Modelling and Experimental Characterisation of Belt Drive Systems in Micro-Hybrid Vehicles

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DI TORINO

LIM - Mechatronics Lab

Goals of Research and Development Plan

MOTIVATIONS

- Belt Starter Generator is a key component in micro-hybrid powertrain configurations
- BSG increases Belt Drive Systems complexity and severity of operations
- Transmission efficiency and belt functionality are two main issues
- Accurate modeling is a need in the design phase

GOALS

→ Design and build a test rig replicating BDS behaviour in different BSG critical operating modes

→ Efficiency evaluation

→ Static and dynamic modeling of different BDS layouts

1° Year

- Literature Research
- Test rig concept
- Specifications definition
- Design
- PhD Courses

2° Year

- Construction
- Functional setup
- First experimental analysis
- Finish PhD Courses

3° Year

- Static and dynamic tests
- Experimental analysis of different BDS layouts
- Efficiency evaluation
- Validation of static and dynamic models
- Comparison of different tensioning devices
- Thesis

Presentation breakdown

State of the Art

- Characteristics of Belt Drive Systems
- Belt Drive Systems in Mycro-Hybrids
- Tensioners for Micro-Hybrids
- Twin-arm Tensioners
- Literature Review

The Test Rig

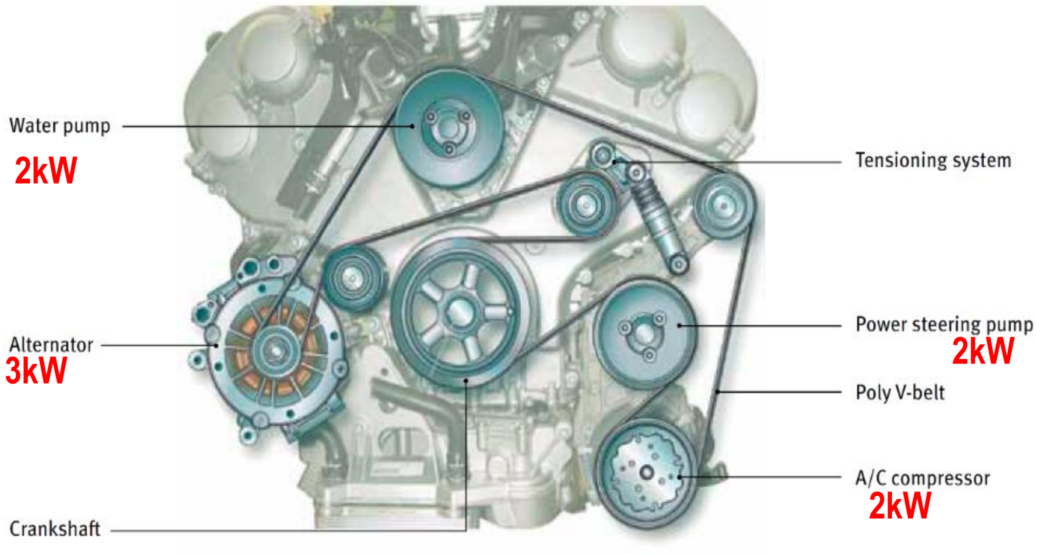
- Characteristics
- Control Architecture

Twin-arm Tensioner Modeling and Charaterisation

- Experimental Setup
- Modelling
- Simulation and Experimental Results

Conclusions

State of the Art: Characteristics of Belt Drive Systems

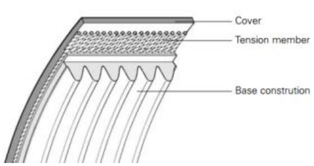


Schaeffler Automotive Aftermarket, "INA Belt Drive Components"

Distributes part of the engine power to the accessories
Vibrations
- Efficiency
- Noise

High tension: premature failure of bearings and belt wear
Low tension: slip, speed loss and efficiency drop

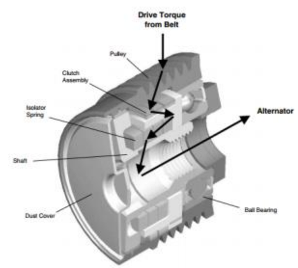
OPTIMIZATION OF BDS COMPONENTS



V-ribbed Belts

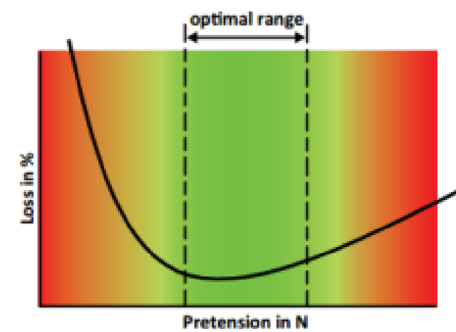
Torsional Vibration Damper

Crankshaft Decoupler Pulley



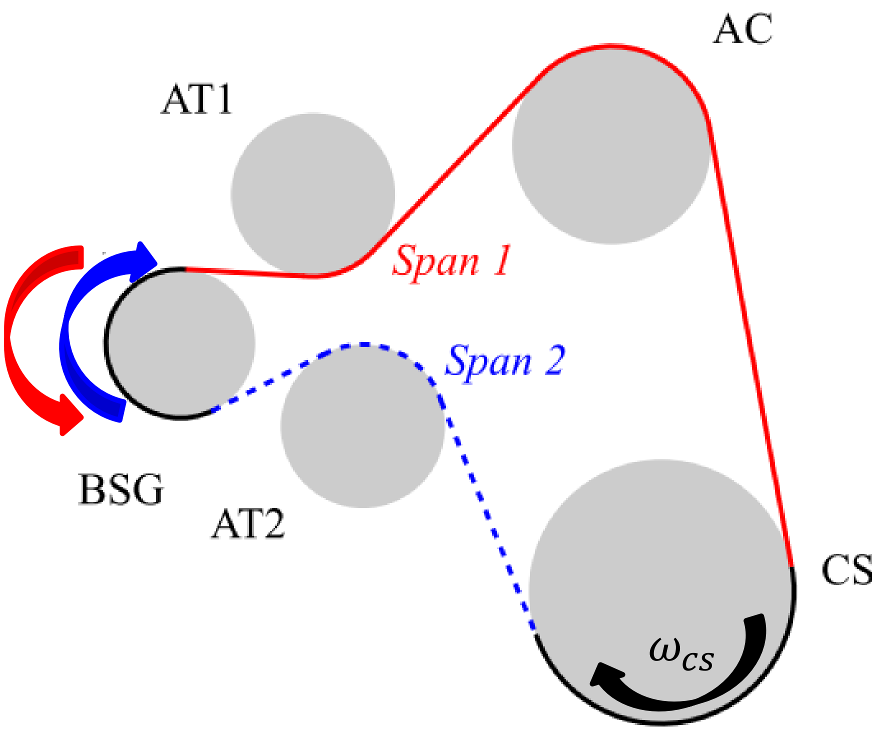
Alternator overrunning decoupler

Belt Tensioner



State of the Art: Belt Drive Systems in Micro-Hybrids

Alternator substituted by Belt Starter Generator (BSG) – electric machine able to work also as motor, transmitting torque to the system, causing a tight/slack span alternation when activated



