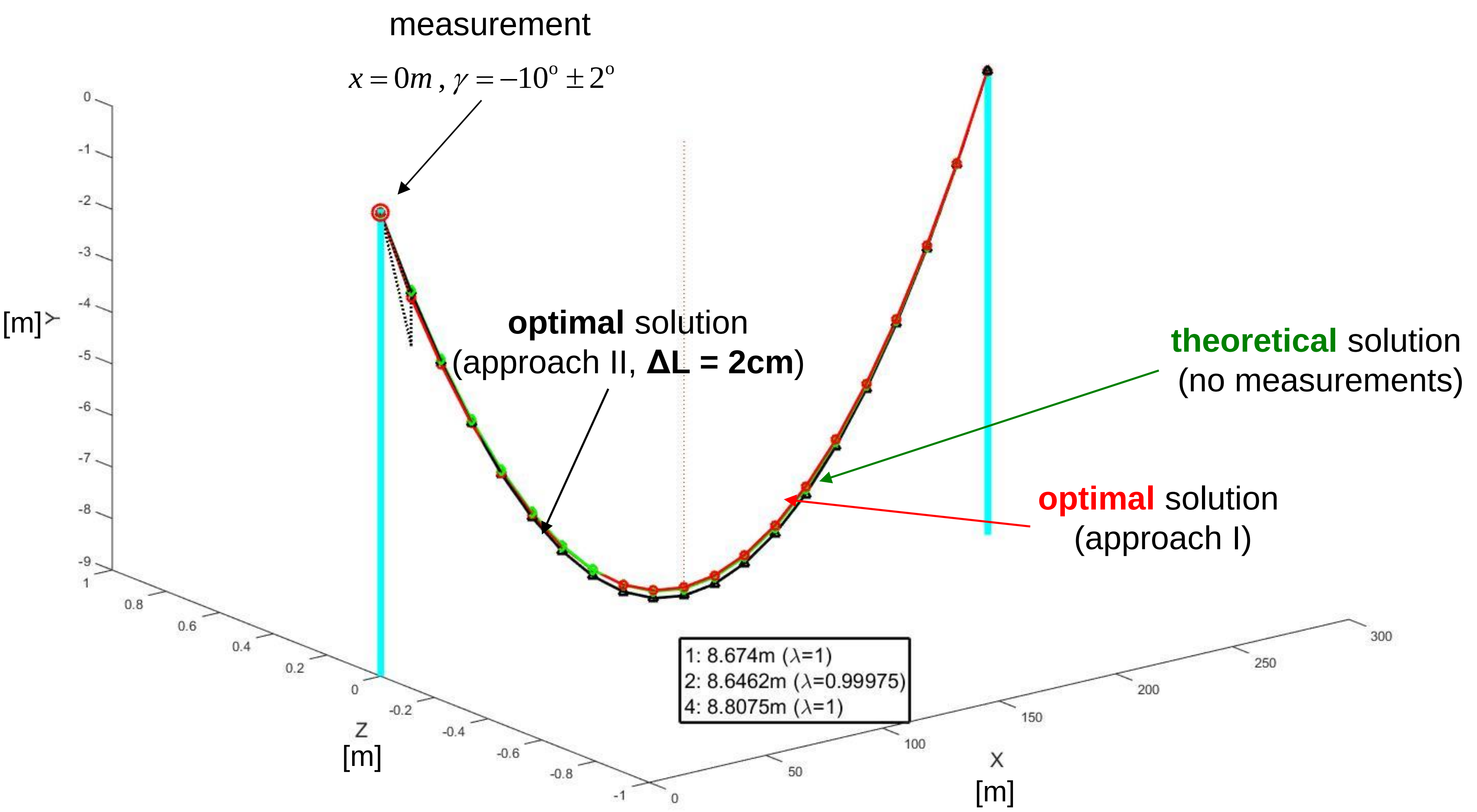
21 nodes, computational time, 1: 1s, 2: 1s, 3: 18s



TEST DATA **#2** (EP) – **Approach I** against **Approach II**

Influence of measurement data (MFDM – approach I, FEM – approach II)

