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A Method to Define Profile Modification of Spur Gear and Minimize the Transmission Error

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&

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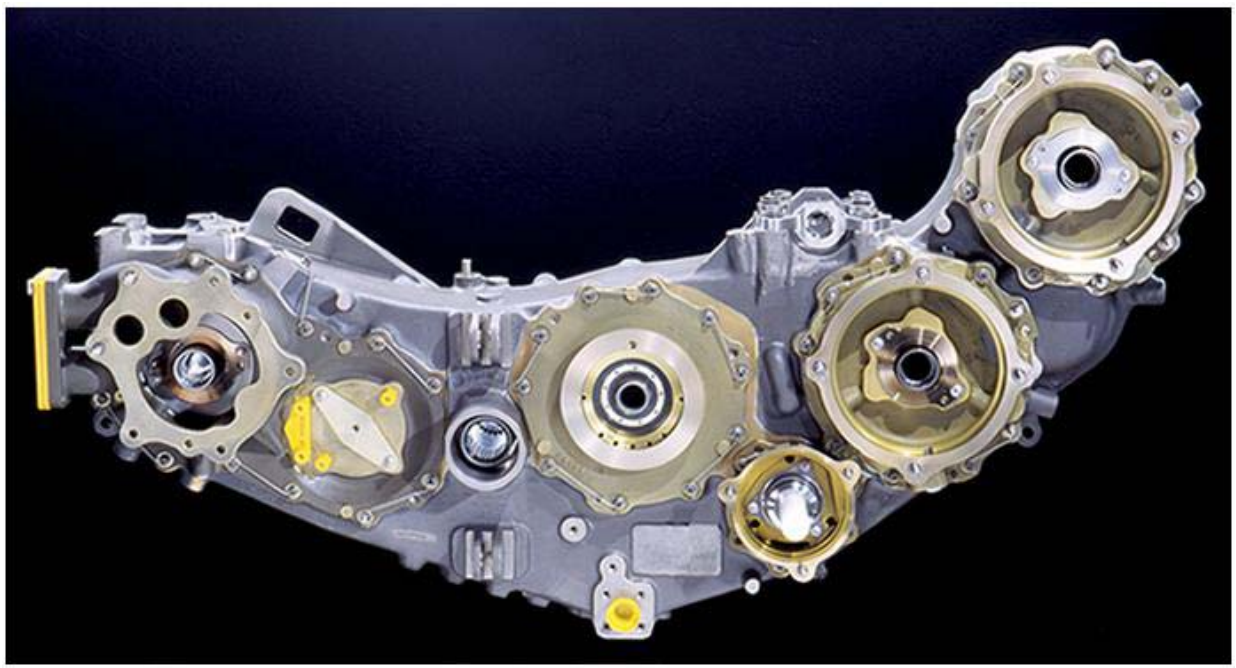
Field of application

Aerospace applications Gear Boxes

- High performance
- Low weight

A very simple lay-out is needed → SPUR GEARS



Spur Gears Vs. Helical Gears

Advantages:

- Simpler assembly, no axial bearings

Spur Gear solution preferred

Disadvantages:

- Full impact at meshing start with spur gear
- Sharing factor function less smooth

Noise reduction needed

Causes of Noise with Spur Gear Transmissions

Transmission Error (TE) is considered to be the primary cause of whining noise, in Gear Boxes:

- J.D. Smith. "Gears and theirs vibration, A Basic Approach to Understanding Gear Noise". *The Macmillan Press LTD.*, 1983.

- G. Niemann, H. Winter. "Machinenelemente Band II, Getriebe allgemain, Zahnradgetriebe", vol. 2. *Grundlagen, Stirnradgetriebe, Springer-Verlag*. Berlin, 1983.

Definitions: Transmission Error

Transmission Error (TE) is defined as the difference between the effective and the kinematics position

TE is generated by:

- teeth spacing errors
- dynamic effects
- deflections induced by the load on teeth

Peak to Peak Transmission Error (PPTE) is the difference between Maximum and Minimum of the TE trace

Profile modification (Tip Relief Modification) is a powerful design tool to interfere with TE

Definitions: Tip Relief Profile Modification

Profile modification definition:

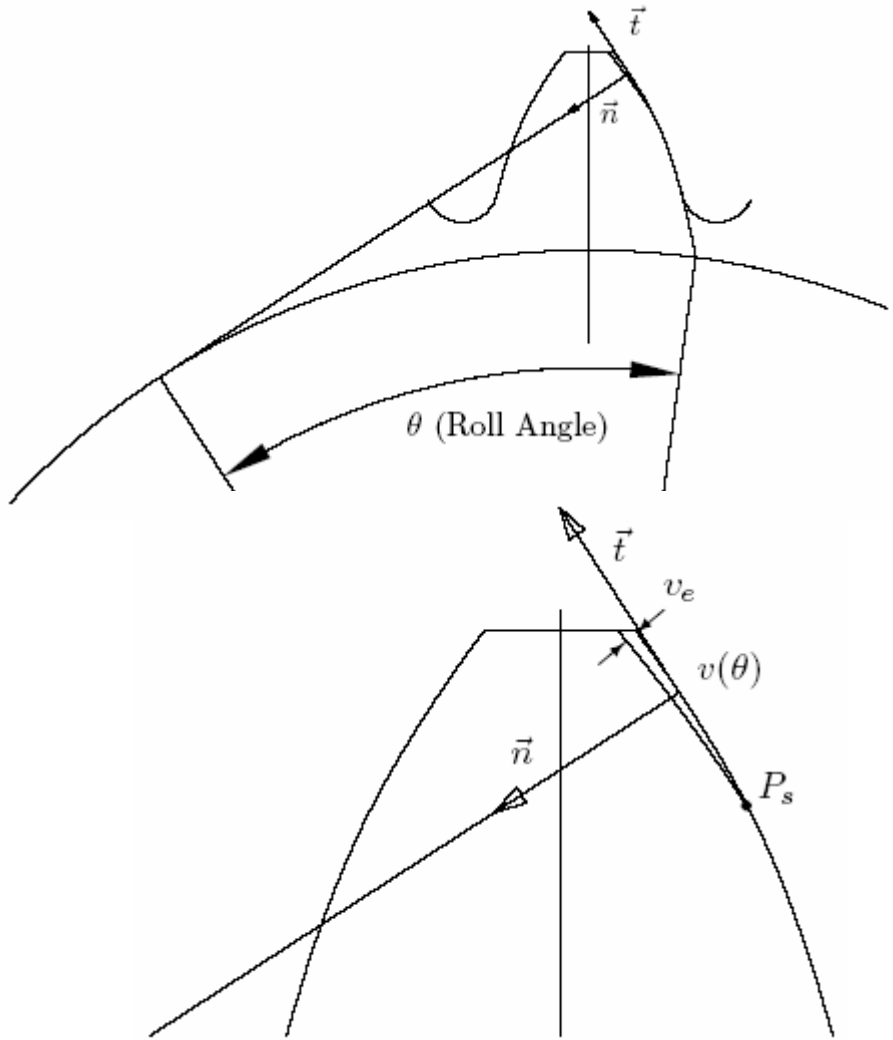
- only at the tip

- definition along the involute nominal profile

- topography shape (ex. Linear or Parabolic)

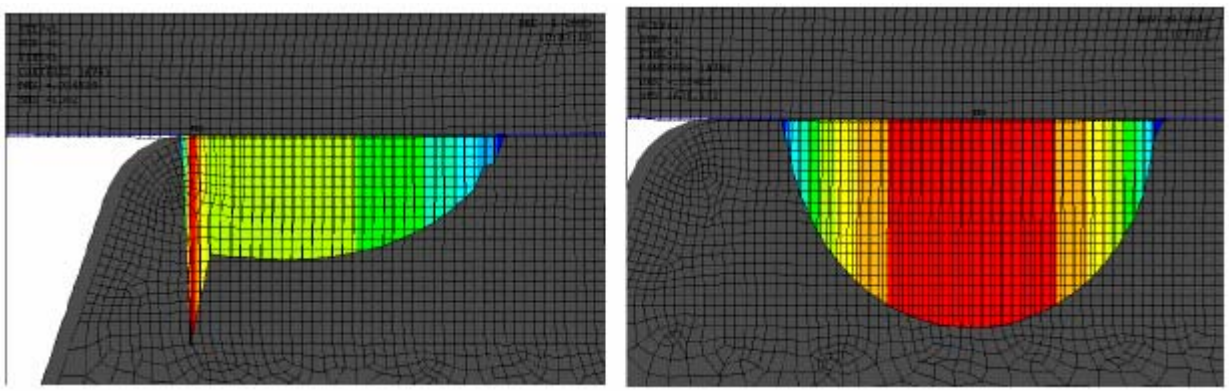
- start relief Roll Angle θ

- total amount of material removal at the tip v_e

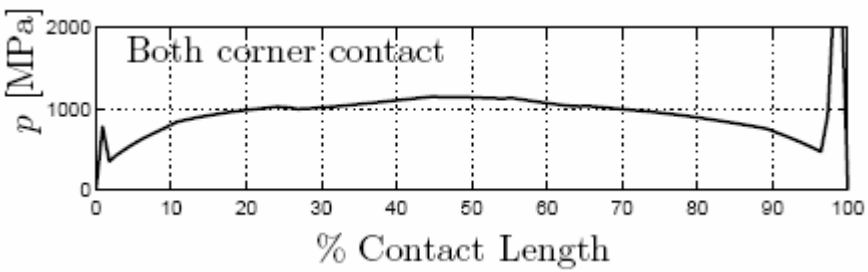


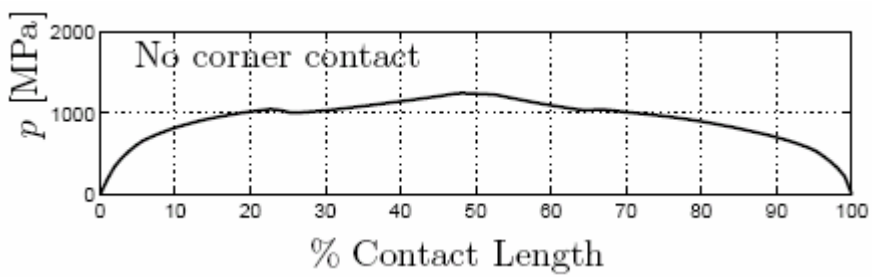
Definitions: Corner Contact

Corner Contact: Contact across the tip fillet,
if no fillet: complete Contact across the tip of the tooth