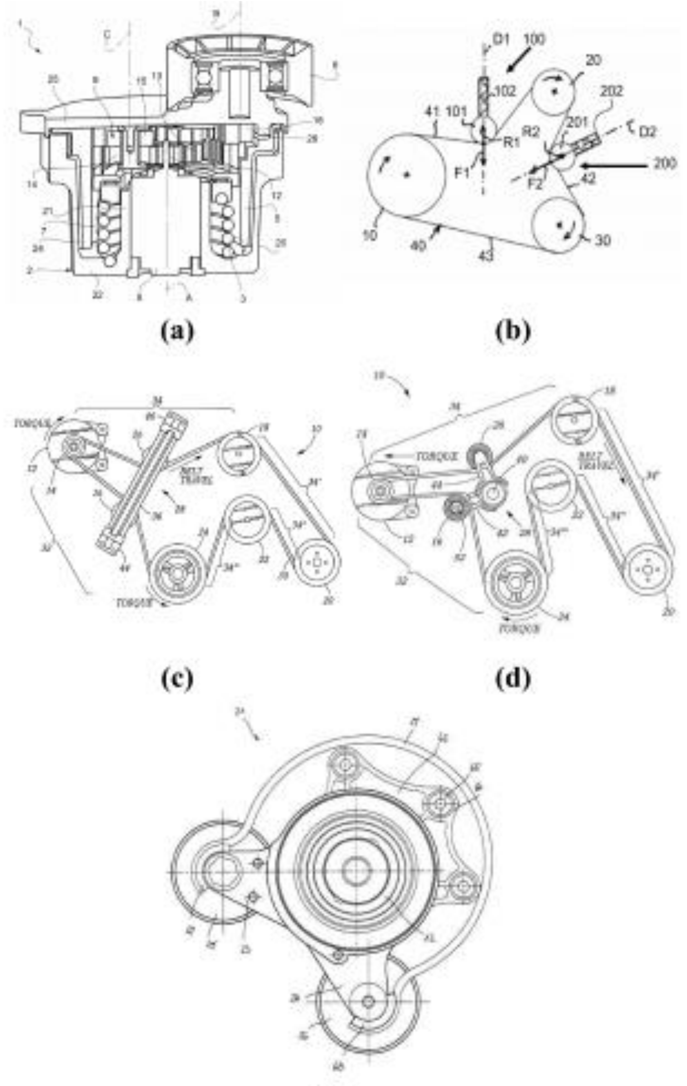
Different operating modes:

MOTOR MODE – exploited as an electric boost, the BSG assists the ICE for transient accelerations. Used also for the start and stop function: cranking of the ICE performed without the need of a separate starter electric machine.

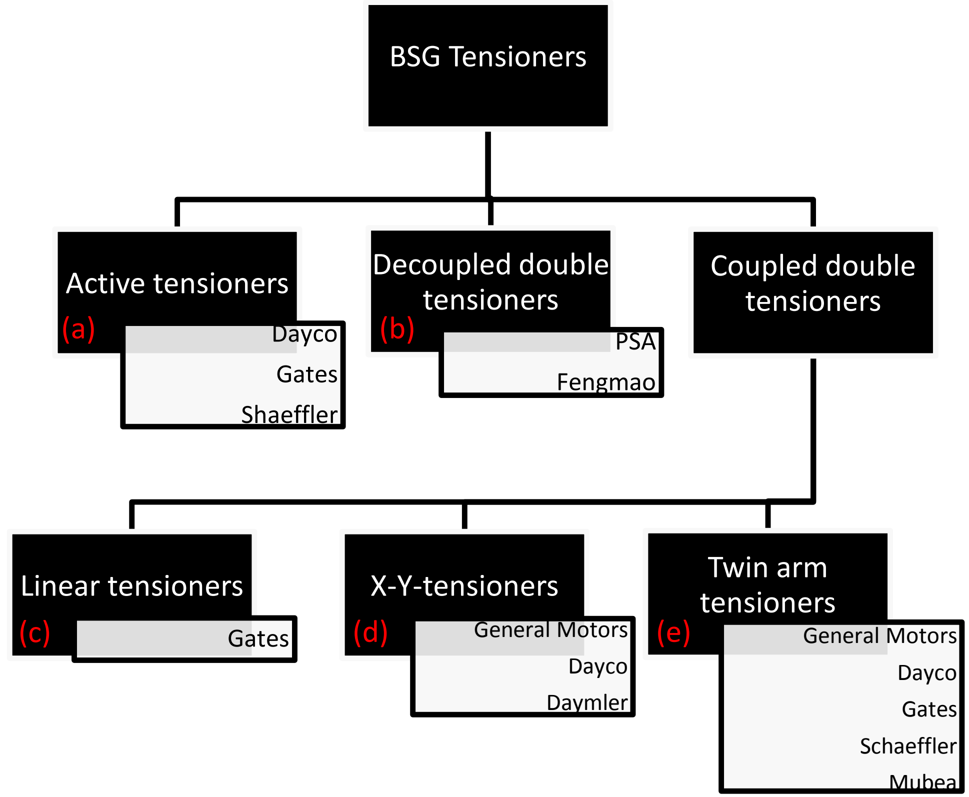
GENERATOR MODE – BSG replicate the function of a traditional alternator that collects the power from the belt to charge the vehicle battery

A traditional automatic tensioner is not sufficient to control the tension in both operating conditions because of its low stiffness.

State of the Art: Tensioners for Micro-Hybrids

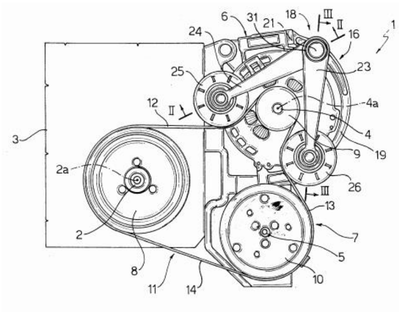


(a) (b) (c) (d) (e)

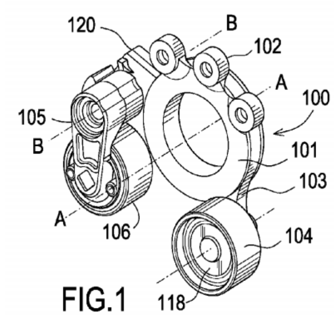


(a) Active Tensioner by Dayco Europe S.r.l.
(b) Double Tensioner by PSA Peugeot Citroen
(c) Linear Tensioner by The Gates Corporation
(d) Y Tensioner by The Gates Corporation
(e) Rotative twin arm tensioner by Mubea Muhr und Bender KG

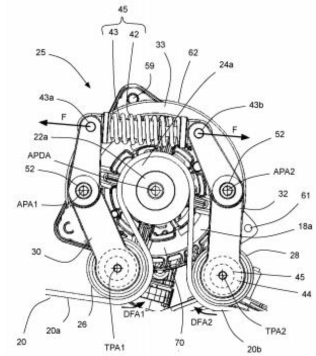
State of the Art: Twin-arm tensioners



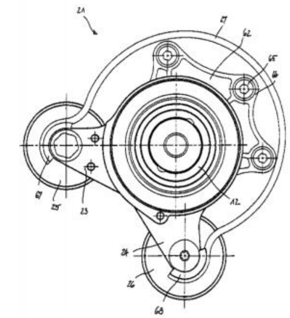
DAYCO Europe S.r.l.