21 nodes, computational time, 1: 1s, 2: 18s, 3: 1s

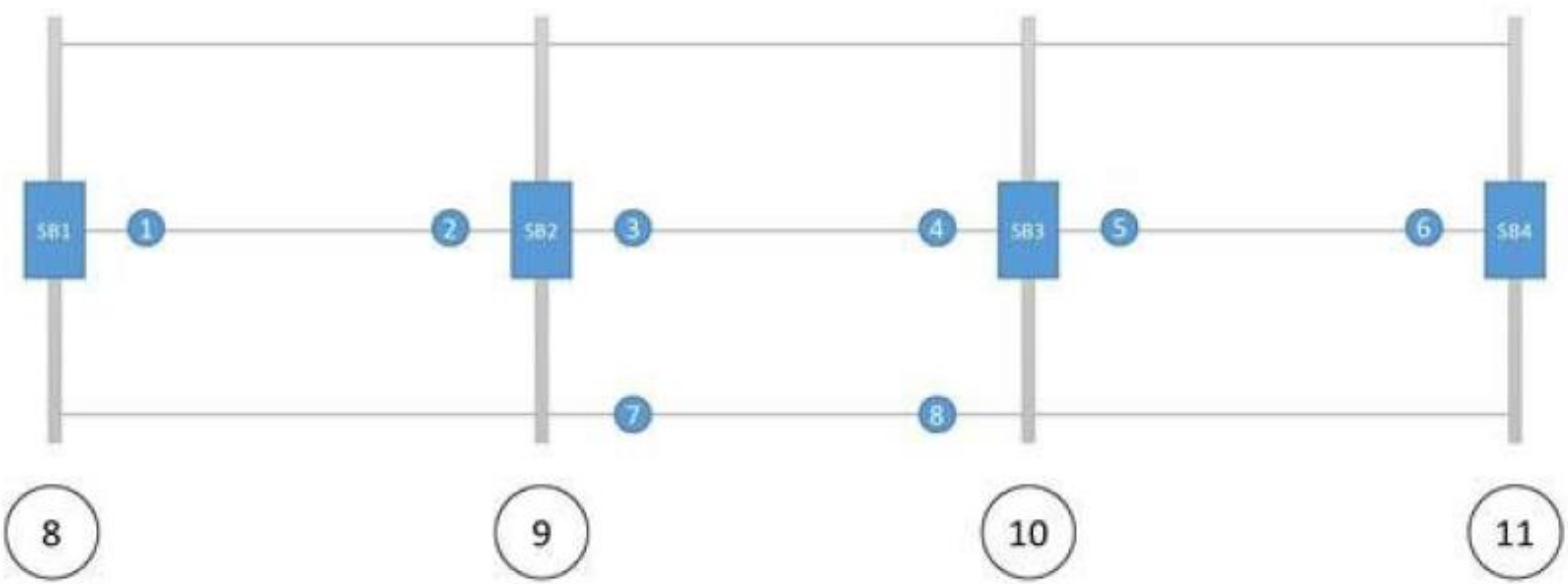


6. PILOT FIELD ANALYSIS FOR CHOSEN SECTION OF TAURON POWER TRANSMISSION LINE IN GLIWICE

6.1 Gliwice layout

6.1 Gliwice layout – cont.

6.1 Gliwice layout – cont.



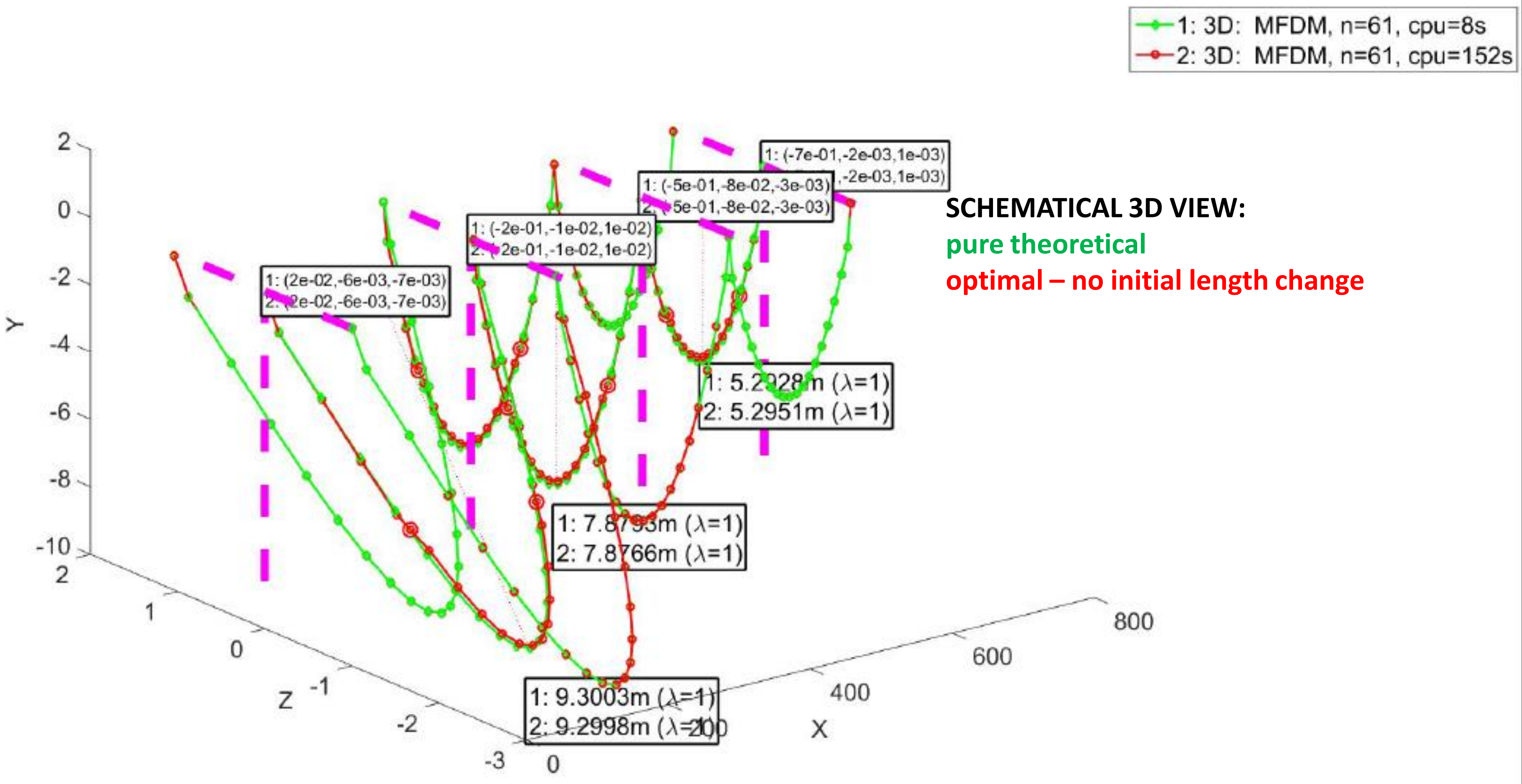
base station tower mounted

tower

cable register device

conductors

6.2 Analysis of 3-span section from Tauron power line – MFDM solution approach – no initial length change

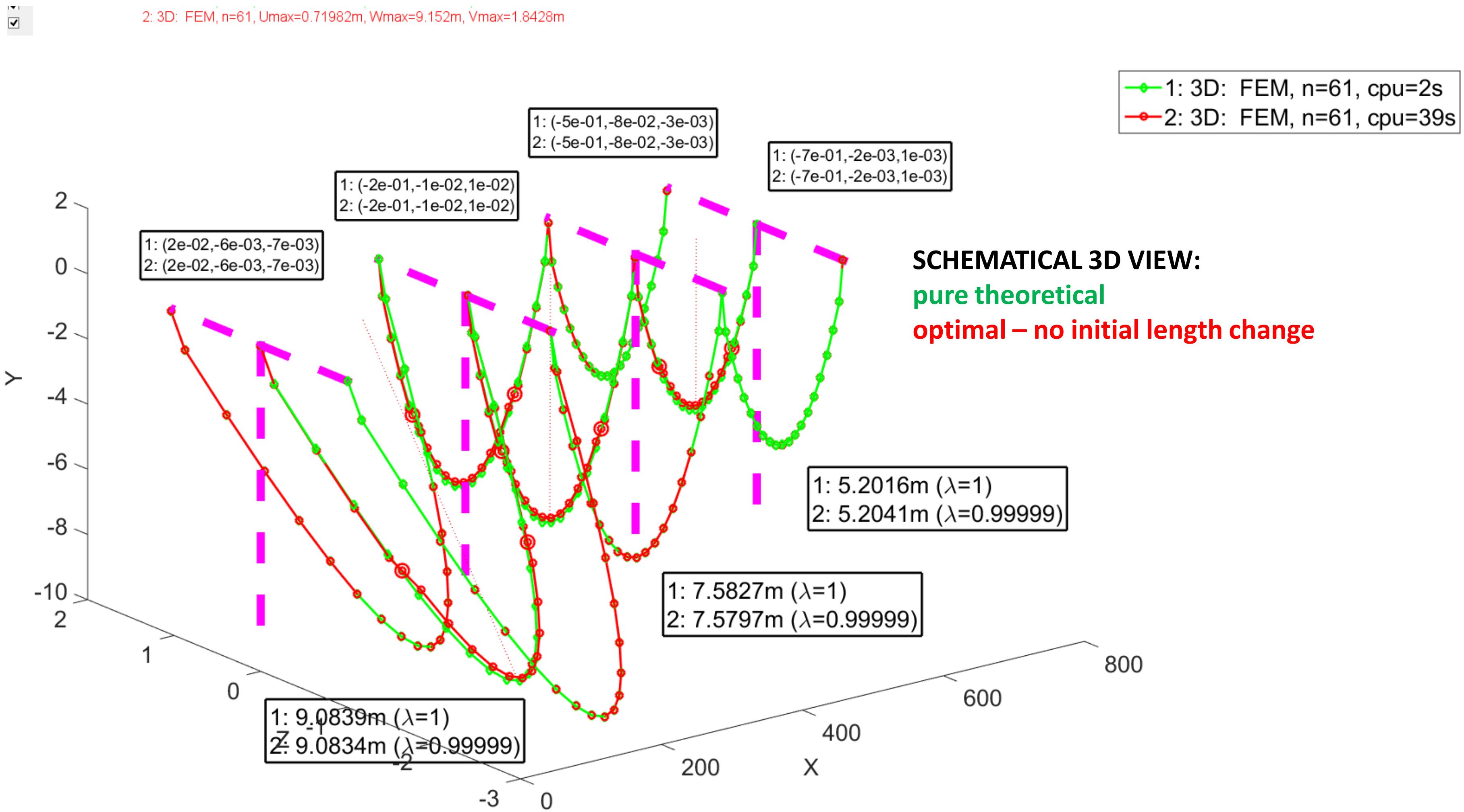


SCHEMATICAL 3D VIEW:

pure theoretical

optimal – no initial length change

6.2 Analysis of 3-span section from Tauron power line – FEM solution approach – no initial length change



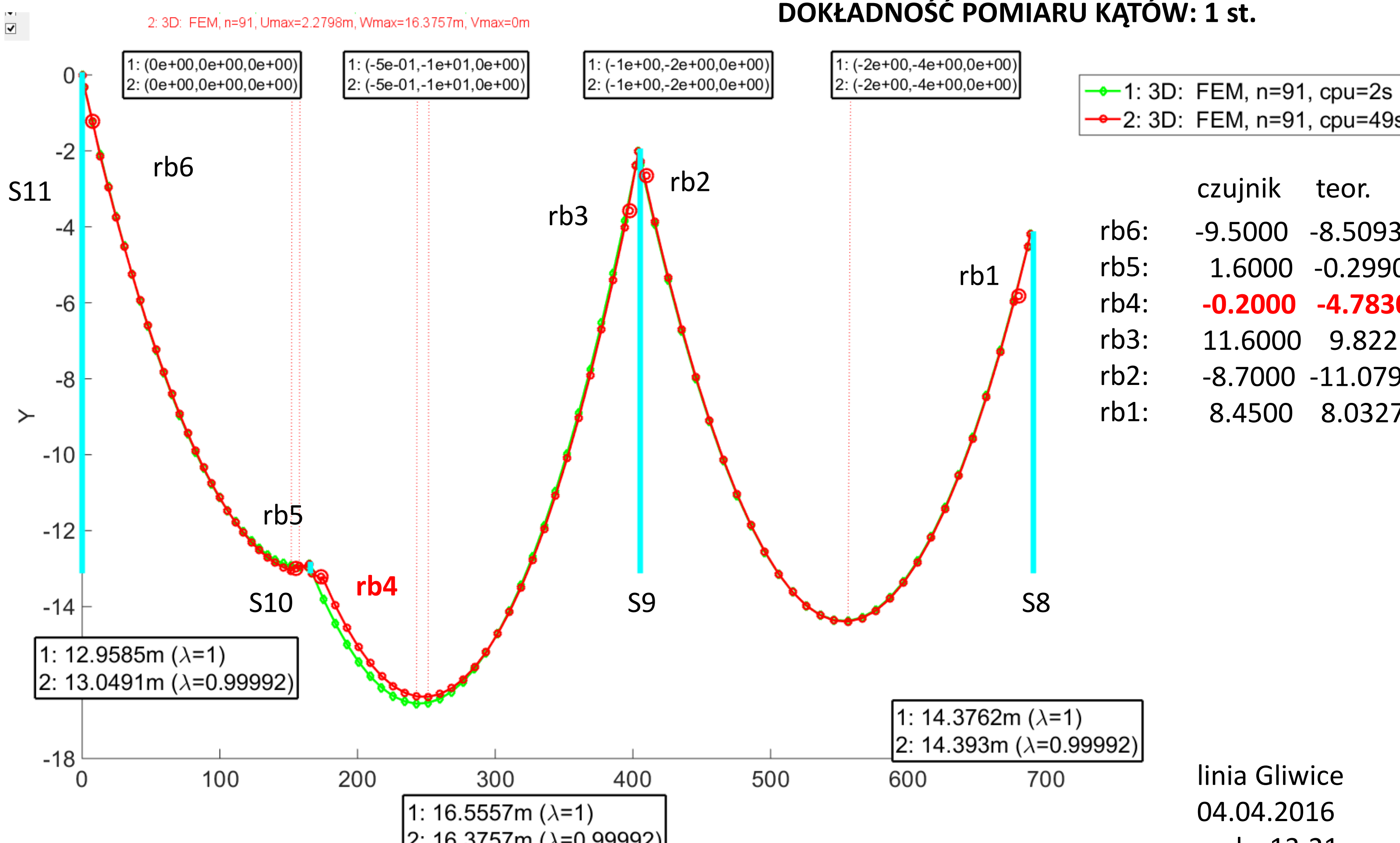
SCHEMATICAL 3D VIEW:

pure theoretical

optimal – no initial length change

6.3 Hybrid theoretical-experimental analysis of exemplary case from Tauron power line in Gliwice after model calibration

DOKŁADNOŚĆ POMIARU KĄTÓW: 1 st.



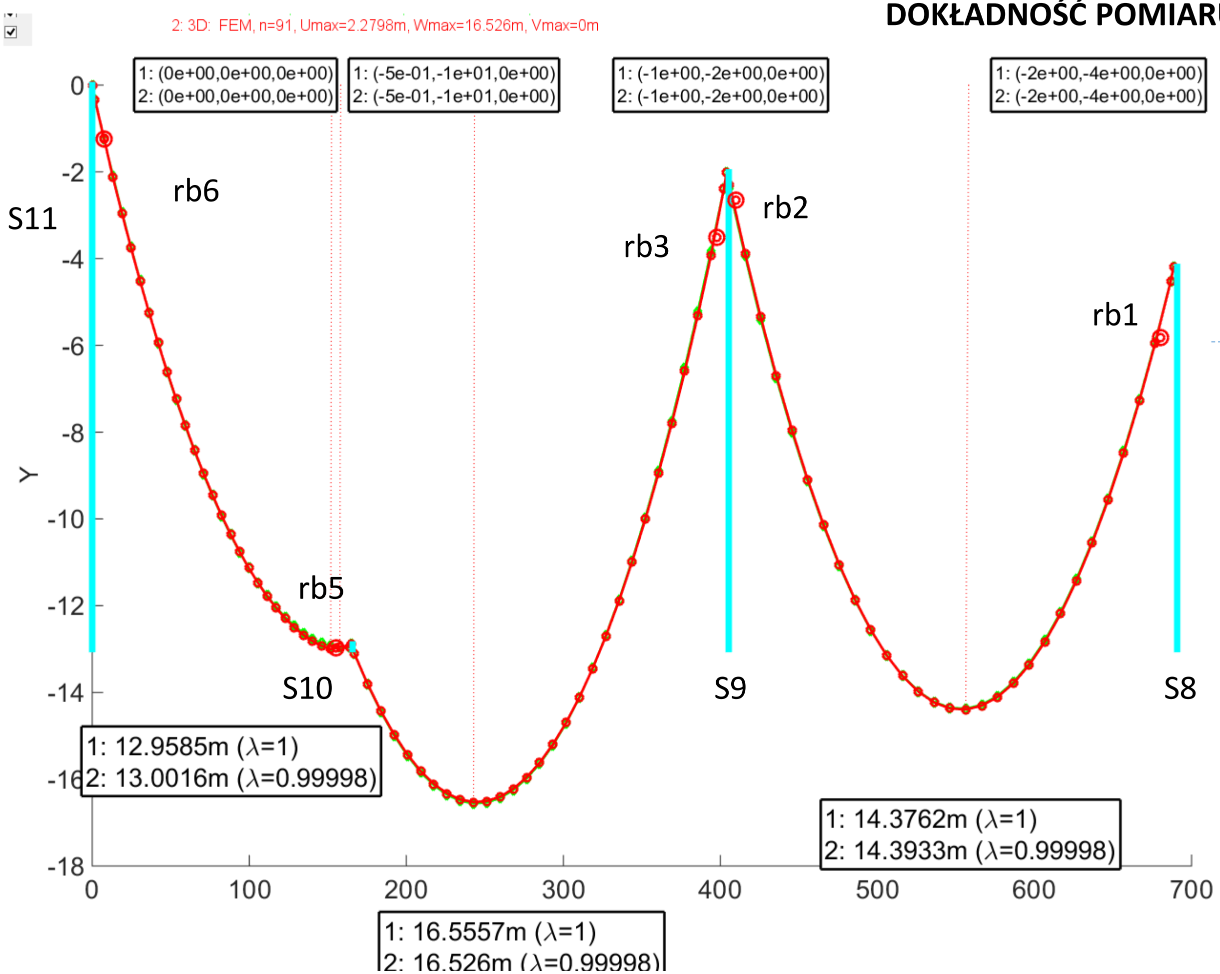
	czujnik	teor.	optym.
rb6:	-9.5000	-8.5093	-9.1574
rb5:	1.6000	-0.2990	1.2304
rb4:	**-0.2000**	**-4.7830**	**-1.1994**
rb3:	11.6000	9.8221	10.9791
rb2:	-8.7000	-11.0790	-8.7132
rb1:	8.4500	8.0327	8.2569

linia Gliwice
04.04.2016
godz. 13:21

6.3 Hybrid theoretical-experimental analysis of exemplary case from Tauron power line in Gliwice after model calibration - RB4 data removed

DOKŁADNOŚĆ POMIARU KĄTÓW: 1 st.