Maximum Pressure rises to very high values if Corn. Cont. appears





Corn. Cont. can be avoided with adequate Tip Relief Modifications

Aim of the paper

Noise and vibration optimization for a given spur gear set, both LCR and HCR are considered

PPTE is the function to minimize

Variables are: Profile Topography shape, Maximum amount of material removal, start relief Roll Angles

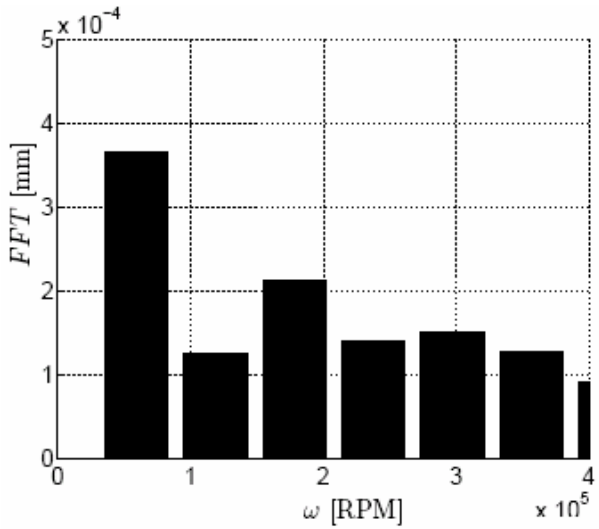
Boundaries are Corner Contact and Pressure Maximum.

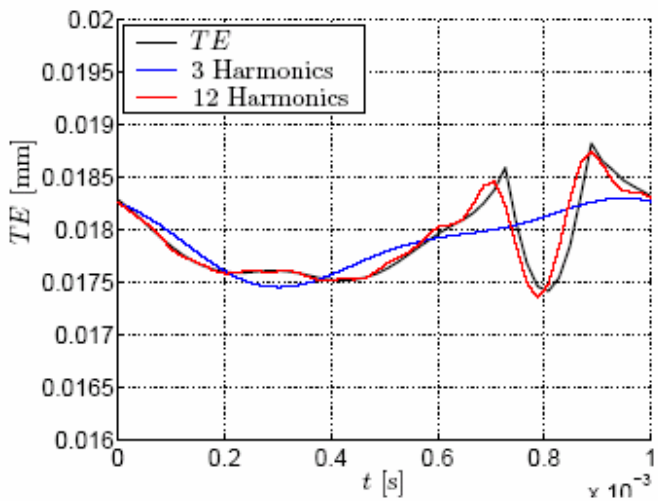
Bending stress are too low sensitive to profile modification, even with HCR gear sets to be taken into account

Choices and parameters ranges

TE trace can be decomposed by FFT, to identify a function to minimize the sum of the first few harmonics can be considered

- M.S. Tavakoli and D.R. Houser. "Optimum profile modification for the minimization of static transmission errors of spur gears". *Proceedings of ASME* 84 - DET - 173, 1986.





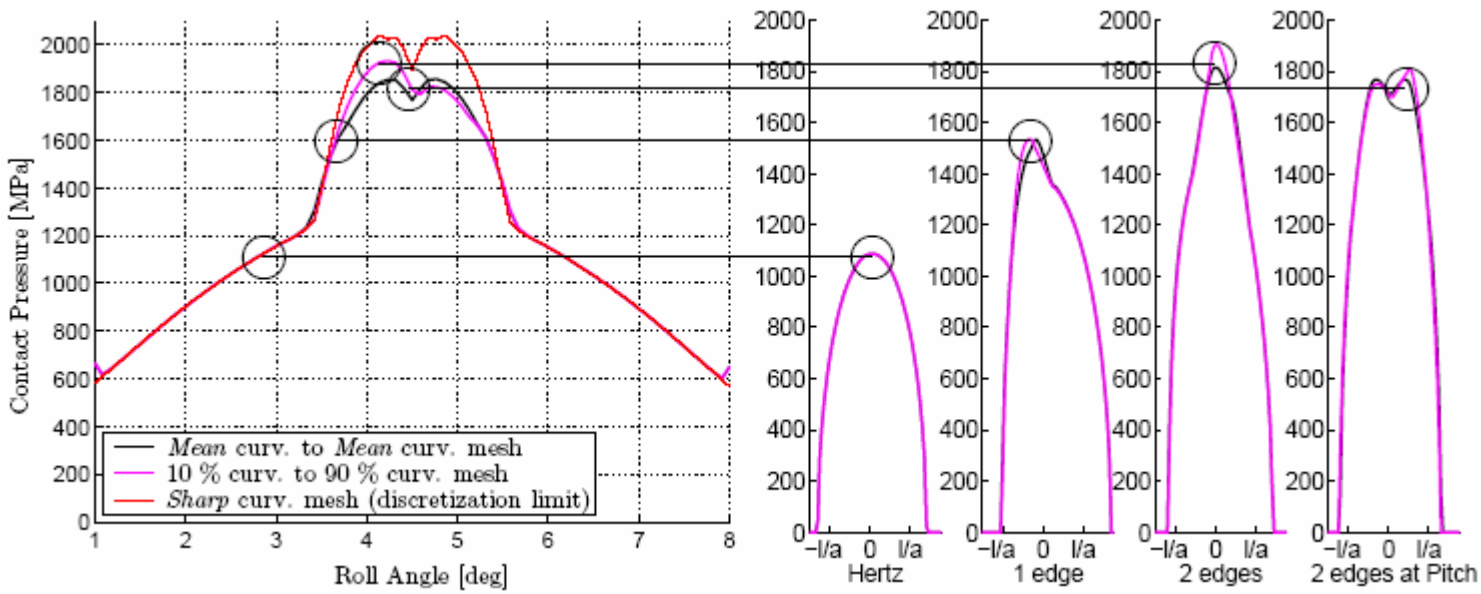
Few components cannot be the main part of the signal (like this)

PPTE is considered to have better correlation with whining noise

Choices and parameters ranges

Linear Tip relief generates a sharp edge at the start relief point then a strong pressure rise

- M.Beghini, G.M.Bragallini, F.Presicce, C. Santus. "Influence of the linear tip relief modification in spur gears and experimental evidence". *Proceedings ICEM12.* Bari, 2004.



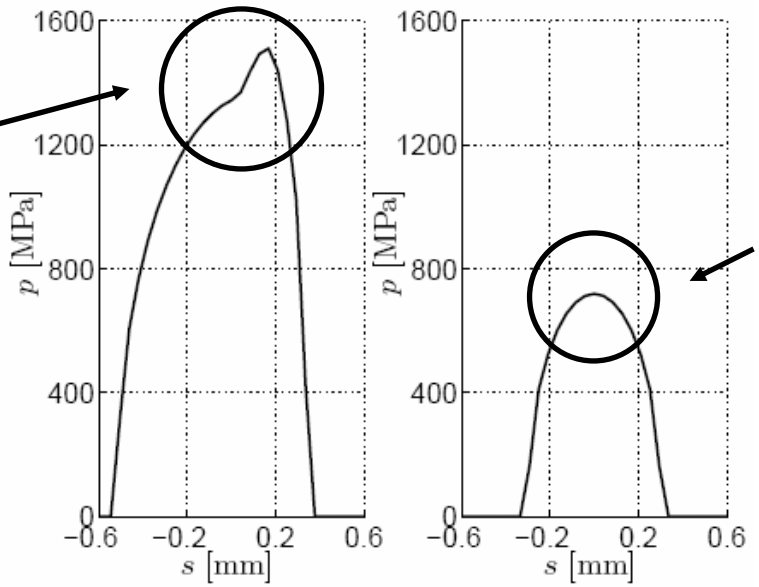
Parabolic Tip relief doesn't show this problem

Choices and parameters ranges

Parabolic Tip relief generates a sharp change of curvature but a mild pressure rise is produced.

- M.Beghini, C.Santus. "Analysis of plane contact with discontinuous curvature". *International Journal of Mechanical Sciences*. 2004. In Press.