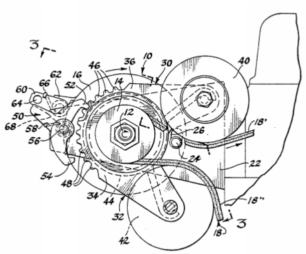
The Gates Corporation



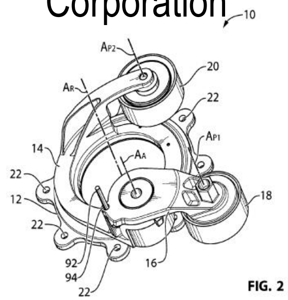
Litens Automotive Partnership



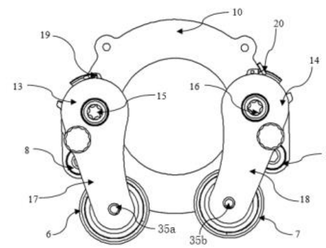
Mubea Muhr und Bender KG



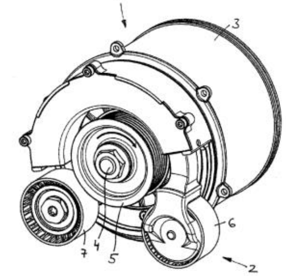
General Motors Corporation



Litens Automotive Partnership



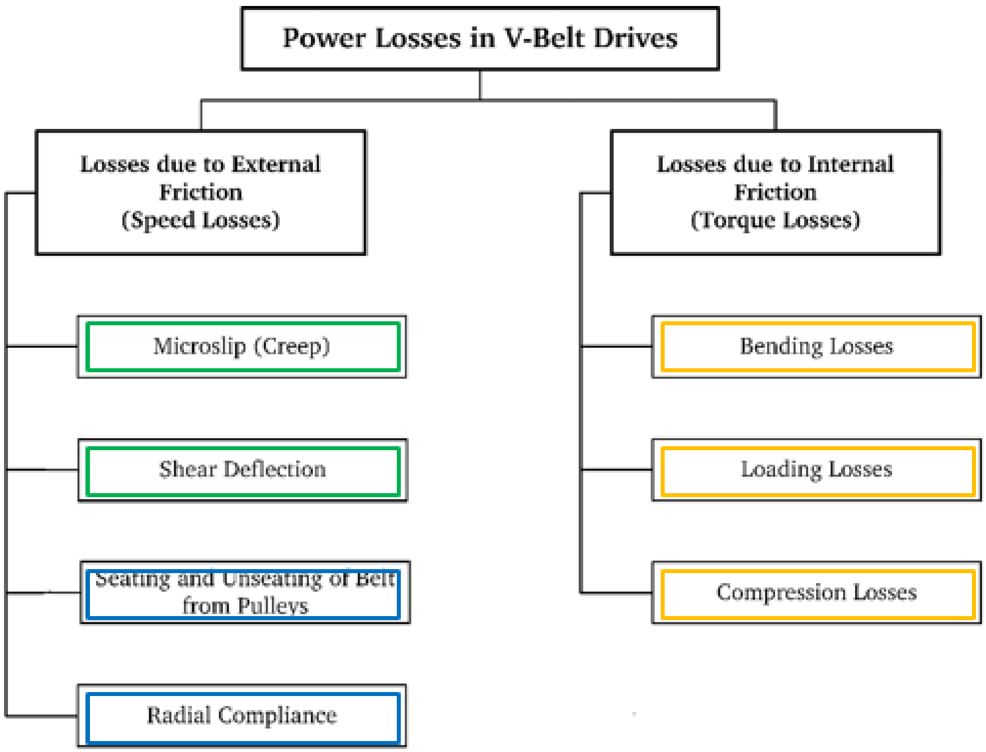
Fengmao



Schaeffler Technologies AG. & Co. KG

State of the Art: Literature Review

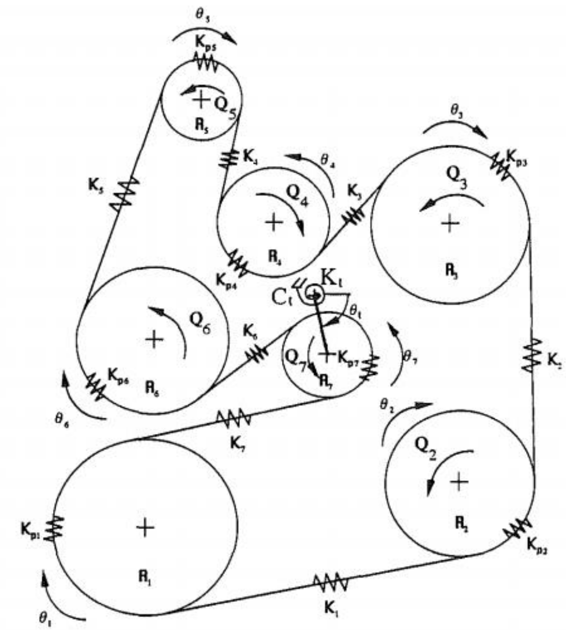
EFFICIENCY OF BELT DRIVE SYSTEMS



AUTHORS: Gerbert, Childs, Hansson, Chen, Balta

DYNAMICS OF BELT DRIVE SYSTEMS

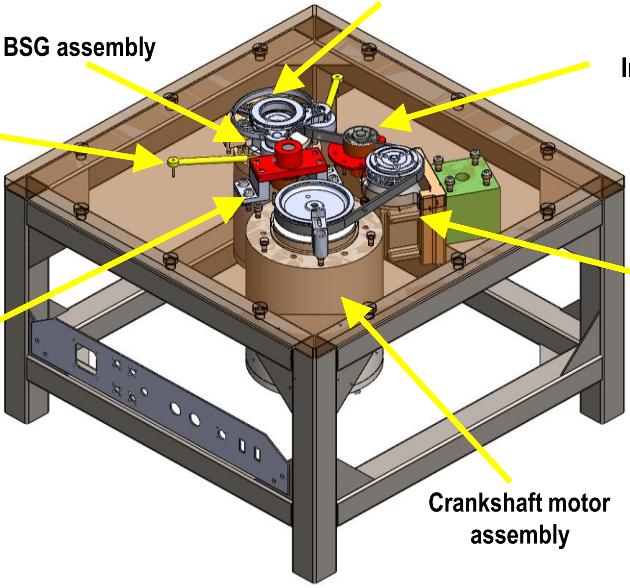
(a) Transverse dynamics – BELT
(b) Rotational dynamics – PULLEYS and TENSIONER
   (a) Driving pulley
   (b) Driven pulleys
   (c) Tensioners