RB4 DATA REMOVED



	czujnik	teor.	optym.
rb6:	-9.5000	-8.5093	-8.8848
rb5:	1.6000	-0.2990	0.6160
rb4:	0	0	0
rb3:	11.6000	9.8221	10.4301
rb2:	-8.7000	-11.0790	-9.1174
rb1:	8.4500	8.0327	8.1577

linia Gliwice
04.04.2016
godz. 13:21

7. ON RELIABILITY AND PRECISION OF NUMERICAL SOLUTION AND MEASURED DATA INVOLVED

- **Variety of models developed and applied as well as tests made**
- **Various sensitivity tests**

Comparison and checking results obtained from various models

- 3 **models** 1D, 2D, 3D (inextensible and extensible)
- 3 mathematical **formulations**
  - 1 **strong** (non-linear PDE)
  - 2 **weak** (variational principle)
    - **global**
    - hybrid **mixed** global-local (**MLPG-5**)
- 2 discretization **methods**
  - **FEM**
  - **MFDM** (Meshless Finite Difference Method)
- **various** approximation **orders** (1-6)
- 3 **methods** of **non-linear** analysis
  (simple iterations, Newton-Raphson, relaxation)
- 3 **independent** computer **codes** (2 own + 1 commercial)
- **a-posteriori error** analysis
- large **variety** of numerical **tests**

8. FINAL REMARKS

8.1 Brief summary

- **Developed** and **tested** were reliable mechanical and mathematical models as well as relevant case study computer codes providing very fast and precise **3D analysis** of **large cable** displacements, as well as up to 3 spans sections of **overhead power transmission** lines.

- Due to real engineering problem considered special attention was paid to **reliability** of the results obtained. Therefore, several **independent approaches** were investigated.

- For these approaches examined and compared were

  =**precision** of results obtained (a-posteriori error analysis ?), their

  =**convergence**, and convergence rate

  =**stability**

  =**efficiency** (computational time)

- Occasional surveying measurements of conductors displacements were used for theoretical model **calibration** and **validation**

- Results of **innovative on-line measurements** (weather data and cable inclination and rotation angles) were incorporated into analysis of large displacements of cables. **Two** different original solution **approaches** are proposed.

- For **prevailing self-weight** loading both the inextensible (catenary curve) and extensible cable models provide results **close** enough to **measured** displacement data as the in-situ validation tests have shown. Otherwise, however, the second, **higher quality** model should be used

- The **original** elements of this research include:

  = **innovative** problem formulation

  = **exact analytical 3D** solution of cable b.v. problem

  = **first MFDM** application to overhead power lines

  = **comparison** of various (also hybrid) solution approaches

- The solution approach developed here is carried out for the benefit of **real engineering** problem of **dynamic management** of overhead power lines.

- The existing policy of **dichotomous** summer and winter **safety** thresholds, limiting power transmission may be now replaced by **dynamic** management based on innovative on-line measurements, and analysis provided by our research reported here. Such policy would allow for more **efficient** use of **existing** overhead power transmission lines.

8.2 Future investigations

In the next step of this research development all tools worked out here should be practically **implemented** in TAURON, PSE and PGE power lines and intensively tested as to **verify** their **true engineering** value. Indications regarding needed **directions** of the **further** research may be also gained in this way.

ACKNOWLEDGMENT

This research was supported by the National Center for Research and Development (NCBiR) and The National Fund for Environmental Protection and Water Management (NFOSiGW) under grant NCBR/214108.

THANK YOU VERY MUCH FOR ATTENTION

2. OVERHEAD ELECTRIC POWER TRANSMISSION LINES- THEORETICAL 3D MODELING AND NUMERICAL ANALYSIS

2.1 Solution approach **strategy**

Special care about:

- assumptions made for **modeling** cables behaviour in a way possibly **close** to **real conductors** condition
- **high reliability** of results obtained due to
  - use of several **different** solution **approaches**
  - solution **stability**
  - **comparison** of our results with other sources of information
  - a-posteriori **error analysis**
- solution **efficiency**
  (**low** computational **time**, and **high** solution **convergence** rate)

2.2 On reliability of results obtained

Comparison and checking results obtained from various models

- 3 **models** 1D, 2D, 3D (inextensible and extensible)
- 3 mathematical **formulations**
  - 1 **strong** (non-linear PDE)
  - 2 **weak** (variational principle)
    - **global**
    - hybrid **mixed** global-local (**MLPG-5**)
- 2 discretization **methods**
  - **FEM**
  - **MFDM** (Meshless Finite Difference Method)
- **various** approximation **orders** (1-6)
- 3 **methods** of **non-linear** analysis
  (simple iterations, Newton-Raphson, relaxation)
- 3 **independent** computer **codes** (2 own + 1 commercial)
- **a-posteriori error** analysis
- large **variety** of numerical **tests**

2.3 References

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KUKDM - Zakopane

2016

- **Theoretical** approach concepts – **models**-software **numerical** analysis
- **Hybrid** theoret. - exp. approach **formulation**

2017

- Experimental **measurements** use
  - routine in situ
  - on-line
- Models **calibration** and **validation**
- **Hybrid** approach analysis – experimental **data handing**
  - simulations
  - hybrid analysis' of **true power line**

2.4 Development of theoretical models - basic **assumptions**

Structures

- overhead transmission line supports (towers)

  towers

  = small elastic displacements, and strains

  = types:

  straight line support

  angle support

- chain of **insulators**

  = rigid body

  = large displacements

- **conductors**

  = next slide

- line **section**

  = up to 1-3 spans – 2-4 towers

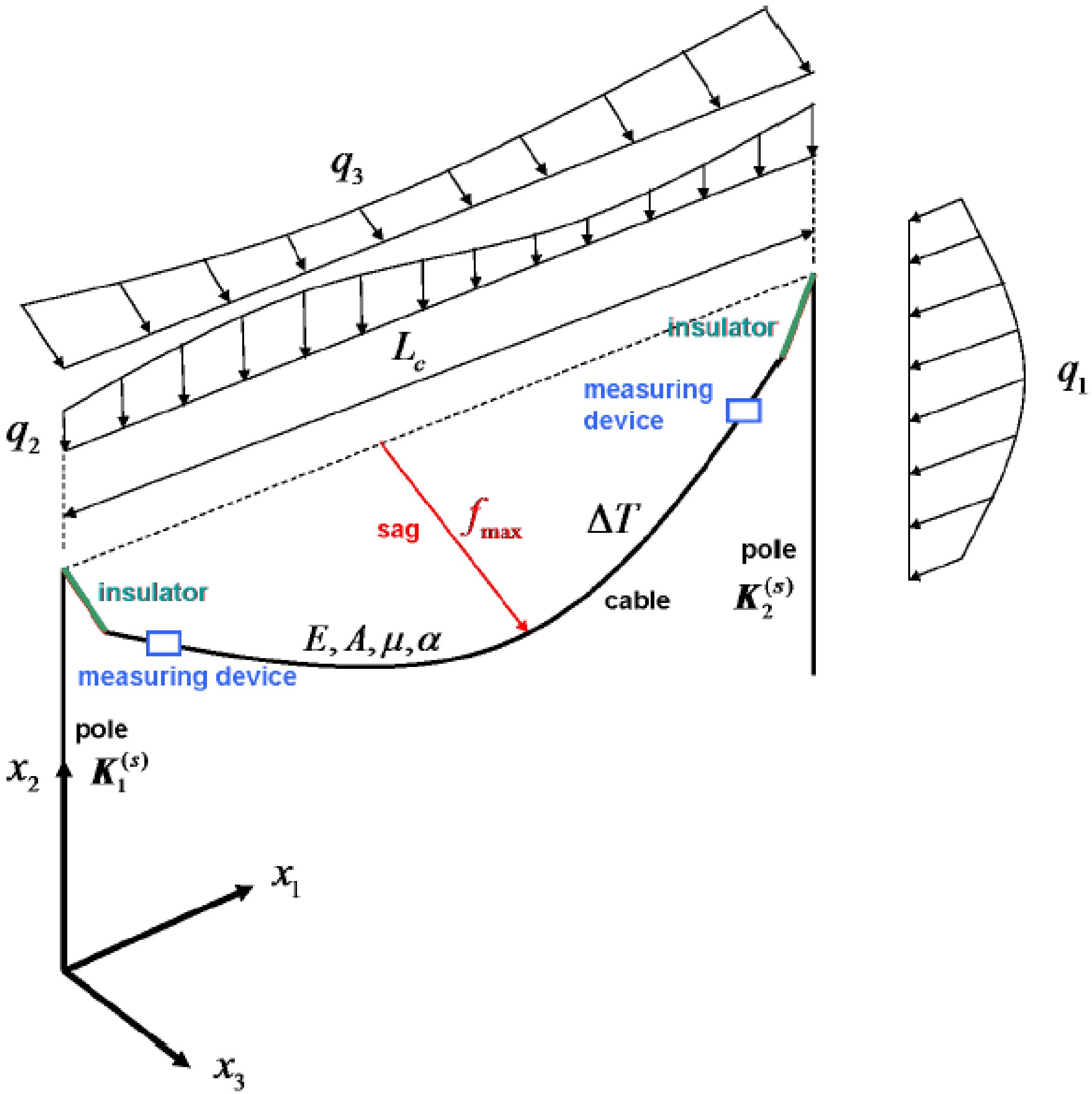
Methods

- **analytical** and
- **numerical**: FEM, meshless FDM, various formulations

Basic assumptions for modeling overhead power line cables

FEATURE	CATENARY CURVE	EXTENSIBLE CABLE	DIFFERENCES
displacements	large	large	no
space	2D	3D	yes
flexural stiffness	none $EJ = 0$	none $EJ = 0$	no
extensibility stiffness	none $EA = \infty$	$0 < EA < \infty$	yes
cable length	constant for constant temperature $L = L_0$	variable $L \neq L_0$	yes
strains	$\varepsilon = 0$	small $\varepsilon > 0$	yes
cable cross-section	constant $A = A_0$	variable $A \neq A_0$	yes
initial cable tension	$N_0 > 0$	$N_0 > 0$	no
loading	self-weight	arbitrary distributed and concentrated	yes
elastic supporting structures with suspension insulators	yes	yes	no

Cable deflection model



2.5 Sources of data used for analysis

Technical data for: conductors, supporting towers, insulators

Energoprojekt Kraków (design office)

Towers **stiffness** (calculated)

Warsaw University of Technology

Wind loading

Cracow University of Technology, A.Flaga approach

Conductors **temperature**

- EC Systems firm – (measured on-line)
- power lines operators (Tauron, PGE, PSE) (**measured on-line current** and **temperature** data)
- Warsaw University, Interdisciplinary Centre for Mathematical and Computational Modeling, (air temperature weather **forecast on-line**)
- AGH University of Science and Technology (temperature calculated upon above **on-line** measured data)

Conductor **deflections**

Surveying Office (**routine** measurements)

2.7 Boundary value problem type A - strong formulation

Find displacement components (in total Lagrangian description):

$u_1(X,t), u_2(X,t), u_3(X,t), \qquad X \in [0,L], \qquad L = L(\beta,t)$

$$\begin{cases} \rho \dfrac{\partial^2 u_i}{\partial t^2} - F_i^{'} = p_i & \textbf{linear momentum} \\ F_i = AE\dfrac{\varepsilon - \alpha \triangle T}{\varepsilon + 1}(\delta_{1i} + u_i^{'}) & \textbf{constitutive relation} \\ \varepsilon = \sqrt{(1+u_1^{'})^2 + (u_2^{'})^2 + (u_3^{'})^2} - 1 & \textbf{strain definition} \\ \boldsymbol{F} + \boldsymbol{K}^s(\boldsymbol{u} - \hat{\boldsymbol{u}}) = 0 \ \ \textbf{(elastic supports)} & \textbf{b.c. for } X = 0, L \\ +initial \ \ conditions & \end{cases}$$

$i = 1, 2, 3$
L – *unloaded cable length*
F_i – *axial force components*
$\boldsymbol{K}^s$ – *elastic support stiffness matrix*
$\hat{u}$ – *unloaded support position*

deflection curve $\gamma : \begin{cases} x = X + u_1(X) \\ y = u_2(X) \\ z = u_3(X) \end{cases}$

2.8 Boundary value problem type A - weak formulation

$\boldsymbol{u} \in H^1[0, L]$

$$\int_0^L \rho \boldsymbol{v} \cdot \ddot{\boldsymbol{u}} + \int_0^L \boldsymbol{v}' \cdot \boldsymbol{F} \, \mathrm{d}X - \int_0^L \boldsymbol{v} \cdot \boldsymbol{p} \, \mathrm{d}X + \sum_{k=1}^{2} \boldsymbol{v}_k^T \boldsymbol{K}_k^{(s)} (\boldsymbol{u}_k - \hat{\boldsymbol{u}}_k) = 0$$

$\forall \boldsymbol{v} \in H_0^1[0, L]$

Newton-Raphson linearization for static case $\boldsymbol{u}^{(n+1)} = \boldsymbol{u}^{(n)} + \psi$

$$\int_0^L (\boldsymbol{v}')^T \frac{\partial \boldsymbol{F}}{\partial \boldsymbol{u}'} \psi' \, \mathrm{d}X - \int_0^L \boldsymbol{v}^T \frac{\partial \boldsymbol{p}}{\partial \boldsymbol{u}'} \psi' \, \mathrm{d}X +$$

$$+ \int_0^L \boldsymbol{v}' \cdot \boldsymbol{F} \, \mathrm{d}X - \int_0^L \boldsymbol{v} \cdot \boldsymbol{p} \, \mathrm{d}X + \sum_{k=1}^{2} \boldsymbol{v}_k^T \boldsymbol{K}_k^{(s)} (\boldsymbol{u}_k - \hat{\boldsymbol{u}}_k) = 0$$

$\forall \boldsymbol{v} \in H_0^1[0, L]$

2.9 Exact analytical 3D solution – **verification** of numerical model

$$p_1 = 0; \;\; p_2 = \mu = const, \;\; p_3 = const, \;\; u_1(0) = u_2(0) = u_3(0) = 0$$

$$u_1 = \frac{Ct}{p_0} \log \left(\frac{p_0 X + D + \sqrt{C^2 + (p_0 X + D)^2}}{D + \sqrt{C^2 + D^2}} \right) + \left(\frac{C}{AE} - 1 \right) X$$

$$u_2 = \frac{p_2 t}{p_0^2} \left(\sqrt{C^2 + (p_0 X + D)^2} - \sqrt{C^2 + D^2} \right) + \frac{p_0 X + 2D}{2AEp_0} p_2 X$$

$$u_3 = \frac{p_3 t}{p_0^2} \left(\sqrt{C^2 + (p_0 X + D)^2} - \sqrt{C^2 + D^2} \right) + \frac{p_0 X + 2D}{2AEp_0} p_3 X$$

$$p_0 = \sqrt{p_2^2 + p_3^2}.$$

C & D are constants that may be found from two boundary conditions $u_1(L) = c, \; \sqrt{u_2^2(L) + u_3^2(L)} = d.$

