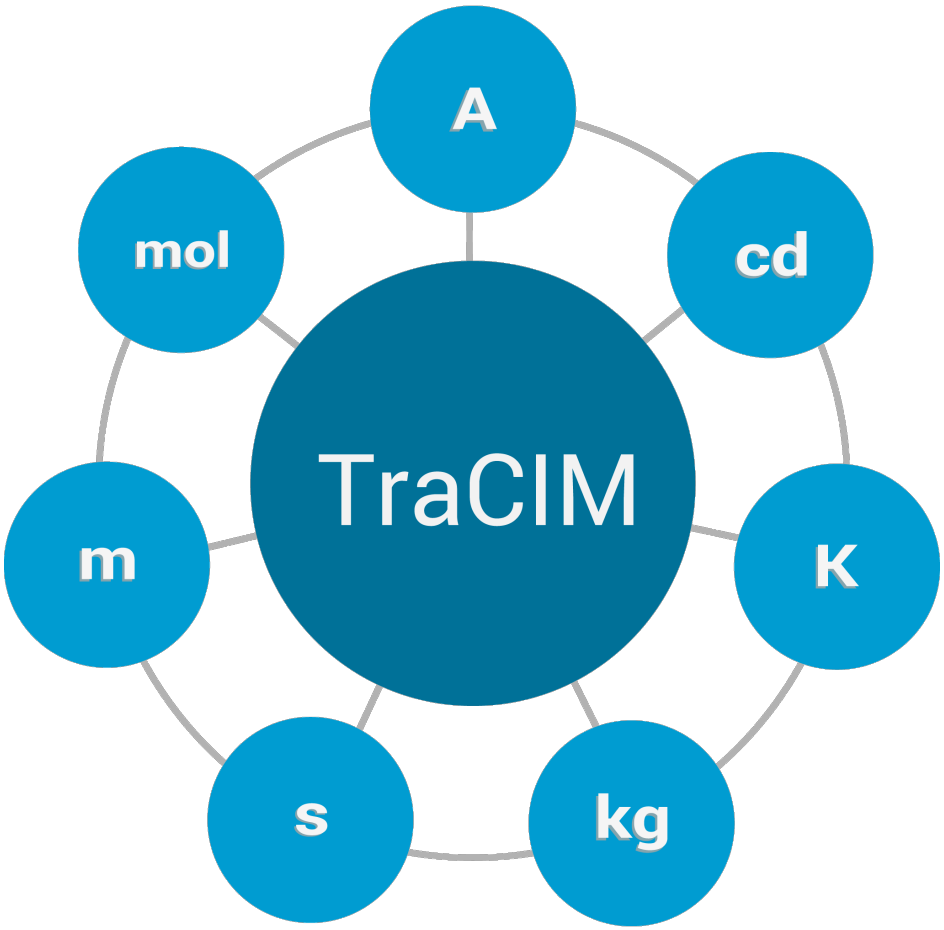
Traceability for Computationally-Intensive Metrology
Validation of Involute Gear Evaluation Algorithms



Authors:
Shan Lin, Frank Keller, Martin Stein

Physikalisch-Technische Bundesanstalt

Contact:
info.tracim@ptb.de
https://tracim.ptb.de

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1 The TraCIM system

1.1 Introduction

The Involute Gear Evaluation test is provided by the PTB TraCIM Online System (`tracim.ptb.de`) and can be ordered by registered customers. To perform a test the customer will get an XML file containing some administrative data as well as data sets with synthetically generated gear data. The data sets are provided as Gear Data Exchange Format (GDE) specified in VDI, VDI 2610-1. Task of the customer is to process this data according to the standards ISO 1328-1:2013, VDI/VDE 2612 Part 1 (2018), and VDI/VDE 2613 (2003) for this task and send back the results to the TraCIM system. The TraCIM system automatically compares the customer results with its own reference values and sends a report with the test conclusion. Evaluation procedures are described in Section 1.2.

The data exchange with the TraCIM system is provided by a RESTful web service. All data is exchanged in XML format. For the communication with the TraCIM system, it is recommended to use a client application which also takes care of the (de)serialization of the XML strings. In Section 1.3.1 support for developing such a client can be found. The XML schemata used for data exchange are described in Section 1.4.

Tests can be bought in a web shop (`tracim.ptb.de`) by registered customers. A test consists of 47 test data sets, each representing the data for a gear measurement of pitch, helix or profile lines. After successful purchase of a test the customer will get an order key that allows him to request test data from the TraCIM system with his client application.