AUTHORS: Hwang, Leamy, Perkins, Ulsoy, Shangguan

The Test Rig: Characteristics

Comparison of different tensioning solutions



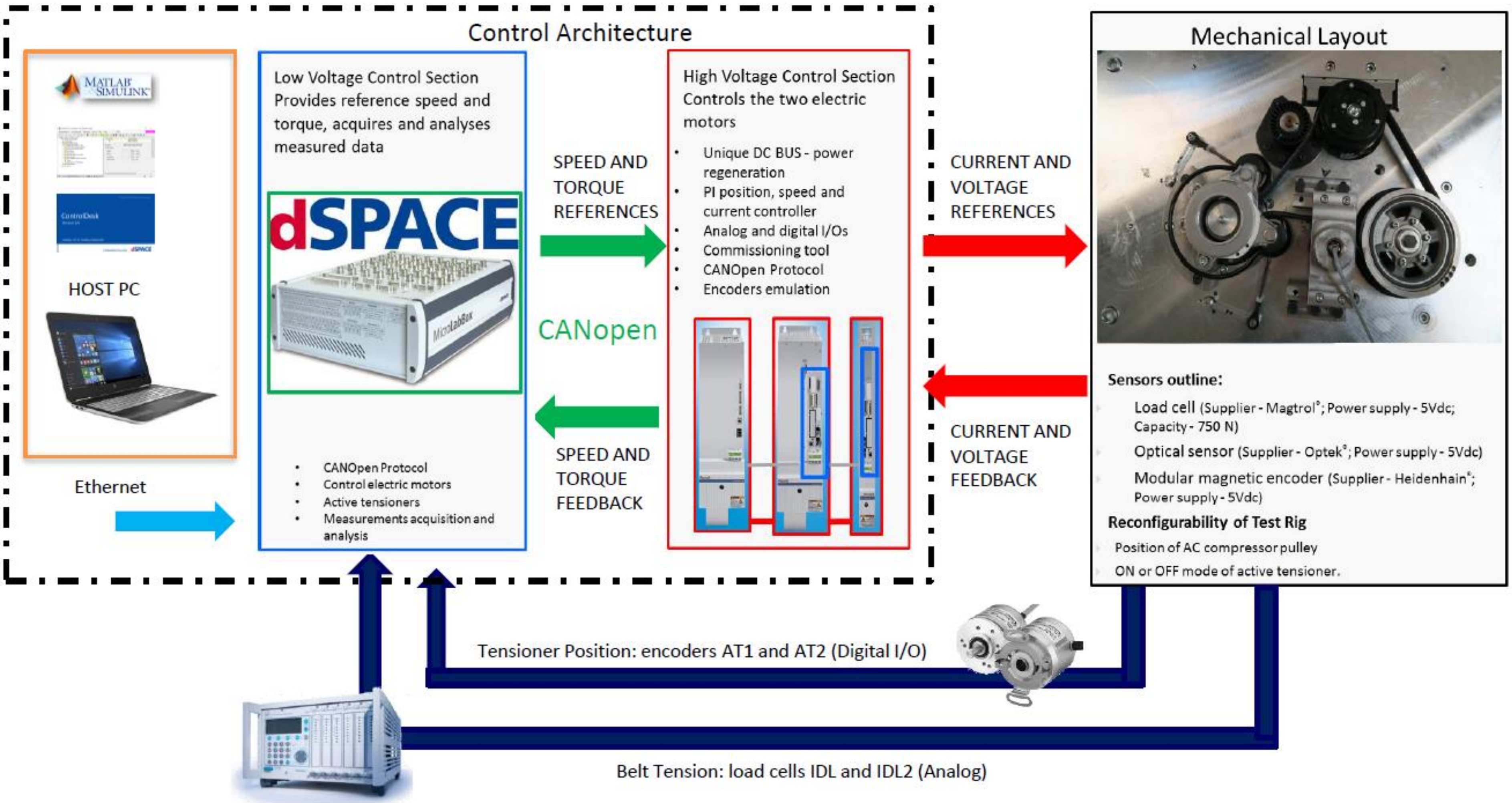
Crankshaft Motor:
BoschRexroth MSS182D-0260-D

Rated speed	Maximum speed	Rated Torque	Maximum Torque	Rated Power	Moment of Inertia
n [1/min]	n_max [1/min]	M [Nm]	M_max [Nm]	P [kW]	[kg*cm²]
2600	12000	140	320	38,1	53,4

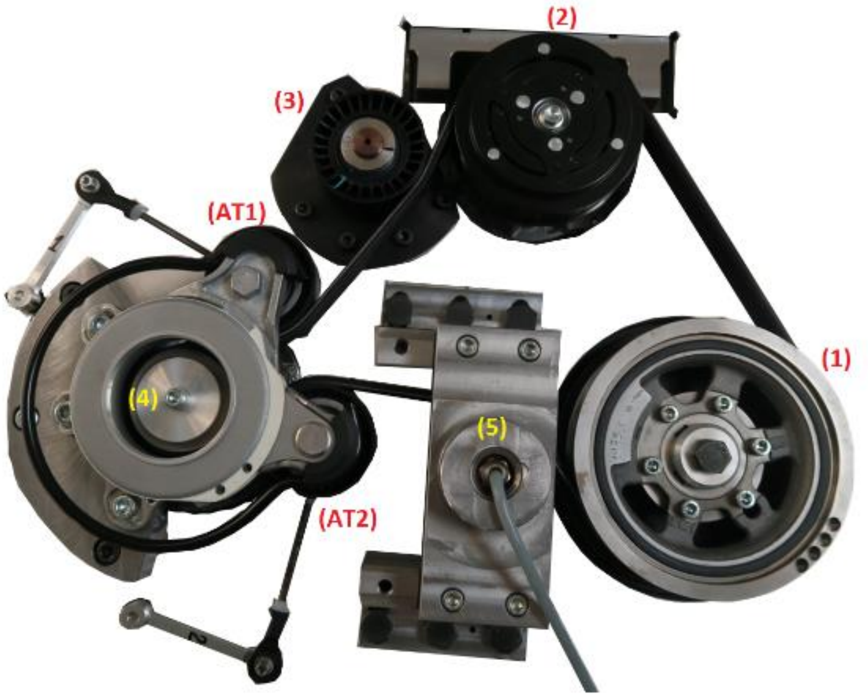
BSG Motor:
Bosch Rexroth MSS102D-0800-F

Rated speed	Maximum speed	Rated Torque	Maximum Torque	Rated Power	Moment of Inertia
n [1/min]	n_max [1/min]	M [Nm]	M_max [Nm]	P [kW]	[kg*cm²]
8000	22500	20	45	16,8	4,5

The Test Rig: Control Architecture



Twin-arm Tensioner



Automotive BDS layout with 7 pulleys:

(1) crankshaft, (2) AC compressor, (3) instrumented idler, (AT1) tensioner pulley, (4) BSG, (AT2) tensioner pulley, (5) instrumented idler

FEATURES

- Passive device
- Two pulleys connected by a torsional spring and rotating around a pivot, coaxial to the BSG axis
- Tensioner arm of the first pulley mounted on the tensioner housing
- Second tensioner arm hinged on the first tensioner arm