Contact zone encompassing the start relief point



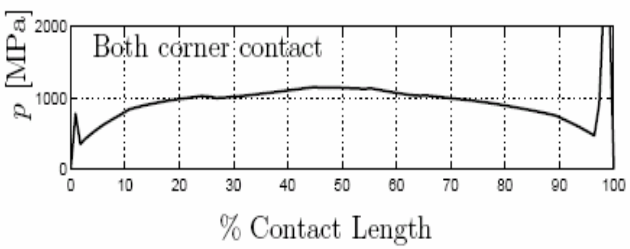
Contact zone not encompassing any discontinuity

This kind of tip relief is accepted. Only parabolic relief is considered

Choices and parameters ranges

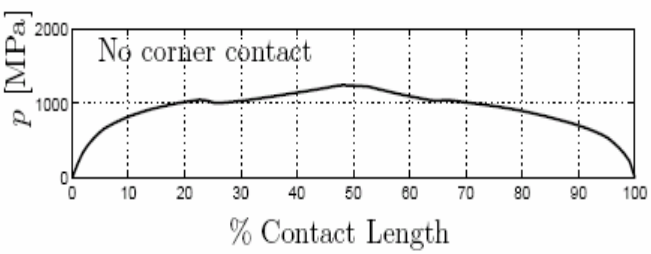
To asses the Total Amount Removal:

Gear Pair is simulated with no Modification Corn. Cont. found



Niemann Rule, increasing Tip Relief Modif.

Gear Pair is simulated with Modification until no Corn. Cont. is found



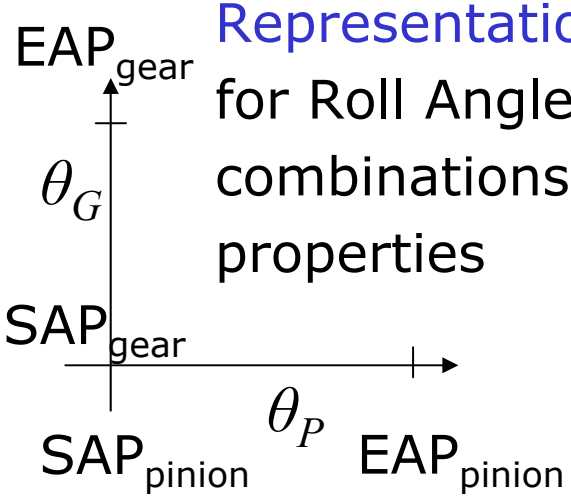
According to the Niemann rule the total amount is chosen to avoid the Corner Contact

- G. Niemann and J. Baethge. "Transmission error tooth stiffness, and noise of parallel axis gears". *DIZ*, 112(4), 1970.
- G. Niemann, H. Winter. "Machinenelemente …

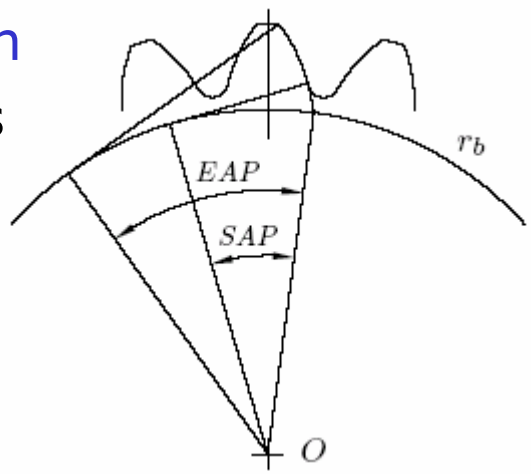
Choices and parameters ranges

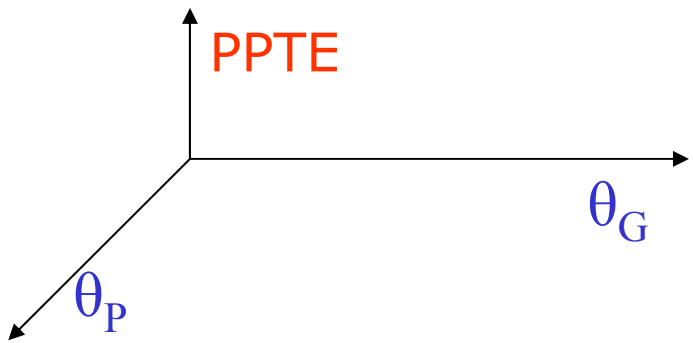
Start Relief Roll Angles are the Design Parameters left to perform the optimization

It is suggested a 3D map showing the PPTE vs. the 2 Start Relief Roll Angles Coordinates



Good Representation for Roll Angles combinations properties



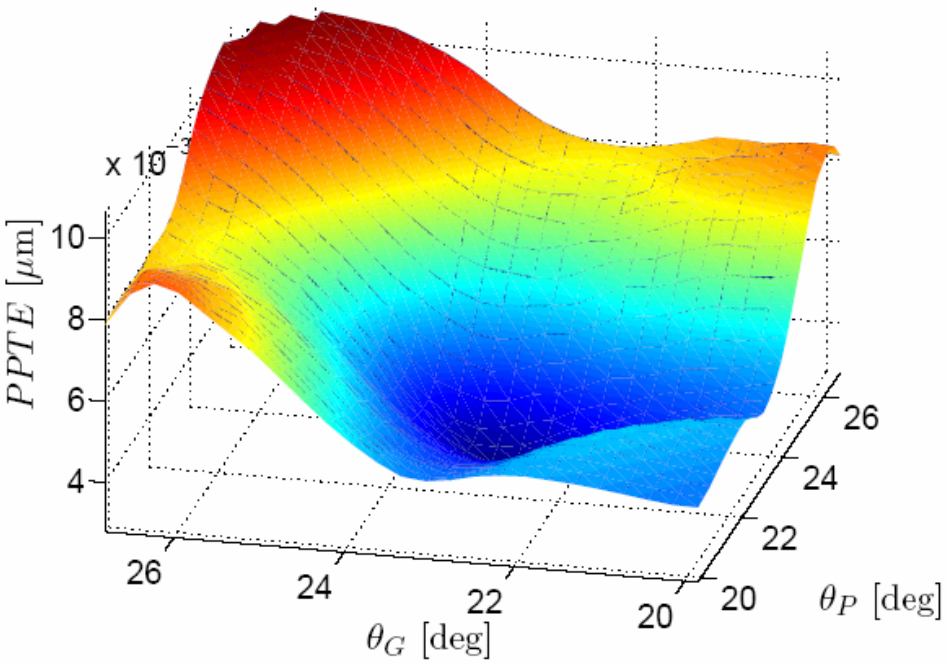


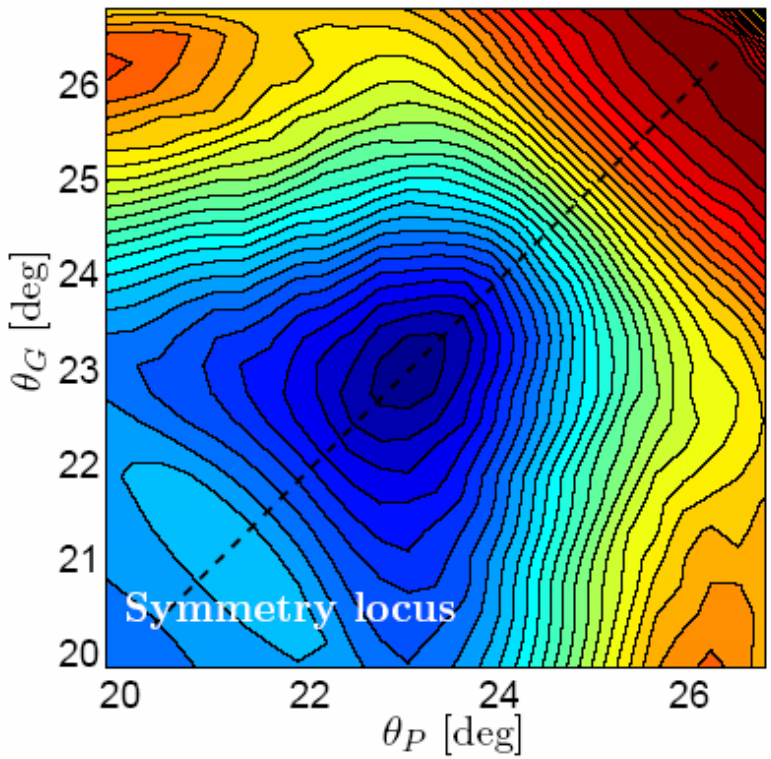
Immediate and intuitive Optimum Direct Search

Results: LCR Spur Gear Set

Equal teeth number Gear Set analyzed:

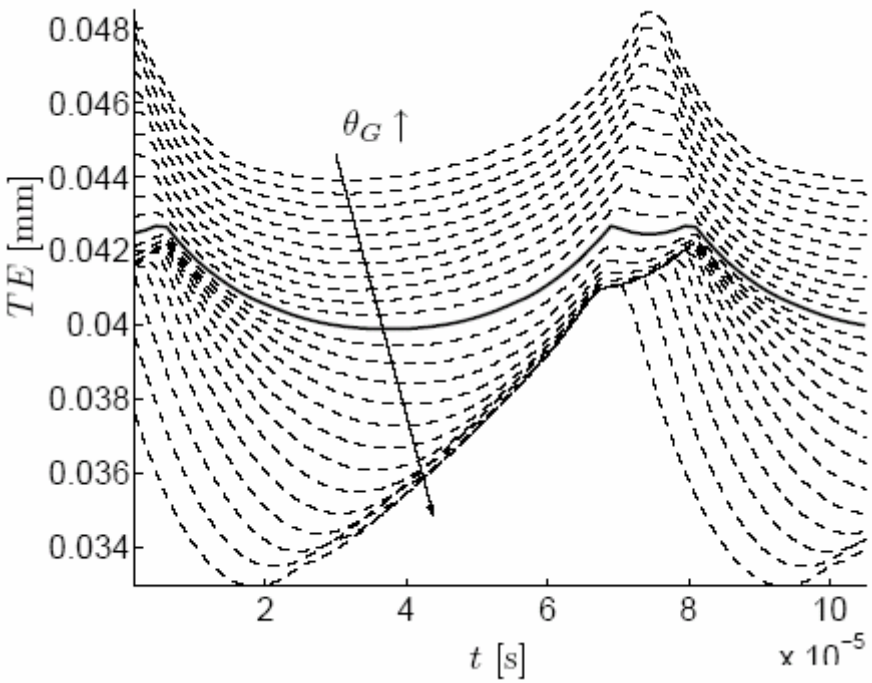
- Symmetry Locus
- Absolute Minimum found
- Local regularity at the absolute minimum

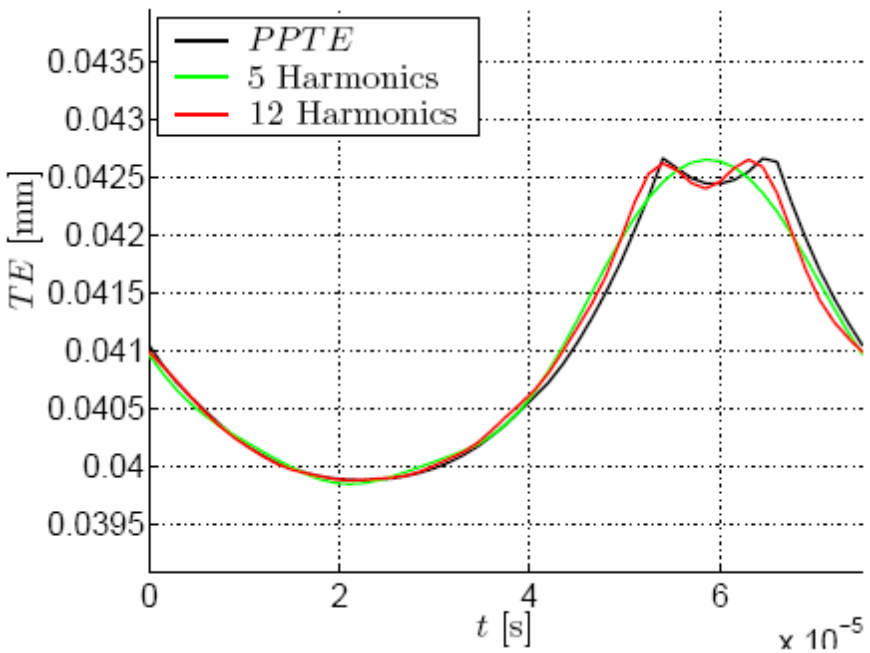




Results: LCR, properties of the minimum

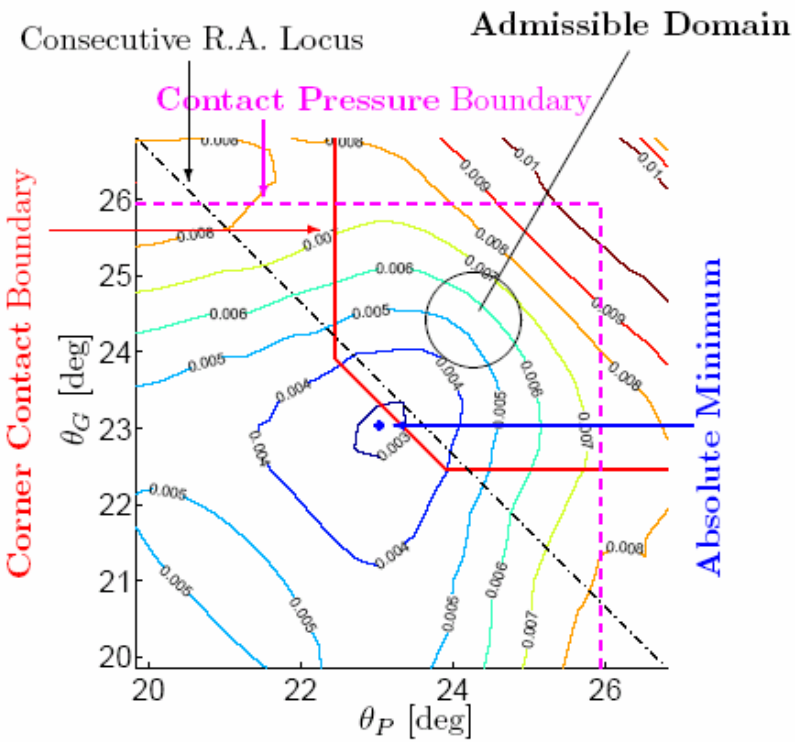
- (θ_P, θ_G) minimum is symmetric for equal teeth number
- parabolic modification is easily recognizable
- change between 1 – 2 Contact Pairs have to be at the same level in the optimum PPTE trace



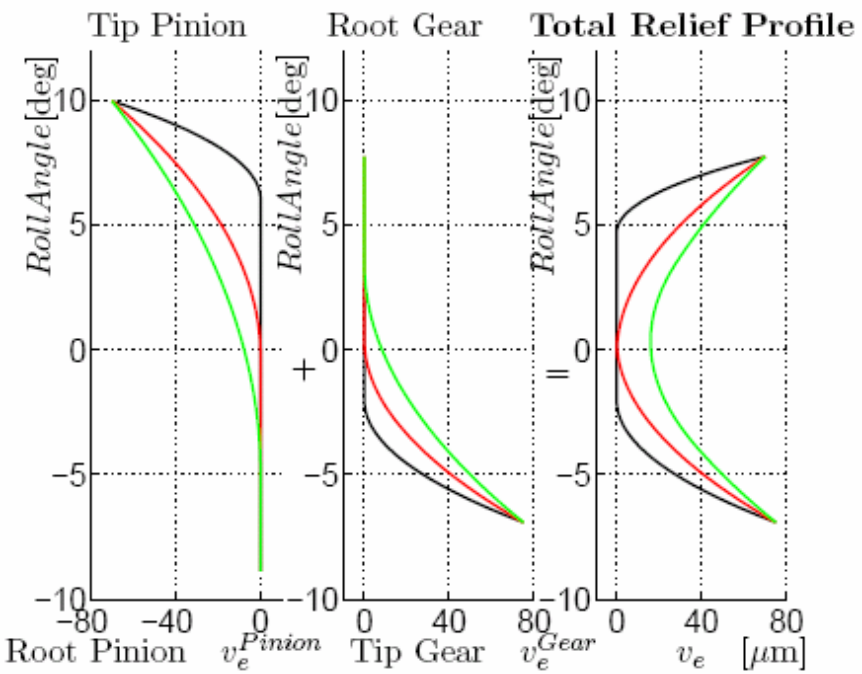


Results: LCR, application of boundaries

- (θ_P, θ_G) minimum falls out the Corner Contact boundary
- the other boundary is not crucial
- Consecutive Roll Angle Locus parallel to the Corn. Cont. bound.
  and near the absolute minimum