In order to check the functionality of the customer's TraCIM client, a charge free test with public sample data is provided. Registered customer can request a test with these data sets from the TraCIM system at any time in order to evaluate the correct function of his client-server communication. See Section 1.3.2 on how to request sample test data sets.

The PTB TraCIM system was developed within the frame of an EURAMET project founded by the European Union (EMRP project NEW06: Traceability for computationally-intensive metrology, www.ptb.de/emrp/tcim.html) and is under strict quality control of TraCIM e.V. Association.

1.2 Test result evaluation

For the validation, the test results calculated by the customer software are compared to the associated reference results in the TraCIM system data base. For a positive test conclusion all deviations between customer values and reference values must be smaller than the maximum permissible error values (MPE). This MPE, which is the same for all test values, is specified by the customer.

- If the customer specifies an MPE equal to zero, the default value $\mathrm{MPE} = 10^{-6}\,\mathrm{mm}$ is used.
- Admissible non-zero values specified by the customer must satisfy

$$10^{-6}\,\mathrm{mm} \leq \mathrm{MPE} \leq 10^{-4}\,\mathrm{mm}. \tag{1}$$

Other values for the MPE are not accepted and cause an error message.

1.3 Client-server communication

The test procedure is highly automated using internet based data exchange by client-server communication via a REST interface. Using a REST client application the user is able to obtain test data sets and send back the calculated results.

The data exchanged between client and server is encapsulated within XML. A proper specification of the applied XML data schemata is given in Section 1.4. The messages send between the client application and the TraCIM system server are treated as plain character strings.

1.3.1 Development of a client application

Configuration of the HTTPS connection: The communication between the TraCIM server and the client application is established via HTTPS (Hypertext Transfer Protocol Secure = encrypted HTTP) connection that allows to send and receive content in the form of character strings containing messages in XML format. Each HTTPS connection is created from a specific URL (Uniform Resource Locator). The following configurations are necessary:

- Set the request method "POST" (request comprising input and output)
- Set connection property "Content-Type" to "application/xml"
- Set connection property "Accept" to "application/xml"

Packages for creation and configuration of an HTTPS connection are available for different programming languages, e.g.:

- Java: java.net API
- C/C++: Microsoft C++ REST SDK or similar
- C#: .NET Framework (System.Net.Http)

POST request for obtaining test data sets: The URL of an HTTPS connection for the POST request to obtain test data sets is

`https://tracim.ptb.de/tracim/api/order/<SWTG_ORDER_KEY>/test` (2)

where `<SWTG_ORDER_KEY>` has to be replaced by the order key for the Involute Gear Evaluation test purchased at the TraCIM web shop. When the TraCIM system receives the client message it will create a unique process key associated with this test process. Test data and process key are then returned to the client. In case of an incorrect order key the TraCIM server will send an error message. Details about the format of the delivered test data are described in Section 1.5.1. Error messages are addressed in Section 1.5.4.

Example 1.1. *A simple way to communicate with the TraCIM server is using the command line tool cURL (https://curl.haxx.se). To get test data for the order key* `<SWTG_ORDER_KEY>` *and save the response to the file* `testdata.xml` *one can use the following command:*

```
curl -X POST https://tracim.ptb.de/tracim/api/order/<SWTG_ORDER_KEY>/test
     -o testdata.xml
```

(In case one gets an error about unknown CA certificates or similar, one may need to download the certificate bundle `cacert.pem` *from* `https://curl.haxx.se/docs/caextract.html` *and use additionally the option* `--cacert cacert.pem`*.)*

POST request for sending test results and obtaining the certificate: When the customer has processed the test data sets according to the standards, he has to prepare the XML content with his results as described in Section 1.5.2. The URL of the HTTPS connection for a POST request in order to send the prepared XML string is

`https://www.tracim.ptb.de/tracim/api/test/<PROCESS_KEY>` (3)

where `<PROCESS_KEY>` has to be replaced by the individual process key that was returned by the TraCIM system together with the test data. The TraCIM system will then evaluate the content and generate a test report. It states whether the test is passed, or otherwise contains a list of the values which didn't pass the test for all elements `S01-S47`. (In case of a free sample test the report is not signed and does not contain the PTB seal.) The report is encoded in XML and sent to the customer as return message to the POST request (3). See Section 1.5.3 for a description of the XML content returned by the TraCIM system. As soon as the test report is sent to the customer, the associated process key cannot be used again, irrespective of whether the test was passed or not.