2.10 Large deflections of inextensible catenary curve

MATHEMATICAL MODEL

differential equation:

$$a\frac{d^2y}{dx^2} = \sqrt{1 + \left(\frac{dy}{dx}\right)^2} \qquad \text{in } (0, L)$$

with kinematic boundary conditions

$$y(0) = H_0, \; y(L) = H_L$$

analytical solution

$$y = a\cosh\left(\frac{x - C}{a}\right) + D, \qquad x \in [0, L]$$

conditions for the Newton – Raphson procedure

$$\begin{cases} y(0) - H_0 = 0 \\ y(L) - H_L = 0 \\ \Delta L(T) - L_0(1 + \alpha T) = 0 \end{cases}$$

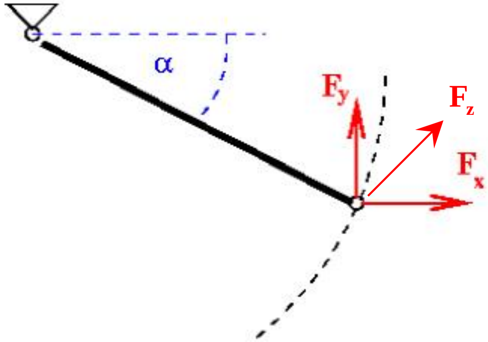
where

$$\Delta L_0 = \frac{\Delta L(T_c)}{1 + \alpha T_c}$$

$$\Delta L(T_c) = a\left[\sinh\left(\frac{C}{a}\right) - \sinh\left(\frac{C - L}{a}\right)\right]$$

2.11 MODELING OF SUSPENSION INSULATORS

Insulator suspension of length l and weight Q



Insulator modeled as a rotating rigid body

2.12 Numerical analysis – methods and tests used for theoretical solution approach

2.12.1 Objectives of numerical tests done

Comparison of:

(i) various **formulations** of b.v. problem (strong, weak, hybrid mixed)

(ii) various discrete solution **methods** (FEM, variational MFDM, MLPG-5 MFDM)

(iii) various types and **orders** of **approximation**

(iv) results obtained from **different** computer **codes**

(v) various types of **loading** (temperature, distributed loads and concentrated forces)

Each time considered were: solution **precision** and **convergence**, **computational** time.

Moreover the influence of

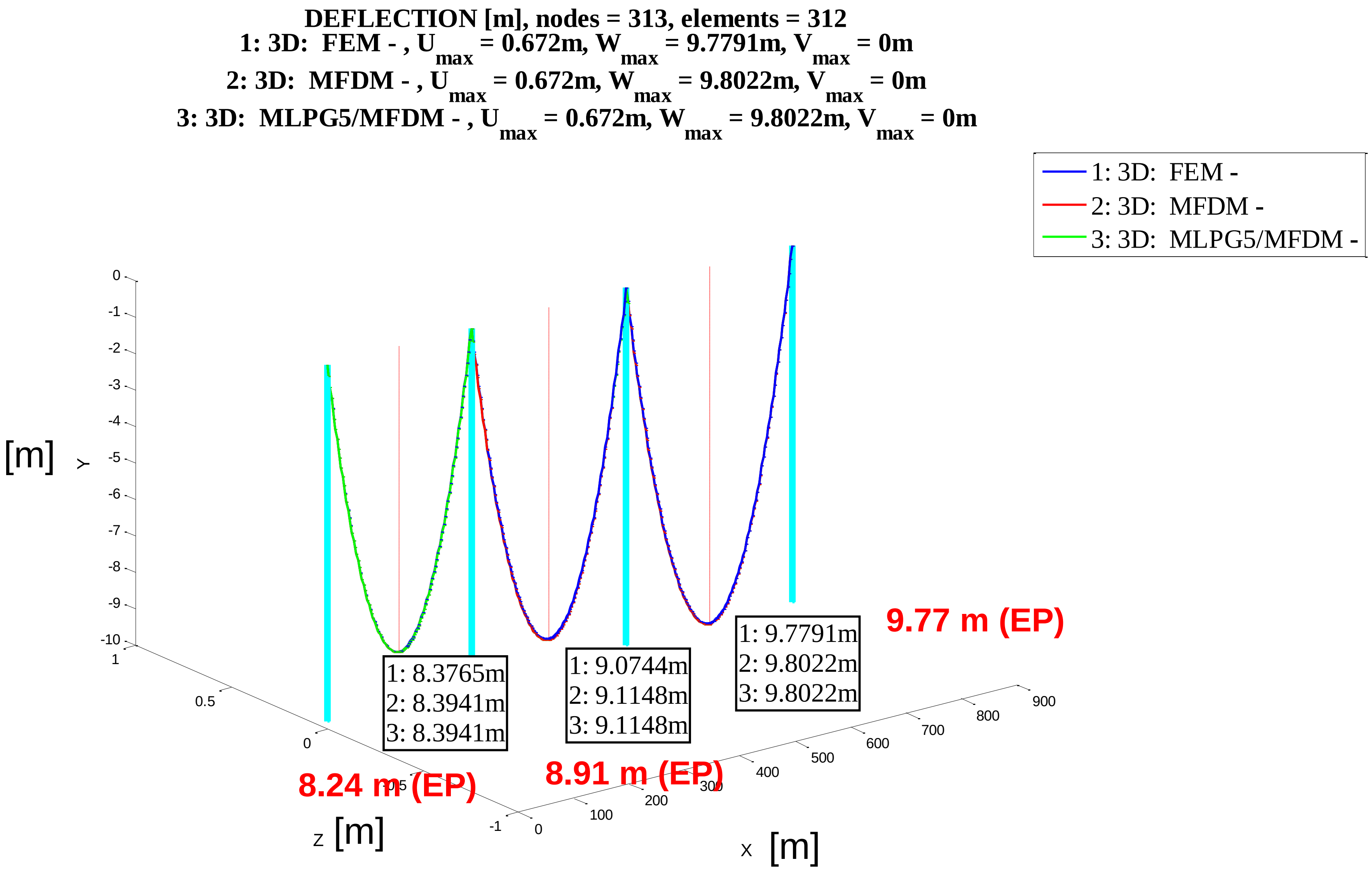
- elastic **supporting structures**
- different **phases**, ...
- number of **spans** considered

on **cable deformation** was analysed.