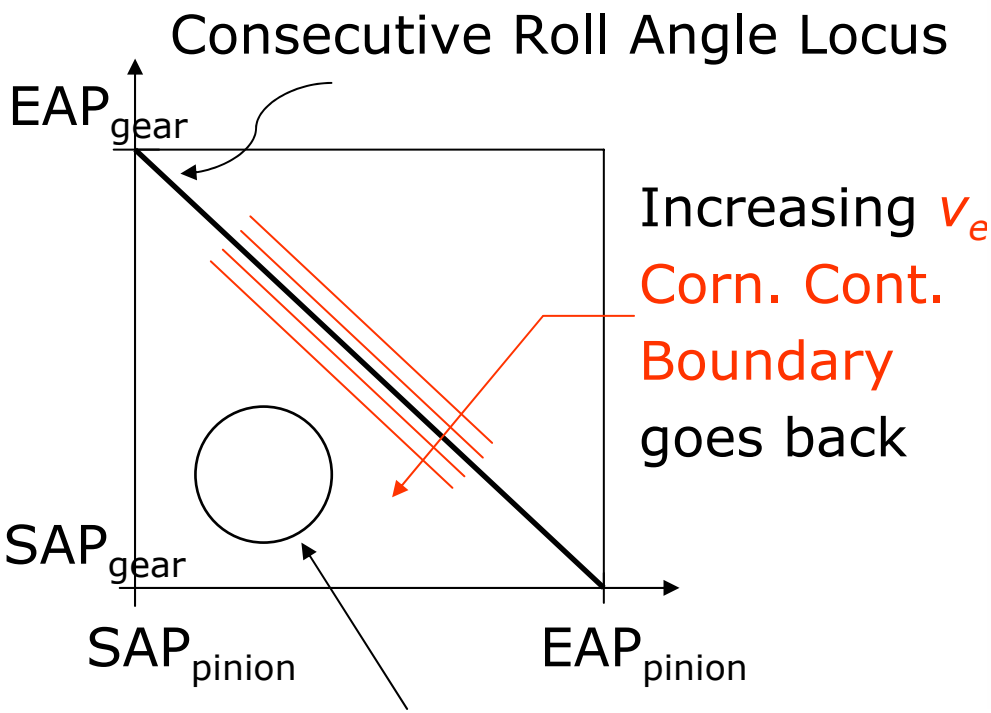
Consecutive Roll Angle Locus

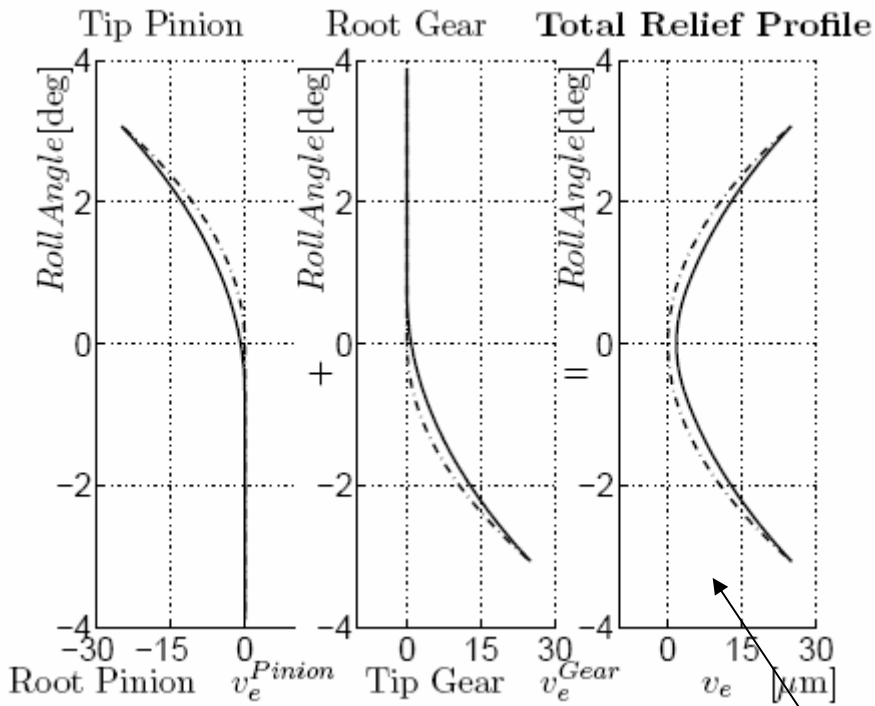


Consecutive Start Relief Roll Angle Rule

Definition of the Consecutive Roll Angle Locus and Corner Contact Boundary

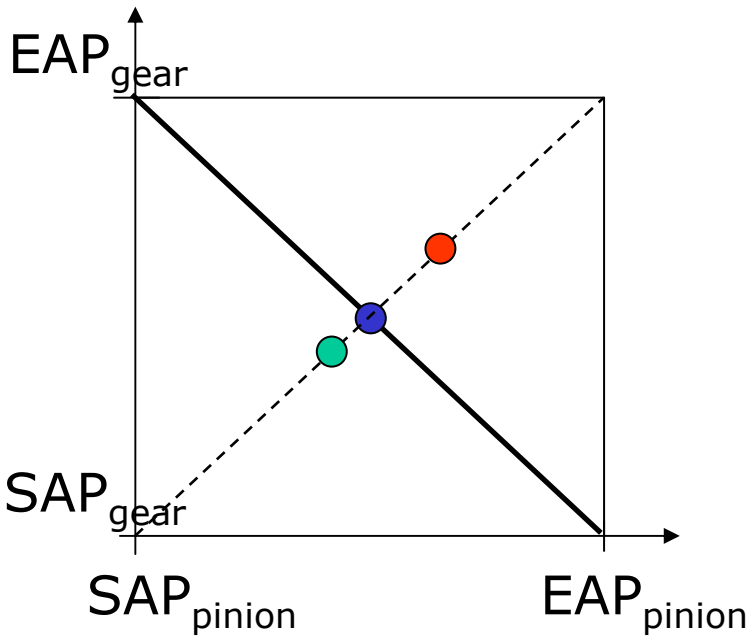
Consecutive Roll Angle Locus vs. Absolute minimum





Roll Angle Overlapping, effective Total Amount reduced

Result of the optimization (LCR)



- Absolute Minimum
- Optimum Found
- Niemann Opt. (HPSTC)

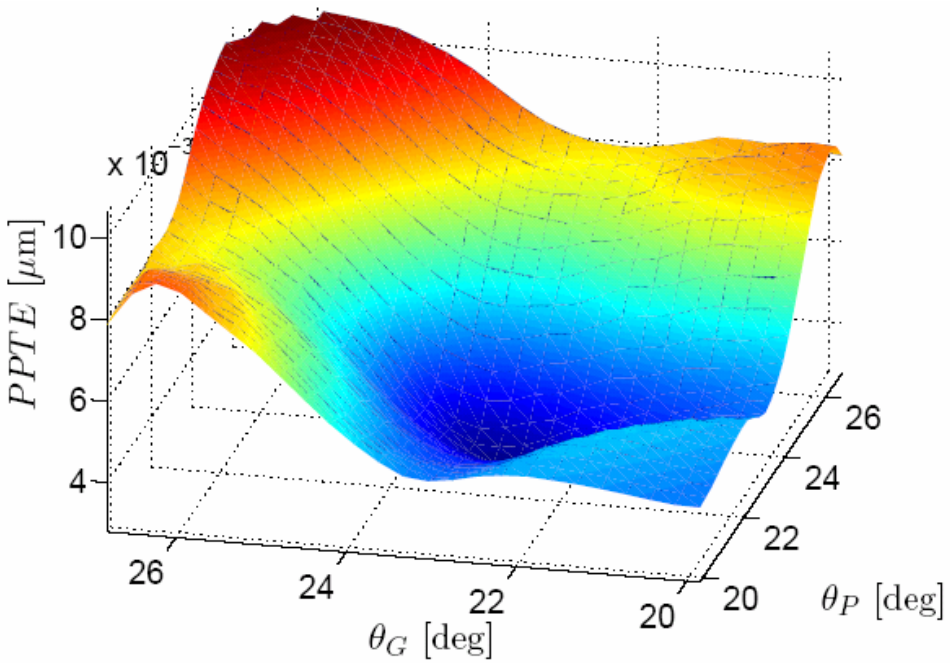
Niemann Suggestion is to start the profile modification at the HPSTC Point either for Pinion and Gear (Long Profile Modification)

Suggestion here proposed is an even longer modification:

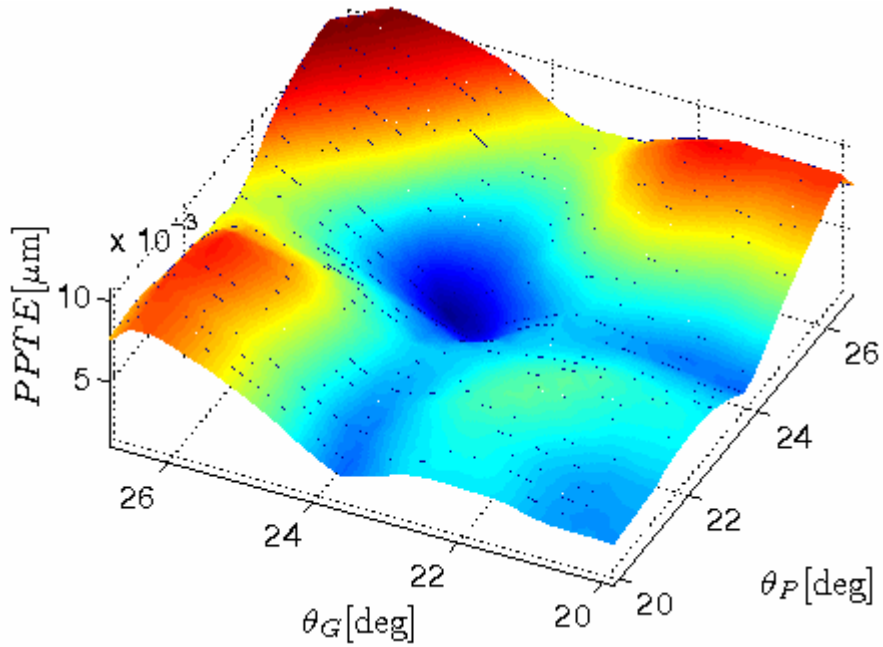
- the whole relative profile is modified (K-chart),
- no involute-involute point in contact is held.