Example 1.2. *To send the file* `results.xml` *with the calculated results for the process with key* `<PROCESS_KEY>` *to the TraCIM server and save the server response to the file* `validation.xml` *with the command line tool cURL use*

```
curl -d @calculated_result.xml  -H "Content-Type: application/xml"
     -X POST https://tracim.ptb.de/tracim/api/test/<PROCESS_KEY>
     -o validation.xml
```

(As in Example 1.1 one may also need to use the option `--cacert cacert.pem`*.)*

For the case of an improper process key or an malformed or incomplete XML content the TraCIM system returns an error message, see Section 1.5.4 for a description. In this case, the associated process key is still valid, so the customer can fix the problems in the XML content an send the results again.

Remark 1.3. *After receiving an order key a customer has a total of 200 days for performing the Involute Gear Evaluation test. The TraCIM system will occasionally send warning messages to the customers e-mail address stating the remaining time for the order. A final information message is sent three days before the order expires.*

1.3.2 Public sample data for client testing

Any registered customer can order sample test data free of charge with unlimited request amount for backtracking errors within the client application that could compromise a commercial test. In comparison to a test with commercial test data the certificate returned by the server is not countersigned by PTB as legally valid certificate. Sample order keys are available in the webshop (tracim.ptb.de) for registered customers.

1.4 XML message content

1.5 TraCIM XML schemata

The XML schemata which specify the format of the XLM files for the data exchange with the TraCIM system can be obtained from the following URLs:

- General TraCIM report schema
  `https://tracim.ptb.de/tracim/api/schema/tracim.xsd`

- Involute Gear Evaluation test data schema
  `https://tracim.ptb.de/tracim/api/schema/PTB_MATH_SWTG_v1_test.xsd`
- Involute Gear Evalution result data schema
  `https://tracim.ptb.de/tracim/api/schema/PTB_MATH_SWTG_v1_result.xsd`
- Gear Data Exchange Format schema
  `https://www.vdi.de/fileadmin/xml/2610/GDE_3_3.xsd`

All messages delivered by the TraCIM server have the root element `tracim` of type `tracimMessage` defined in the general TraCIM report schema. These messages may contain order or process information, test data sets according to the GDE schema, test conclusions, or error messages.

The only XML messages send by the customer are the test results according to the GDE schema with root element `swtgResultPackage`. It is recommended to make use of this schemata during client development, i.e. to automatically build Java, C++ or C# classes.

1.5.1 Test data

Test data returned by the TraCIM system are composed of the three major elements order identification, process identification and test data sets. The order element contains the order key, the date of the creation of the order and the date for the expiration of the order.

The process element contains the process key associated with the test data request. Finally, the test element contains the test data for the Involute Gear Evaluation test in GDE format, consisting of 47 test data sets with the IDs `S01-S47`

```
<?xml version="1.0" encoding="UTF-8" standalone="yes"?>
<tracim:tracim xmlns:tracim="http://tracim.ptb.de/tracim" xmlns:swtg-test="http://
    tracim.ptb.de/swtgear/test" xmlns:gde="https://www.vdi.de/fileadmin/xml/2610"
    xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance">
  <tracim:order>
    <tracim:key>[ORDER_KEY]</tracim:key>
  </tracim:order>
  <tracim:process>
    <tracim:key>[PROCESS_KEY]</tracim:key>
  </tracim:process>
  <tracim:test xsi:type="swtg-test:swtGearTestPackage">
    <swtg-test:swtGearTestData>
      <swtg-test:basicID>S01</swtg-test:basicID>
      <gde:gear_data_exchange_format version="3.3">
        [...]
      </gde:gear_data_exchange_format>
    </swtg-test:swtGearTestData>
  </tracim:test>
</tracim:tracim>
```

The process key `[PROCESS_KEY]` is created by the TraCIM system when the test data is delivered. This key has to be used by the customer when sending the test results as described in the next section. The test data contains 47 GDE test data sets `S01-S47`.

1.5.2 Test results

The calculated results of the software under test must be send to the TraCIM system as XML string compliant with the XML schema for the result data (see 1.5, result data schema). The client has to specify the following information:

- `[PROCESS_KEY]`: process key received with the test data (section 1.5.1)

- [SOFTWARE_VENDOR]: software vendor (can be different from customer name)
- [SOFTWARE_NAME]: name of software under test
- [SOFTWARE_VERSION]: version of software under test
- [SOFTWARE_REVISION]: revision of software under test (optional)
- [MPE]: MPE (in mm) for all test values (set the MPE to 0.0 to use the default values)