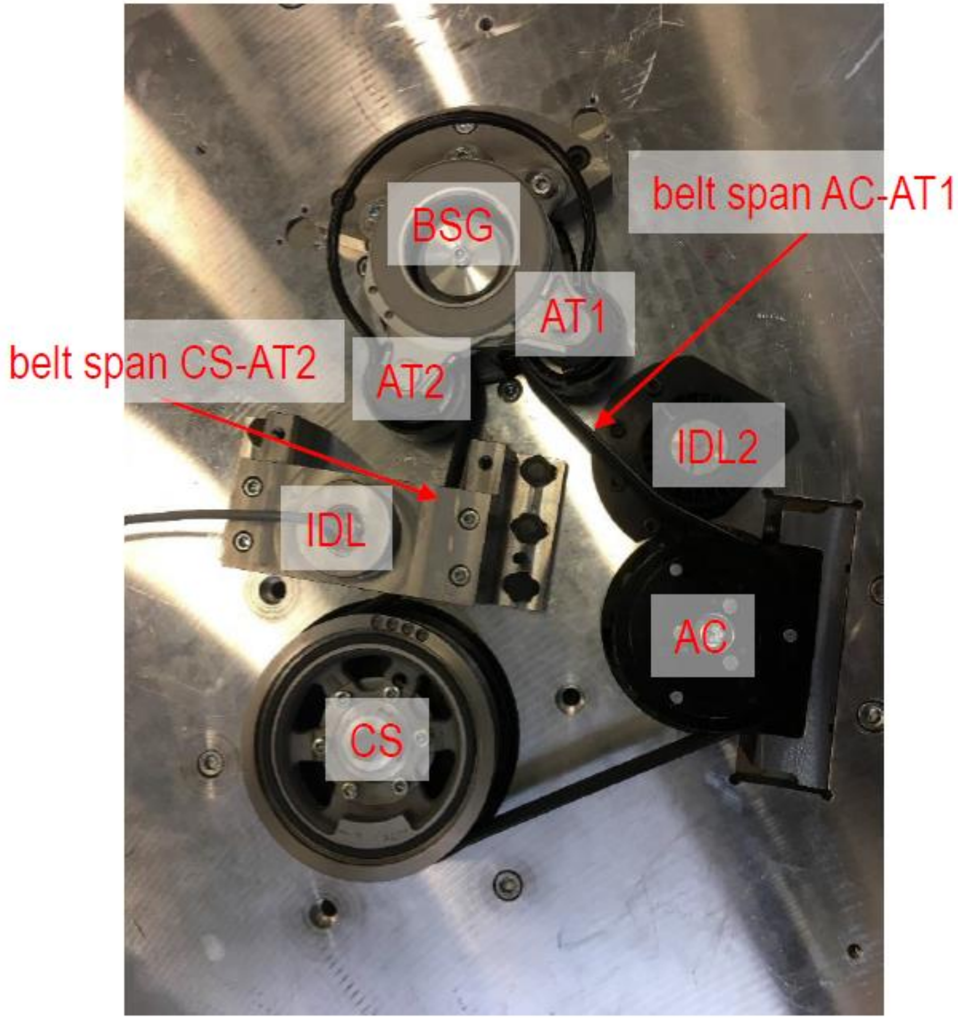
FUNCTION

- When BSG torque is applied, variation of tensioner arms absolute position and of relative aperture
- Keeps the tension inside an acceptable range for both generator and motor modes

BACKGROUND

- Several Patents
- Few available research works
- No experimental characterization

Twin-arm Tensioner: Experimental Setup



- The **crankshaft (CS)** motor is speed-controlled.
- The **belt-driven starter generator (BSG)** motor is current-controlled.
- The inverters that control both electric motors are able to yield **torque** and **speed** signals.
- The **idlers (IDL and IDL2)** are equipped with load cells to estimate the **belt tension** for both belt spans.
- The **Dual arm tensioner (AT1 and AT2)** are linked to incremental rotary encoders to measure their **angular position** during the tests.

Twin-arm Tensioner: Quasi-static Tests

Objective

- To evaluate the system behavior under constant BSG boost and brake operations and validate the static model

Procedure

- The CS motor is driven with constant angular speed.
- The BSG applies a boosting or braking torque ramp.

Outputs of interest

- Behavior of the following variables as a function of the BSG torque:
  1. Belt slip
  2. Power loss
  3. Transmission efficiency
  4. Angular position of tensioner arms
  5. Belt tensions on tight and slack span

Twin-arm Tensioner: Dynamic Tests

Objective

- To understand the behavior of the tensioner arms in transient conditions

Procedure

- The CS motor is driven with constant angular speed.
- The BSG applies boosting or braking torque steps.

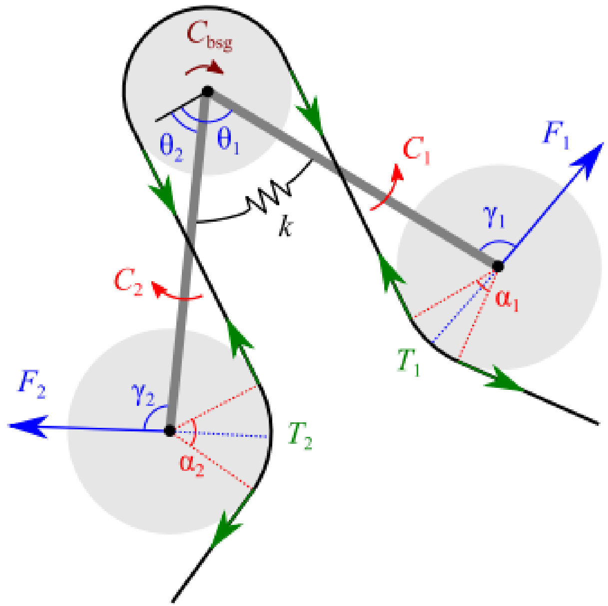
Outputs of interest

- Time histories of the following variables
  1. Input torque
  2. Tensioner arm angles
  3. Belt slip

Twin-arm Tensioner: Static Analysis

ASSUMPTIONS

- tensioner arms infinitely rigid.
- tensioner arms perfectly hinged on their supports, where friction effects are neglected
- The friction of the bearings of the pulleys is neglected.
- The tensioner spring acts with no friction and perpendicularly to the axis of each tensioner pulley.
- The belt is considered ideal, i.e. without energy dissipation and infinitely rigid.



EQUILIBRIUM EQUATIONS

TORQUE EQUILIBRIUM AROUND TENSIONER PIVOT

$$C_i = C_{i+1},$$

TORQUE ON EACH TENSIONER ARM

$$C_i = F_i L_i \sin \gamma_i,$$

HUB LOAD

$$F_i = 2T_i \sin\left(\frac{\alpha_i}{2}\right)$$

SPRING TORQUE

$$C_i = k(\theta_v - \theta_u - \Delta\theta_0),$$

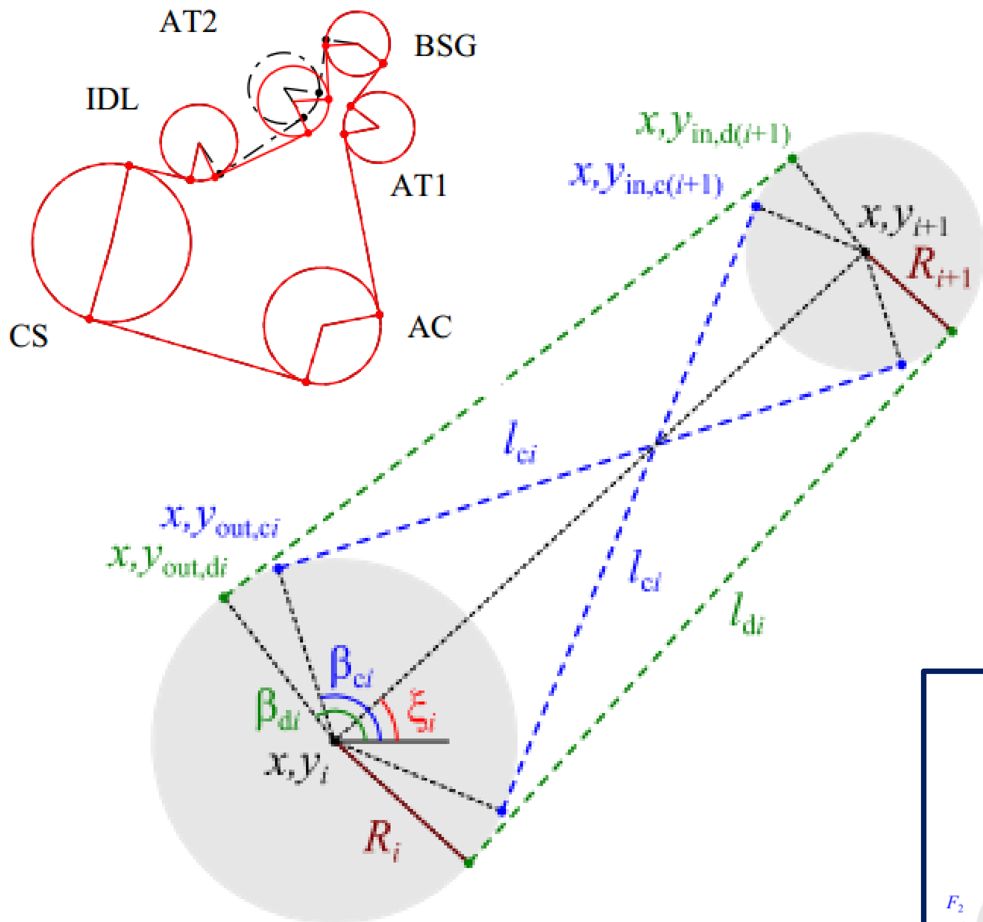
MOTOR MODE $\begin{cases} v &= i-1 \\ u &= i \end{cases}$