Comparison with Linear modification

PPTE function with Parabolic Tip Relief Modification



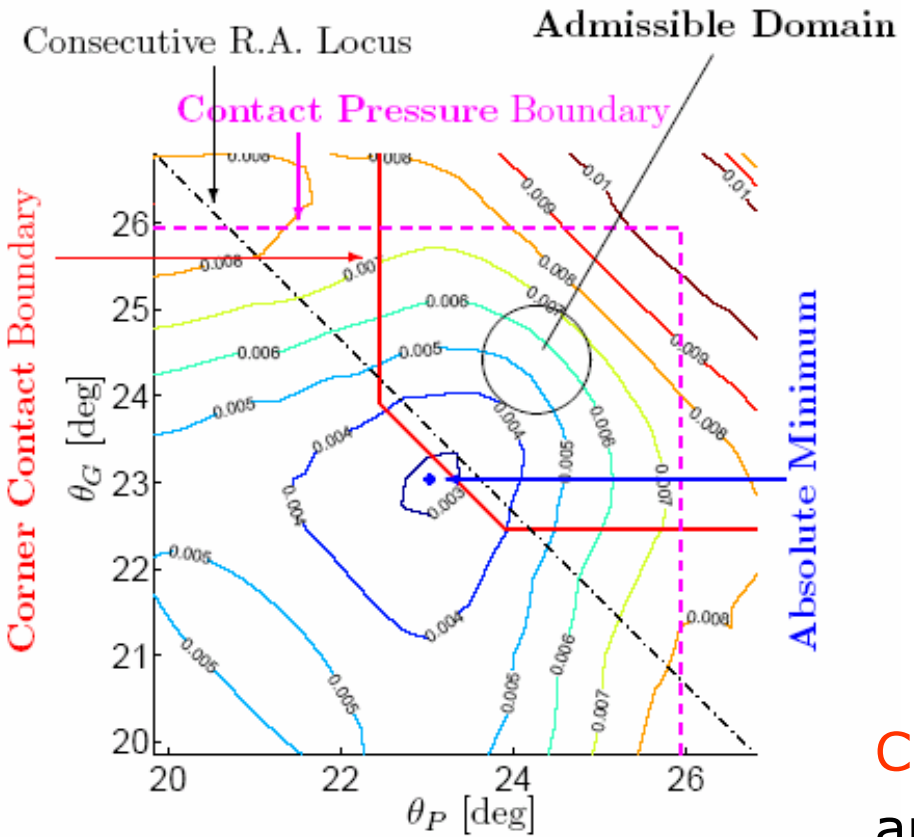
PPTE function with Linear Tip Relief Modification



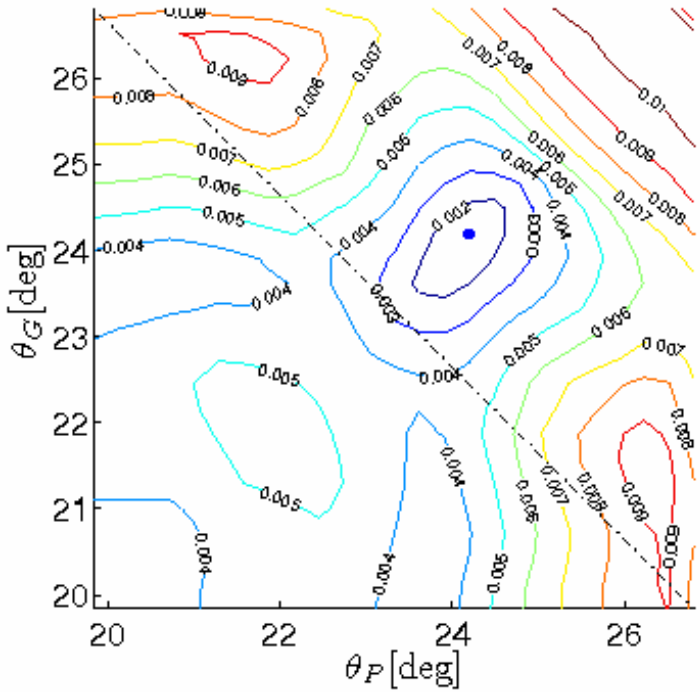
Linear shows the aforementioned singular Contact Pressure

Comparison with Linear modification

PPTE function with Parabolic Tip Relief Modification



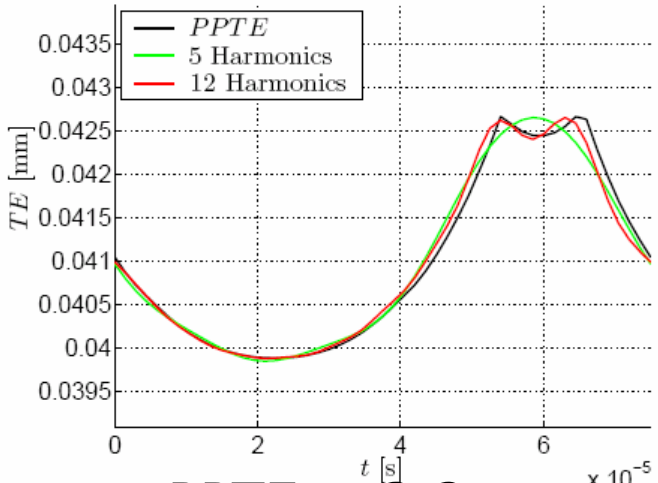
PPTE function with Linear Tip Relief Modification



Consecutive Roll Angle does not apply, Niemann rule more effective

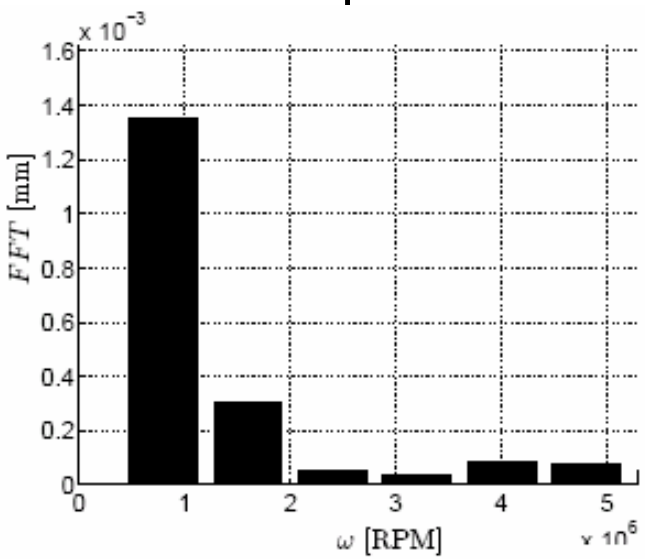
Comparison with Linear modification

TE function with Parabolic Mod.

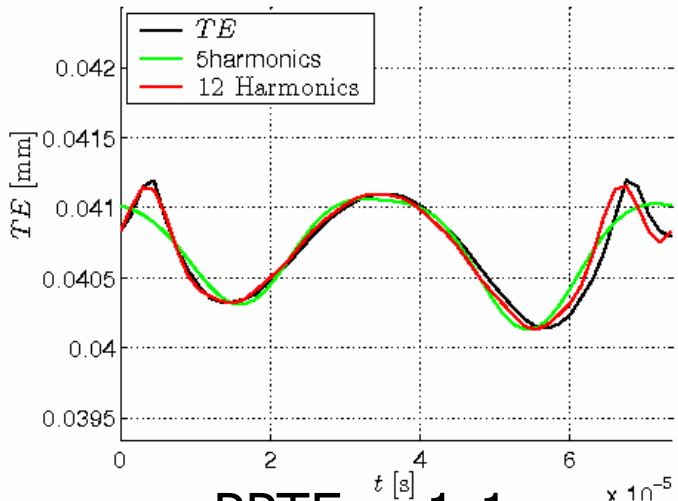


PPTE = 3.2 μm

1st harmonic predominant

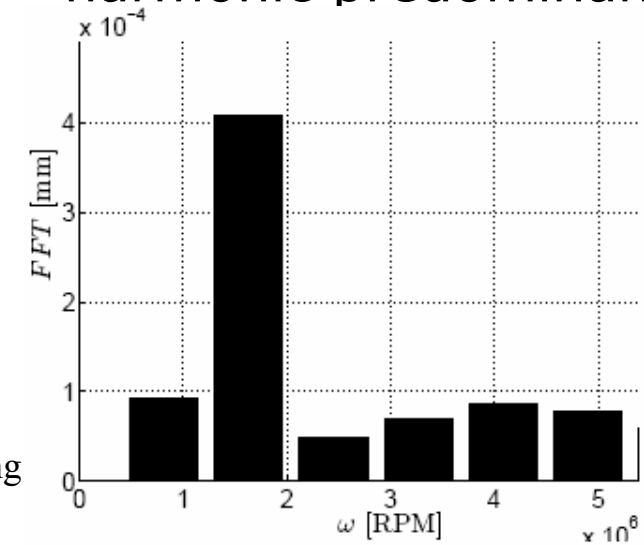


TE function with Linear Mod.