This information is followed by elements that contain the results of the software under test for the basic IDs S01–S47 in GDE format.

```
<?xml version="1.0" encoding="utf-8"?>
<swtg-result:swtGearResultPackage xmlns:tracim="http://tracim.ptb.de/tracim"
    xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" xmlns:gde="https://www.
    vdi.de/fileadmin/xml/2610" xmlns:swtg-result="http://tracim.ptb.de/swtgear/
    result">
  <swtg-result:processKey>[PROCESS_KEY]</swtg-result:processKey>
  <swtg-result:softwareVendor>[SOFTWARE_VENDOR]</swtg-result:softwareVendor>
  <swtg-result:softwareName>[SOFTWARE_NAME]</swtg-result:softwareName>
  <swtg-result:softwareVersion>[SOFTWARE_VERSION]</swtg-result:softwareVersion>
  <swtg-result:softwareRev>[SOFTWARE_REVISION]</swtg-result:softwareRev>
  <swtg-result:mpe>[MPE]</swtg-result:mpe>
  <swtg-result:swtGearResultData>
    <swtg-result:basicID>S01</swtg-result:basicID>
    <gde:gear_data_exchange_format xsi:schemaLocation="https://www.vdi.de/
        fileadmin/xml/2610␣https://www.vdi.de/fileadmin/xml/2610/GDE_3_3.xsd"
        version="3.3">
      [...]
    </gde:gear_data_exchange_format>
  </swtg-result:swtGearResultData>
</swtg-result:swtGearResultPackage>
```

1.5.3 Test report message

After evaluation of the test results the TraCIM system returns the validation conclusion as XML string according to the general TraCIM XML schema. It comprises the three elements:

- passed: true, if the software passed the test successfully, else false
- report: character string with short report on the test evaluation
- reportPDF: character string with the test report PDF (Base64-encoded)

In order to create the test report PDF document as PDF file, the Base64-encoded character string contained in the reportPDF tag has to be decoded and written to a new file with the proper .pdf file name extension. Below is an excerpt of an XML string with the test conlusion:

```
<?xml version="1.0" encoding="UTF-8" standalone="true"?>
<tracim:tracim xmlns:tracim="http://tracim.ptb.de/tracim"
               xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
  <tracim:validation>
    <tracim:passed>true</tracim:passed>
    <tracim:report>passed.</tracim:report>
    <tracim:reportPDF>JVBERi0xLjQKJWlsZX[...]</tracim:reportPDF>
  </tracim:validation>
</tracim:tracim>
```

1.5.4 TraCIM error message

The following XML code is sent by the server in case of errors, where `[error code]` and `[error description]` are replaced with values for the particular error.

```
<?xml version="1.0" encoding="UTF-8" standalone="true"?>
<tracim:tracim  xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
                xmlns:tracim="http://tracim.ptb.de/tracim">
  <tracim:error>
       <tracim:code>[error code]</tracim:code>
       <tracim:description>[error description]</tracim:description>
  </tracim:error>
</tracim:tracim>
```

In case an error message is received, the error description may contain useful hints what caused the error.

1.6 How to get support

For support contact: `info.tracim@ptb.de`

2 Design of the test data

2.1 Basic gear geometry

The test data sets are generated based on ten basic gears. The set of basic gears represents various gear types, including external and internal gears, left- and right-handed helical and spur gears. Table 1 lists the basic geometries of the ten gears, and the six basic geometric parameters of the gears are specified. The number of teeth includes both odd and even numbers. The pressure angle of all ten gears is 20°. The helix angle varies between 0° and 45°. Based on parameters listed in Table 1, the test data for profile, helix and pitch evaluation were generated.

2.2 Test data sets

The gear software test contains 47 test data sets with the following test data set IDs and associated evaluation types:

Table 2: Test data IDs

Test data set ID	**Evaluation type**
S01–S10	Pitch
S11–S22	Helix
S23–S47	Profile

- The format of the test data follows the GDE specifications given in VDI/VDE 2610 [1]. Dimensions for lengths are given in mm, and angles are given in decimal degrees. Some details can be found in Section 4. However, it is supposed that the customer is somewhat familiar with the GDE format. More information can be found here:

  `https://www.vdi.de/fileadmin/xml/2610/V3-3/`

- Each test data set contains 3D points of simulated measurement data, which represent center points of the sphere stylus tip in Cartesian coordinates. The data are provided with up to 12 decimal places.