TEST DATA #1 (EP)

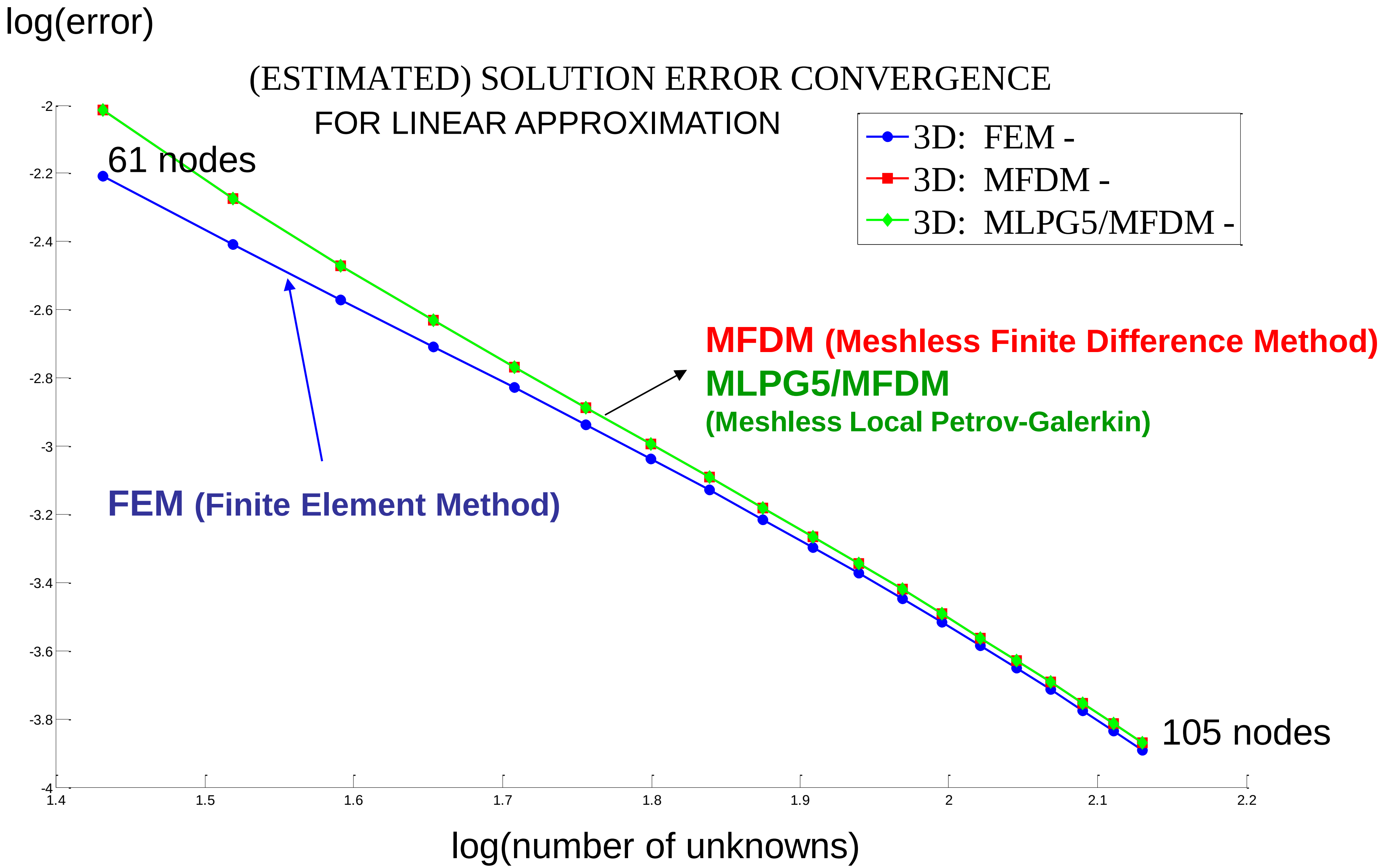
Comparison of methods 1. FEM , 2. MFDM , 3. MLPG-5/MFDM

313 nodes, computational time, 1: 9s, 2: 20s, 3: 44s

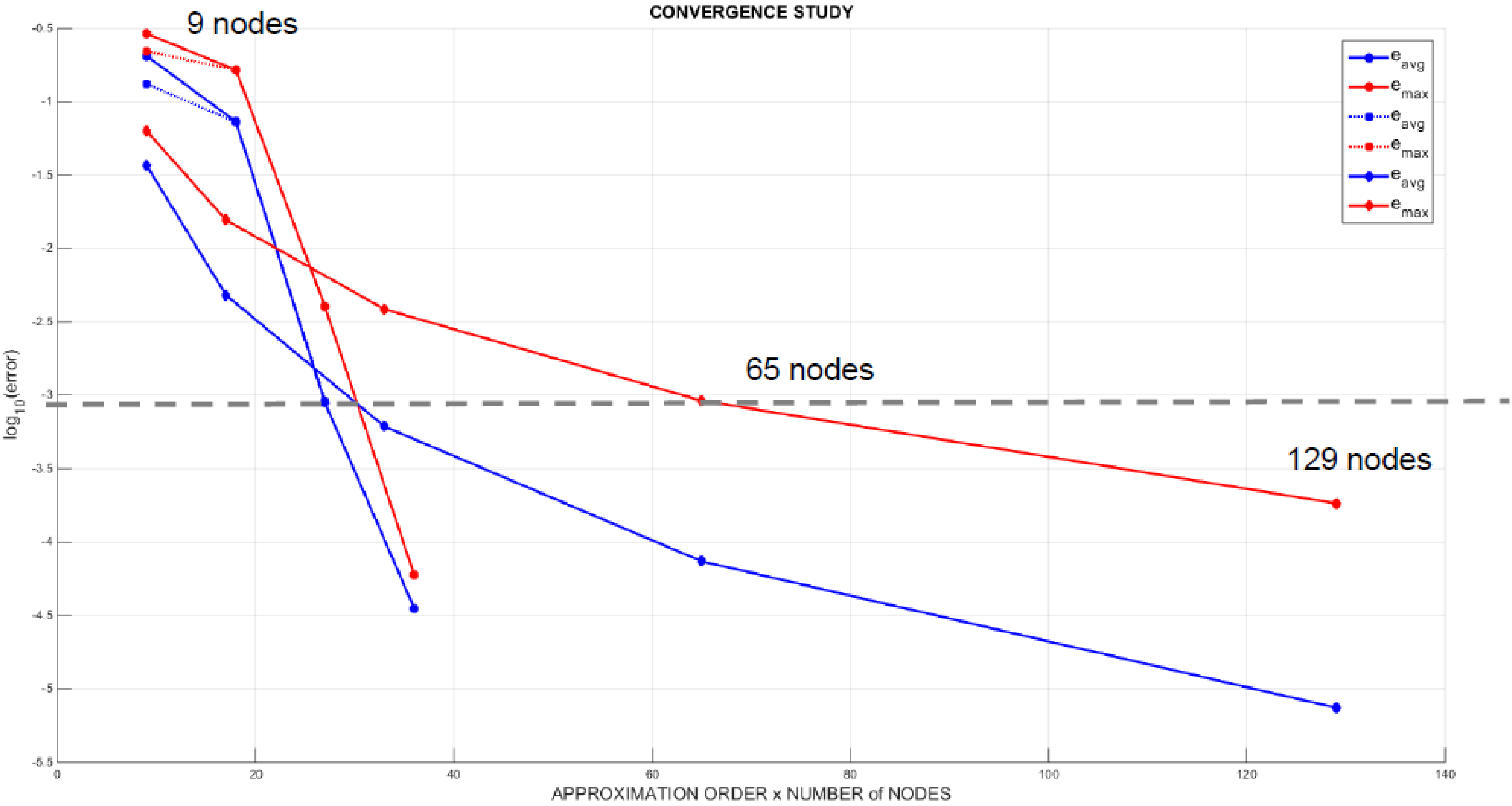


TEST DATA #2 (EP)