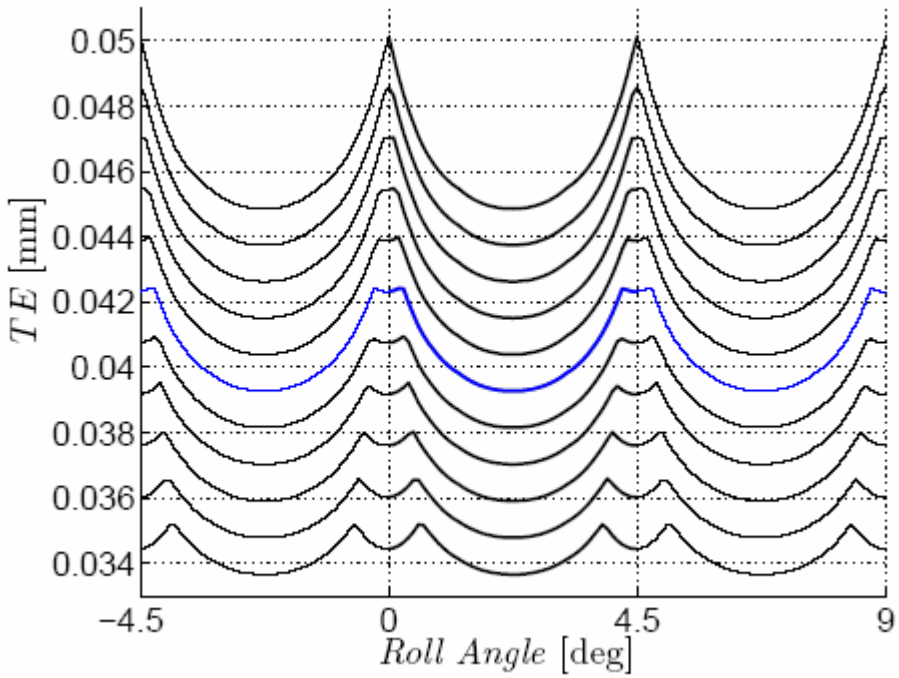
PPTE = 1.1 μm

2nd harmonic predominant

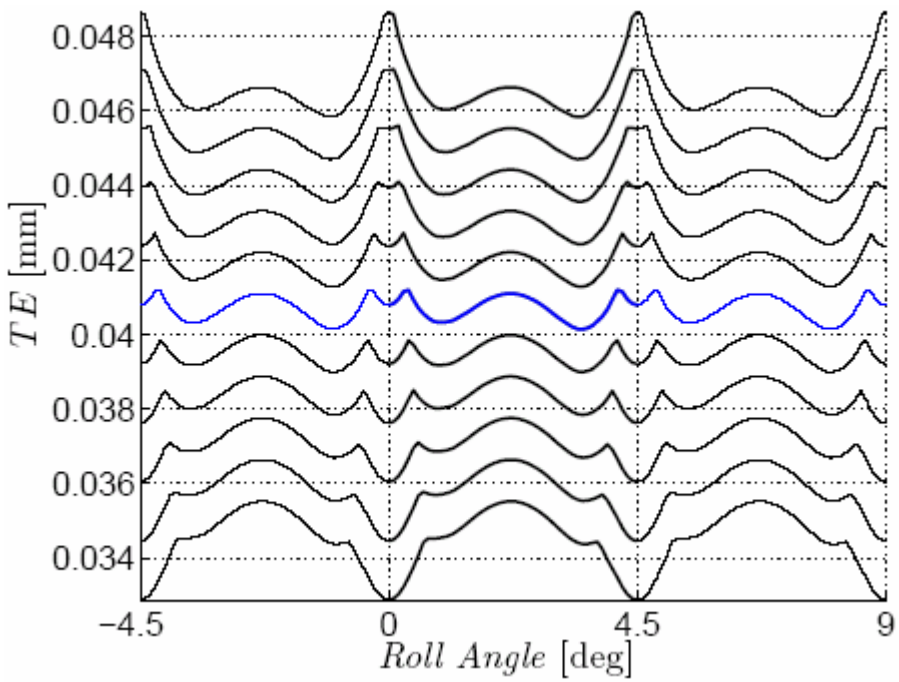


Comparison with Linear modification

TE function with Parabolic Tip Relief Modification



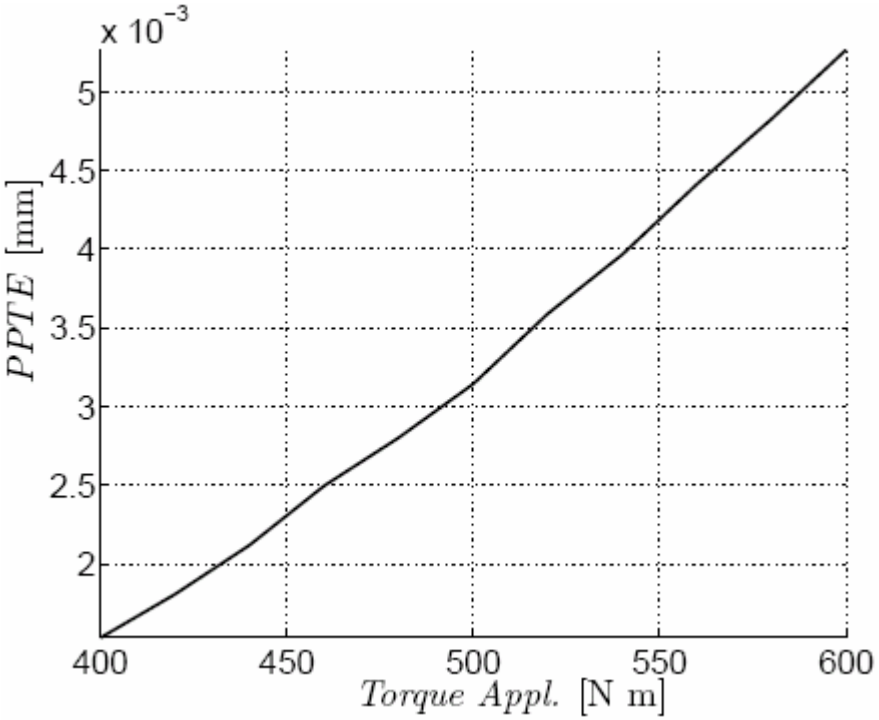
TE function with Linear Tip Relief Modification



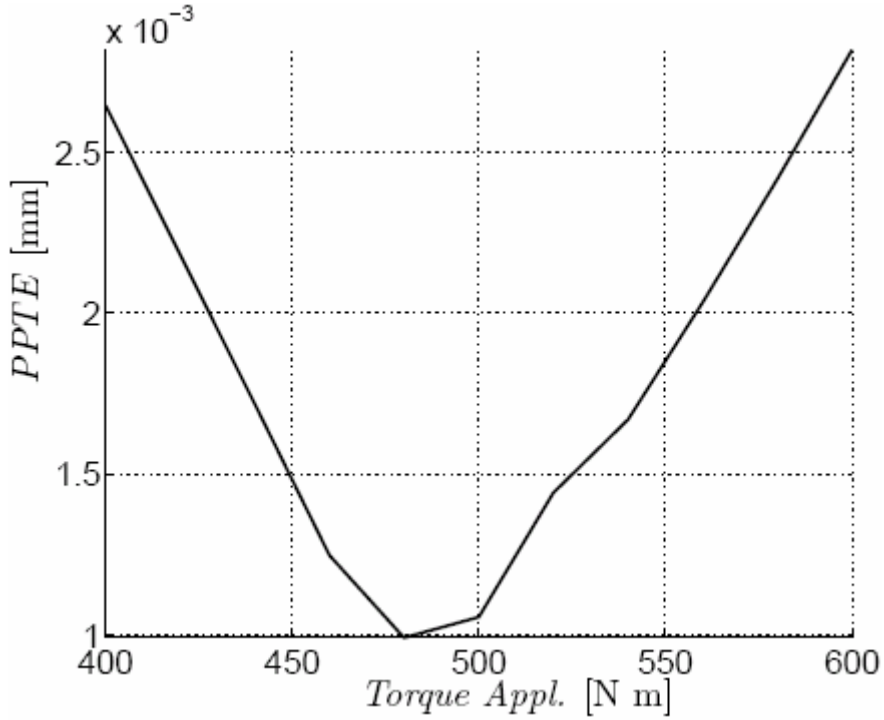
Different behavior in terms of TE sensitivity to the load