ALTERNATOR MODE $\begin{cases} v &= i+1 \\ u &= i \end{cases}$

BSG TORQUE EFFECT

$$C_{bsg} = R_{bsg}(T_v - T_u),$$

Twin-arm Tensioner: BDS Geometries



CONSISTENCY EQUATIONS

PULLEY CENTER POSITION

$$x_{p,ti} = x_i + R_i \cos(\xi_i \pm \beta_{tj})$$
$$y_{p,ti} = y_i + R_i \sin(\xi_i \pm \beta_{tj})$$

BELT SPAN LENGTH

$$l_{ti} = \sqrt{(x_{\text{in},tj} - x_{\text{out},ti})^2 + (y_{\text{in},tj} - y_{\text{out},ti})^2}.$$

WRAP ANGLE

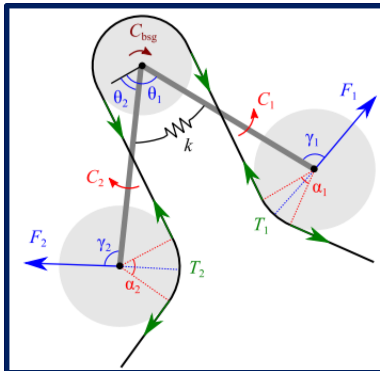
$$\alpha_i = 2 \arcsin \left[\frac{\sqrt{(x_{\text{out},ti} - x_{\text{in},ti})^2 + (y_{\text{out},ti} - y_{\text{in},ti})^2}}{2R_i} \right]$$

WRAP LENGTH

$$l_{wi} = R_i \alpha_i.$$

TOTAL LENGTH

$$l_{\text{tot}} = \sum_i l_{wi} + l_{ti}.$$



ANGLE BETWEEN FORCE AND ARM

$$\gamma_i = \pi - \frac{\alpha_i}{2} - \arccos\left(\frac{R_{\text{bsg}} + R_i}{L_i}\right)$$

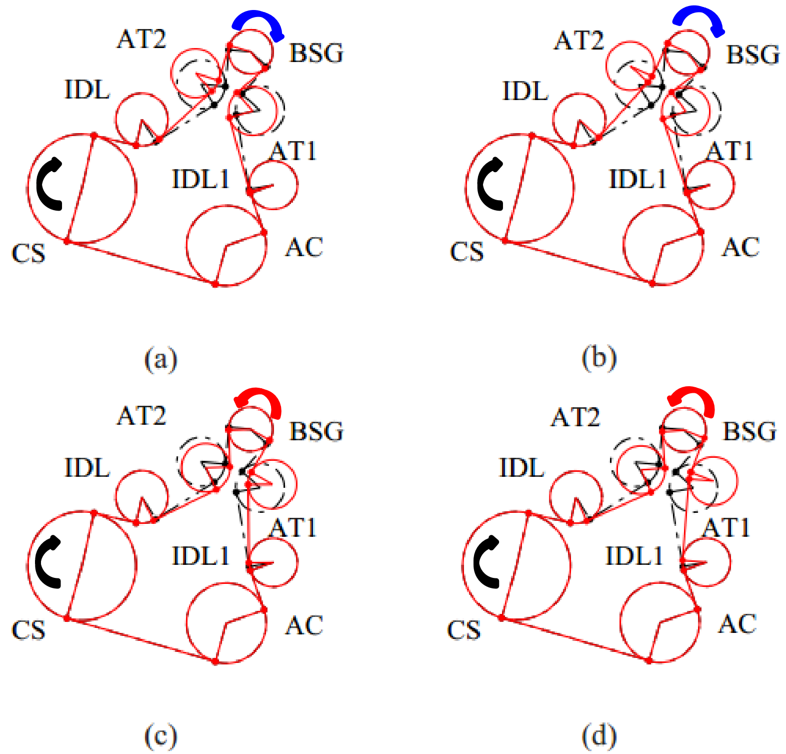
Twin-arm Tensioner: Simulation Results

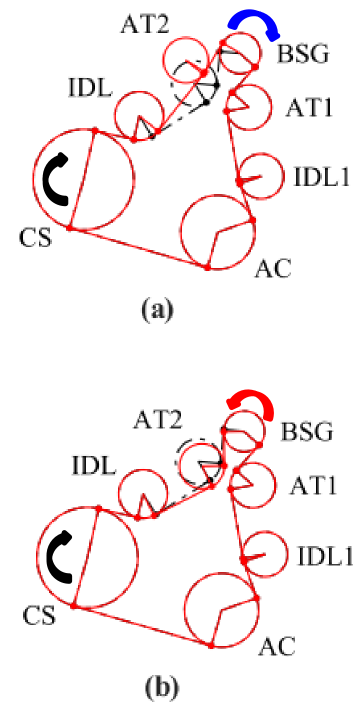
TWIN ARM TENSIONER BEHAVIOR

TRADITIONAL TENSIONER BEHAVIOR

MOTOR MODE

ALTERNATOR MODE





Sliding arc

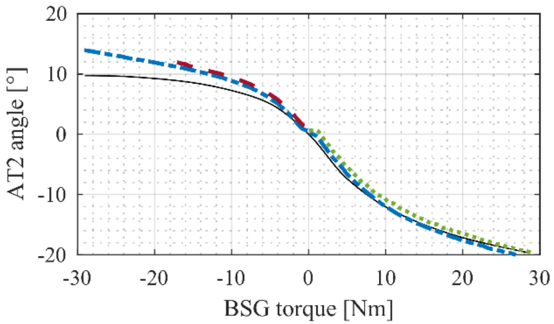
$$\phi_s = \frac{1}{\mu_r}\ln\left(\frac{T_v}{T_u}\right)$$

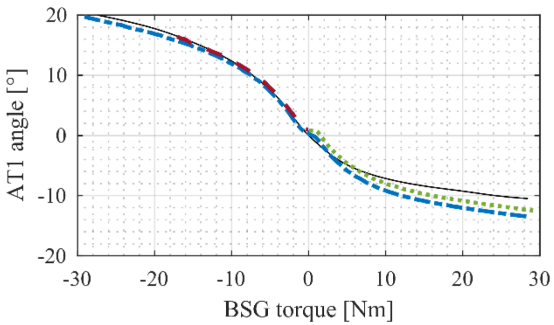
condition	BSG torque [Nm]	tight span tension [N]	slack span tension [N]	BSG sliding arc [%]	BSG wrap angle [deg]
(a)	10	603.5	250.5	19.8	212
(b)	30	1307.6	247.7	38.2	207.6
(c)	-10	600.9	247.7	19.9	212
(d)	-30	1317.7	257.8	37.8	206

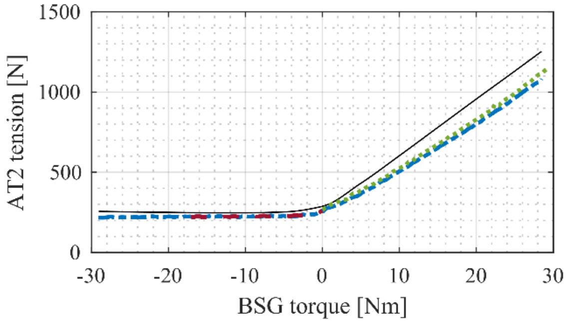
condition	BSG torque [Nm]	tight span tension [N]	slack span tension [N]	BSG sliding arc [%]	BSG wrap angle [deg]
(a)	10	450.1	49.6	55	191.2
(b)	-10	568.2	247.7	17.7	223.5