FEM , MFDM , MLPG-5/MFDM results **convergence** for regular mesh



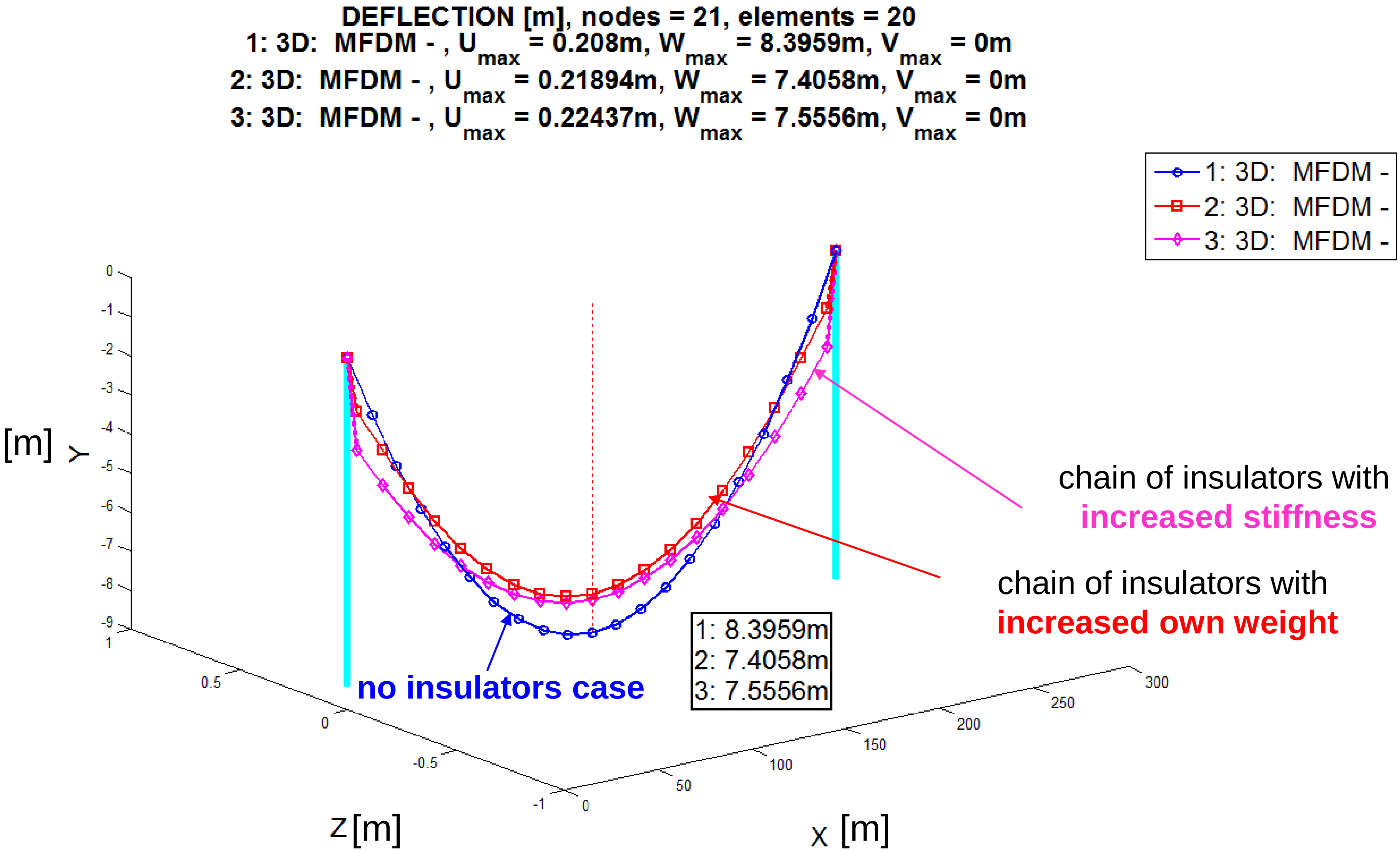
h and p type convergence test



TEST DATA **#2** (EP)

Influence of chains of **insulators** (MFDM)

21 nodes, computational time, 1: 2s, 2: 2s, 3: 2s



1.4 Types of general mathematical formulations of I , II , III problems

A) – **b.v. problem**
measured cable **inclination** and **rotation angles** are **not** taken into account

B) – nonlinear constrained **optimization** problem
all available data are considered **including measured** cable **inclination** and **rotation** angles

Mutual relation of tasks and types of problems

TASK	I	II	III
FORMULATION TYPE	B	A	A, B

2.6 Data

(i) Live (time dependent) parameters:

- T^E, T (temperature, measured or computed)
- p (wind pressure determined on the basis of its direction and velocity)
- q (distributed loading due to ice and frost - magnitude possible to be determined indirecly)
- ω^E, γ^E (cable inclination angles measured at selected places)
- concentrated forces

(ii) Parameters determined by in-situ measurements

- T_0 (initial temperature)
- ξ_0 (position of the sensor)
- L (unloaded cable length - determined indirectly)
- $a_1, ..., a_6$ (support coordinates)
- $\omega_0^E(T_0^E), \gamma_0^E(T_0^E), s_0^E(T_0^E), \omega_1^E(T_1^E), \gamma_1^E(T_0^E), s_1^E(T_1^E), \ldots$ (angles and sags for various temperatures for model validation)

2.6 Data continued

(iii) Material parameters:

- μ - self-weight (dead load)
- A - cable cross section area (effective)
- E - cable Young's modulus (effective)
- α - cable thermal expansion coefficient
- β - viscous parameter
- L_i, Q_i - insulator parameters
- K_1, K_2 - support stiffness matrices

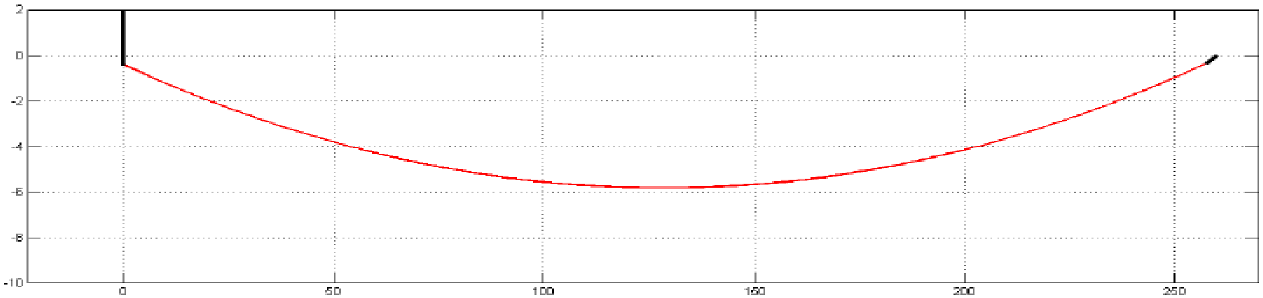
(iv) Measurement accuracy:

- e_T (of temperature)
- $e_{\omega,\gamma}$ (of angles)

MODELING OF SUSPENSION INSULATORS - continued

$$\mathrm{tg}\alpha = \frac{\frac{1}{2}Q - F_y}{F_x} \qquad \Rightarrow \qquad \begin{cases} u_1 = x_0 + l\cos\alpha - X \\ u_2 = y_0 + l\sin\alpha \end{cases}$$

Such a condition is updated at each NR step



Numerically determined deflection of a cable with insulator suspension

Another possibile modeling of insulator

- use the same equations as for the cable but assume larger self-weight
- approximate insulator displacements by only 1 finite element with linear shape functions

OPTIMIZATION PROCEDURE FOR VARIABLE CABLE LENGTH L AND TEMPERATURE T

1. solve above FBA problem assuming fixed values $T = T^E$ and $L = L^E$

2. fix $T = T^E$ vary L , find $L = L_{opt}$

minimising cable curvature and satisfying the constraint

$$\min_L \kappa^2 \quad , \quad \kappa^2 \approx \frac{1}{L}\int_0^L \left(\frac{d^2 w}{dX^2}\right)^2 dX \qquad\qquad \Delta L = \left|L - L^E\right| \le e_L = \Delta L_{\max}$$

3. fix $L = L_{opt}$ vary T , find $T = T_{opt}$

minimising the same cable curvature κ^2 while satisfying constraints $\Delta T = \left|T - T^E\right| \le e_T = \Delta T_{\max}$