Comparison with Linear modification

PPTE(Torque) with Parabolic Tip Relief Modification

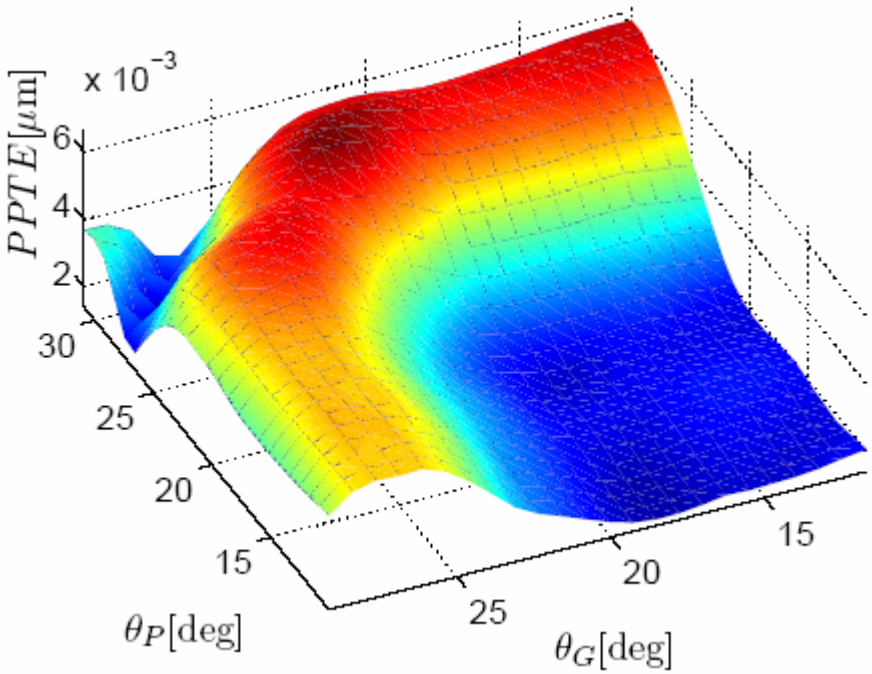


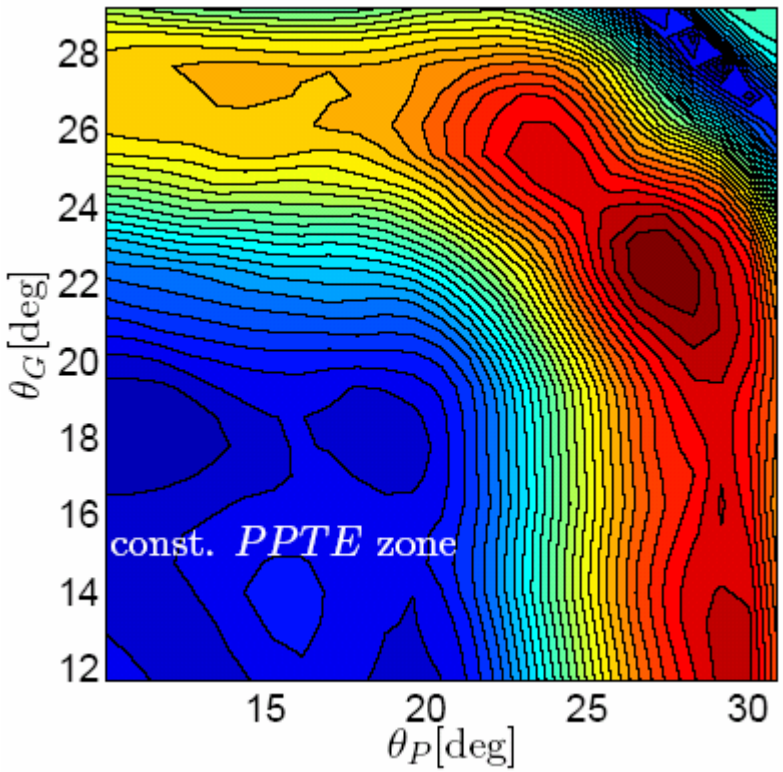
PPTE(Torque) with Linear Tip Relief Modification



Different behavior in terms of PPTE sensitivity to the load:
NO minimum with Parabolic, Minimum with Linear

Results: HCR Spur Gear Set

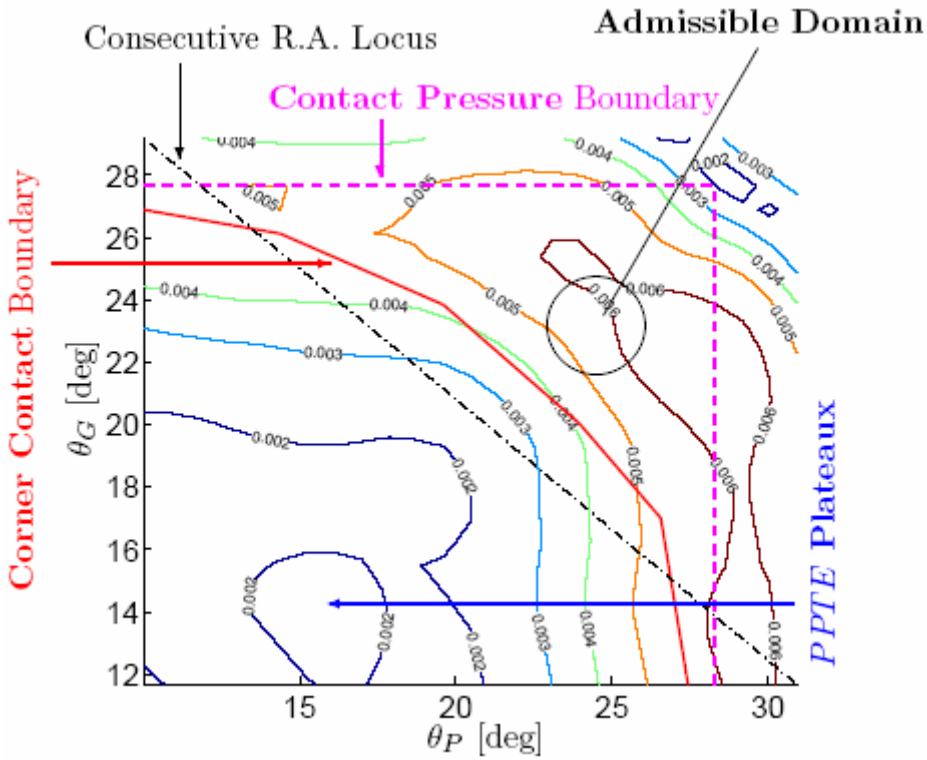


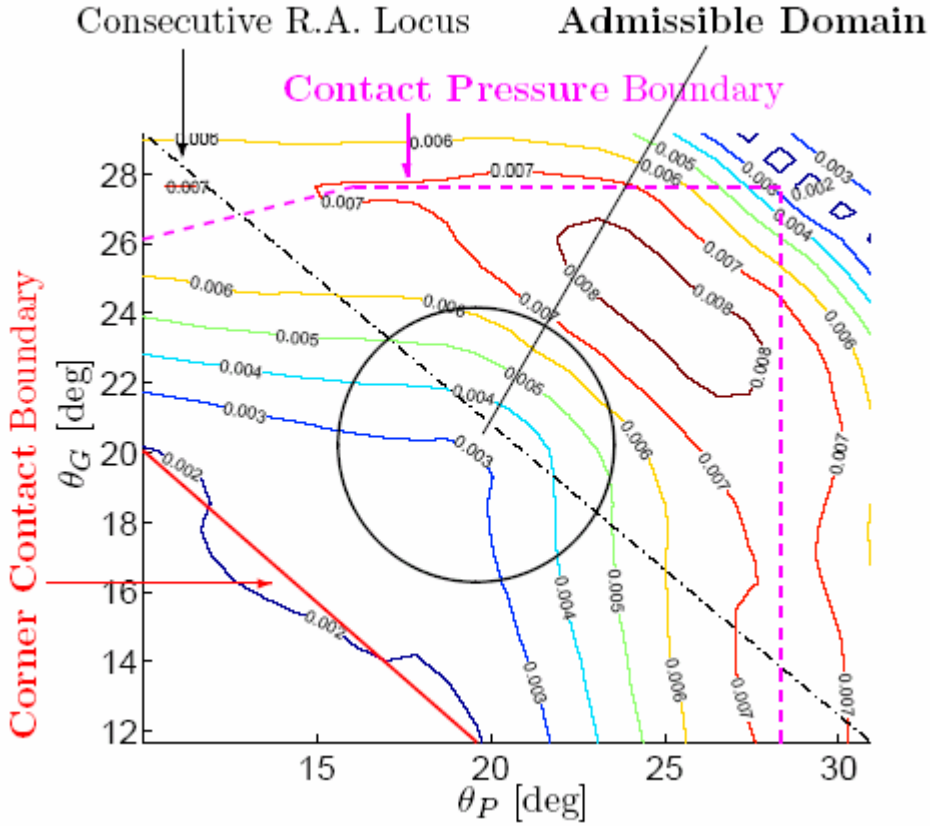


Results features:

- PPTE Constant at low Start Relief Roll Angle
- Low PPTE even at high Roll Angle

Results: HCR, application of boundaries





For HCR geometries Corner Contact boundary encompasses the whole part of the PPTE plateaux (v_e assessment)

By increasing the Total Amount v_e by a factor 1.5 the Consecutive Roll Angle Locus falls in the admissible domain

Conclusions

- An optimization method is here performed
- Corner Contact and Contact Pressure Boundaries are explained and applied to the optimization procedure
- Roll Angle vs. PPTE 3D maps are presented
- Consecutive Start Relief Roll Angle is introduced and mono-dimensional search, with Parabolic Modification, is performed
- Parabolic and Linear tip relief are compared:
    - Linear Mod. produces lower PPTE then Parabolic Mod.
    - Linear Mod. generates singular Contact Pressure at start relief point, and so it is not acceptable
    - with Parabolic Mod. first harmonic is the strongest, while with Linear Mod. second harmonic is the predominant
- Both LCR and HCR Gear Set are considered

Further Development

- To avoid Contact Pressure singularity and keep the linear shape, the BEST profile modification is linear with parabolic fillet.

- The curvature of the fillet is an interesting parameter to investigate

- Other shapes for Tip Relief Modification can be taken into account

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