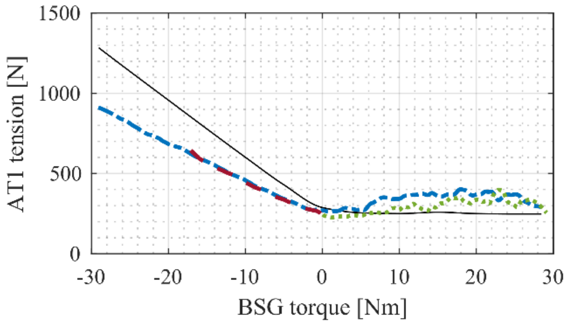
Twin-arm Tensioner: Quasi-static Tests

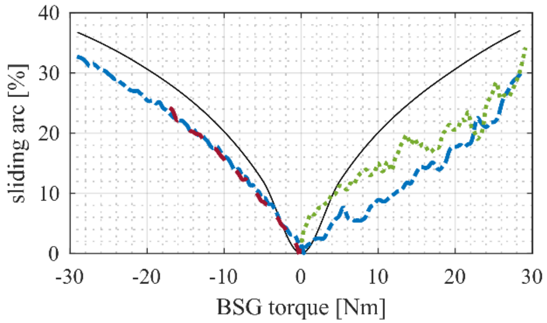
Model Validation









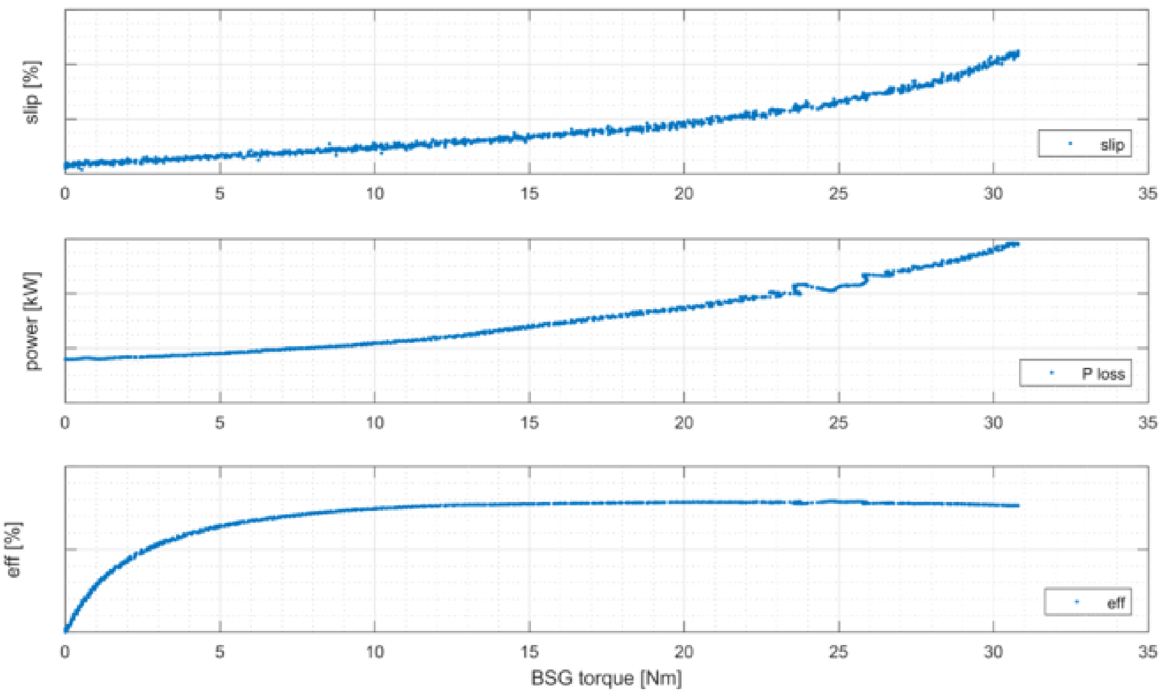


Twin-arm Tensioner: Quasi-static Tests

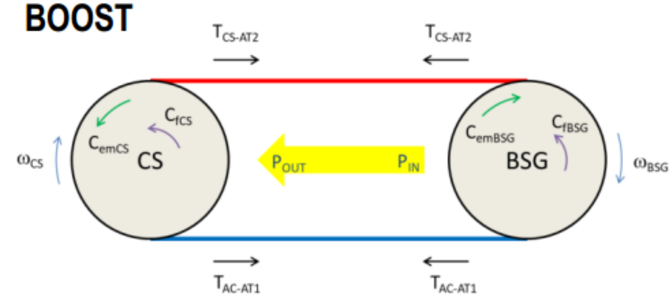
Transmission Performances

$$\tau = \frac{d_{pitchBSG}}{d_{pitchCS}}$$

$$P_{loss} = P_{CS} + P_{BSG}$$



BOOST

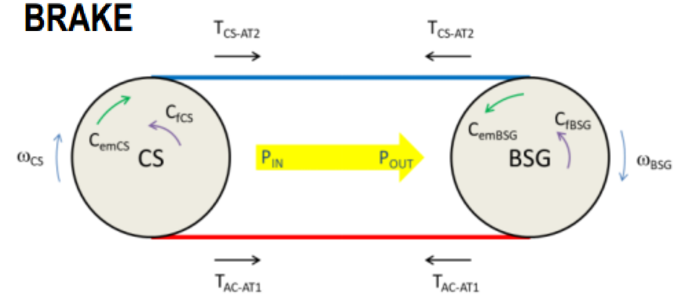


$$eff(\%) = \left(-\frac{P_{CS}}{P_{BSG}}\right).100$$

$$slip(\%) = \left(\frac{\omega_{BSG} - \frac{\omega_{CS}}{\tau}}{\omega_{BSG}}\right).100$$

$$P_{CS} < 0$$

BRAKE



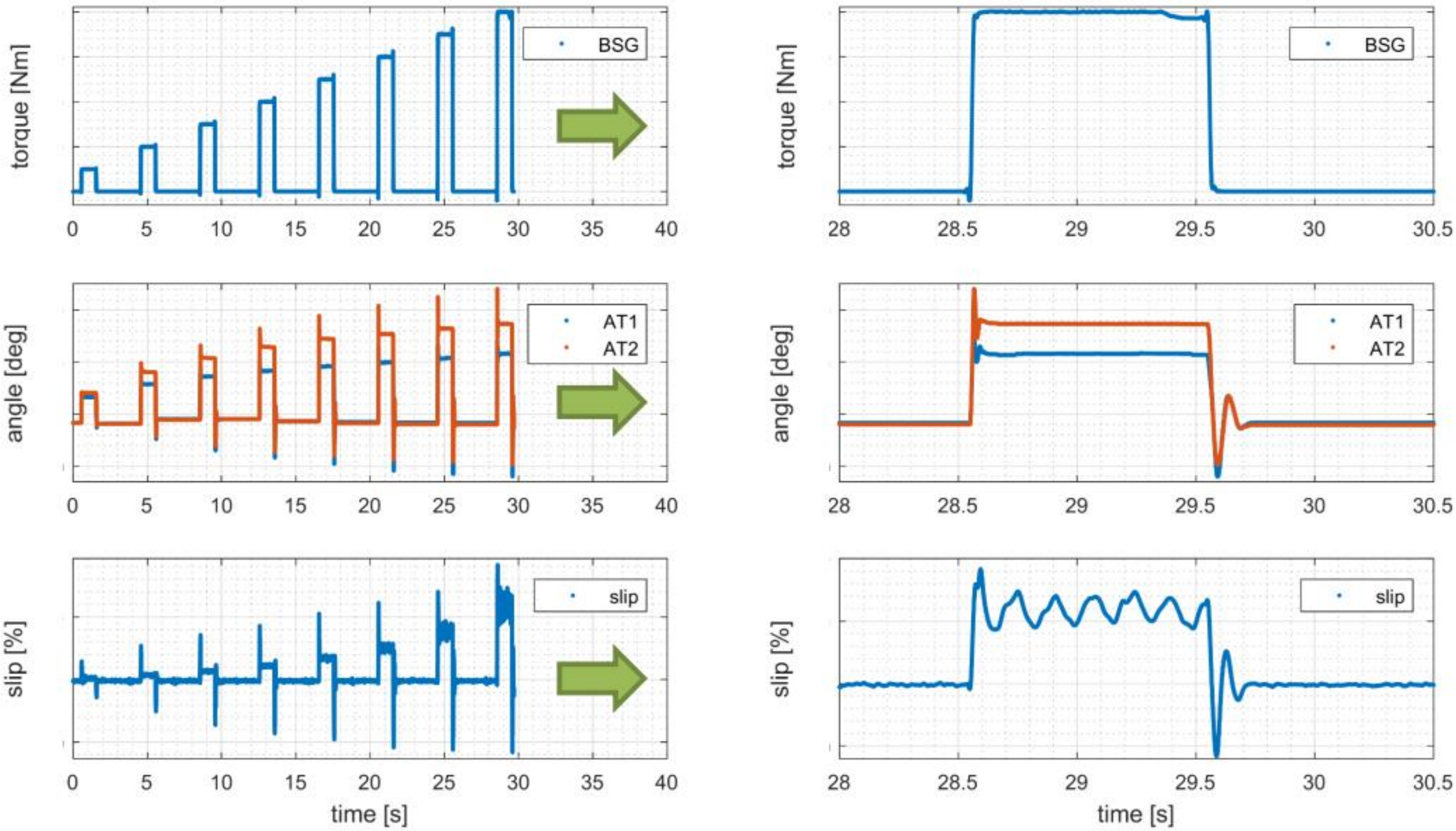
$$eff(\%) = \left(-\frac{P_{BSG}}{P_{CS}}\right).100$$

$$slip(\%) = \left(\frac{\omega_{CS} - \omega_{BSG}\tau}{\omega_{CS}}\right).100$$

$$P_{BSG} < 0$$

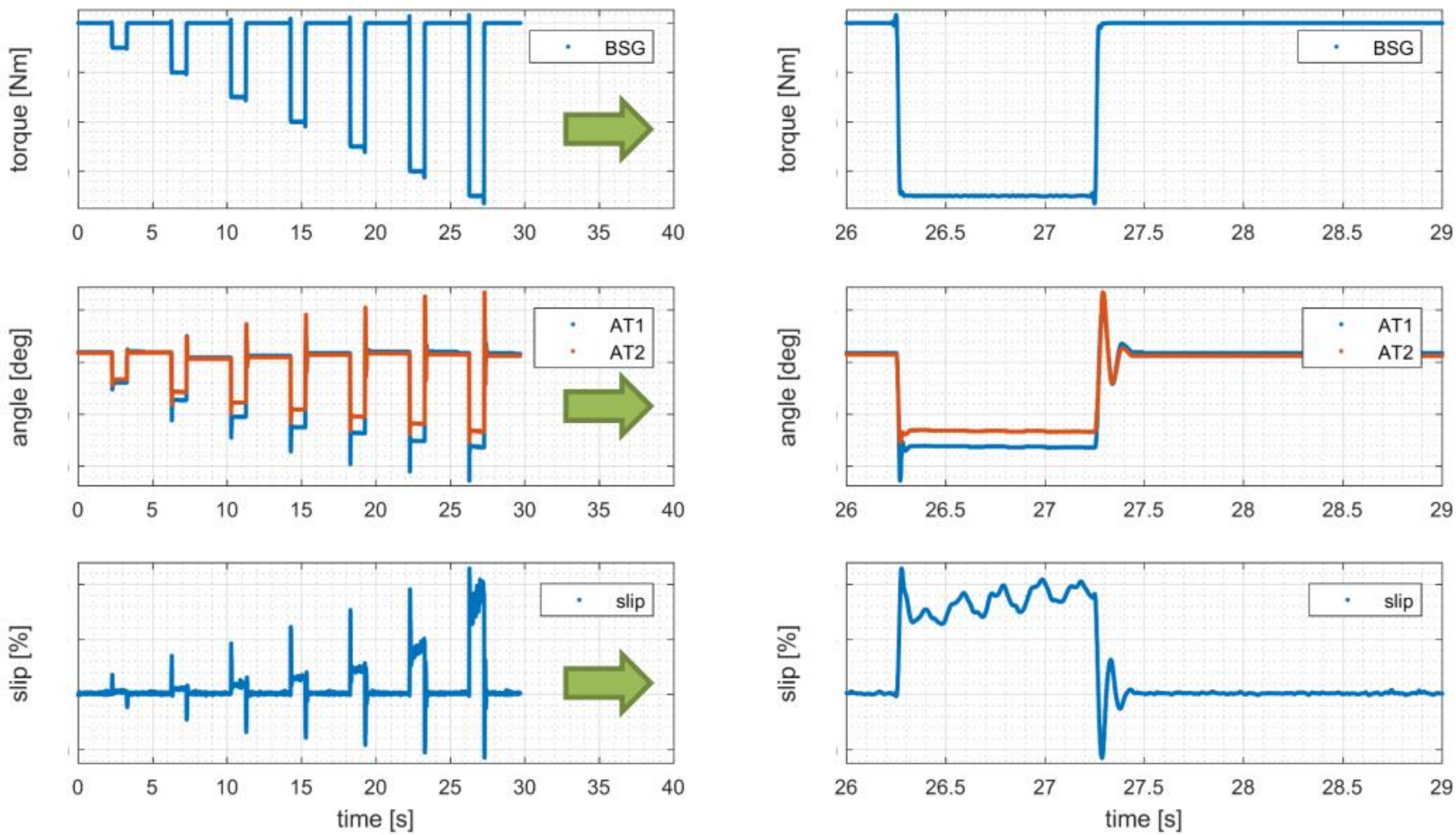
Twin-arm Tensioner: Dynamic Tests

BOOST



Twin-arm Tensioner: Dynamic Tests

BRAKE



Conclusions

- BSG-based BDS are the latest trend of micro-hybrid technologies and the rotary twin-arm tensioners are one of the most investigated solutions among manufacturers. No significant research work can be found in literature and no experimental results are provided.

- The **functionalities** of a twin arm tensioner in keeping the belt tension inside the desired acceptable range were **shown**.

- The **model** of the static behavior of a twin arm tensioner was **built and validated** by means of experimental results.
- The model resulted into a valuable **tool** that can be used for the **design** of twin arm tensioners.

- The dedicated **test rig** was used also for the **efficiency evaluation** and the analysis of the **dynamic behavior** of the reproduced belt drive system layout.
- The test rig can be used for **comparing** different tensioning solutions, **reproducing** different belt drive system layouts and **investigate** them experimentally.