Table 1: Basic geometries of gears

Gear ID	Type	Number of teeth	Normal module [mm]	Pressure angle [°]	Hand	Helix angle [°]	Face width [mm]	Profile shift coefficient	Root diameter* [mm]	Tip diameter [mm]	Root active diameter* [mm]	Tip form diameter* [mm]
G1	external	18	12	20	straight	0	100	0	203	240	208	239
G2	external	12	12	20	right	30	110	0	140	196	153.53	193
G3	external	14	6	20	right	10	60	0.5	78	96	81.5	93.5
G4	external	101	18	20	left	20	420	0.26	1898.1	1980.04	1912.111	1978
G5	external	35	2	20	left	45	19.9	-0.1	94.8	103.8	96.3	102.8
G6	internal	20	8	20	straight	0	45	-0.67	178.8	152	177.5	155.5
G7	internal	39	9	20	right	15	160	0	370	345	366.8	346.5
G8	internal	24	6.7	20	right	45	140	-0.14	242	212	239	214.4
G9	internal	93	18	20	left	10	424	-0.59	1766	1685.06	1755.677	1688.1
G10	internal	16	4.8	20	left	30	40	-1	103	84	99.5	85

* The parameter is provided as a reference and is not necessary to evaluate the gear deviations.

2.2.1 Pitch

Based on the basic geometry of the 10 gears in the table 1, 10 test data sets (from `S01` to `S10`) for pitch evaluation are simulated according to VDI/VDE 2613:2003 [2]. Each test data set contains simulated pitch measurement points for all teeth for both left and right flanks in the middle of the facewidth of the gear on the V-circle. Table 4 lists the diameters of the selected measuring probes.

Table 3: Pitch data sets

Test data ID	Gear ID	Type	Number of teeth	Normal module [mm]
`S01`	G1	external	18	12
`S02`	G2	external	12	12
`S03`	G3	external	14	6
`S04`	G4	external	101	18
`S05`	G5	external	35	2
`S06`	G6	internal	20	8
`S07`	G7	internal	39	9
`S08`	G8	internal	24	6.7
`S09`	G9	internal	93	18
`S10`	G10	internal	16	4.8

2.2.2 Helix

The evaluation algorithms can be tested for non-modified and modified helix, including slope, crowning and end reliefs at datum face and non-datum face (linear or parabolic), as well as their combinations.

Table 4: Diameters of sphere stylus tip in mm.

Gear ID	Pitch	Helix	Profile
G1	10	10	3
G2	10	10	10
G3	5	5	3
G4	10	10	10
G5	2	2	2
G6	6	6	3
G7	10	10	3
G8	6	6	3
G9	10	10	10
G10	6	6	5

Geometric specifications for helix modifications are defined in ISO 21771:2007 and ISO 1328-1:2013 [3, 4]. If helix slope modification is included, the nominal modification parameter helix slope $C_{\mathrm{H}\beta}$ is provided. If helix crowning is included, the nominal profile crowning C_{β} is provided. Helix end reliefs are continuously increasing reliefs of the flank line from defined points of the main geometry in each case in the direction of the datum faces. Here, if end relief at datum face is included, modification parameters, i.e. the length of end relief at datum face L_{CI} and the amount of end relief at datum face $C_{\beta\mathrm{I}}$, are provided. For end relief at non-datum face, length of end relief at non-datum face L_{CII} and amount of end relief at non-datum face $C_{\beta\mathrm{II}}$ are provided.

Based on the basic geometries of the ten gears in the table 1 and the helix modification parameters listed in table 5, twelve test data sets (from `S11` to `S22`) for helix evaluation were simulated. In each test data set, one tooth is randomly selected from the specific gear, and the synthetic measurement data are simulated for both left and right flanks respectively. The helix are distributed from end face to end face along the diameter of the V-cylinder. The simulated measurement points are equally spaced along the z-axis. The diameters of the selected sphere stylus tip for each gear are the same as those used for the pitch evaluation. All points are within the facewidth b in the datum axis direction, i.e. z takes values in the range $-b/2$ to $b/2$. The evaluation strategies of each test data set are given in the table 6.

2.2.3 Profile

The test includes testing of evaluation algorithms for non-modified and modified profile, including slope, crowning, root relief and tip relief, as well as their combinations, as listed in table 7. The tip and root reliefs can be linear or parabolic.

Geometric specifications for profile modifications are defined in ISO 21771:2007 and ISO 1328-1:2013 [3, 4]. If profile slope modification is included, the modification parameter $C_{\mathrm{H}\alpha}$ for the nominal profile slope is provided with the test data. If profile crowning is included, the nominal profile crowning C_{α} is provided. Tip and root reliefs are the continuously increasing reliefs of the transverse profile of the main geometry from defined points in each case (diameter, length of roll, roll angle) in the direction of the tip or root (mostly involute). Here, if tip relief is included, modification parameters, i.e. the length of tip relief $L_{\mathrm{C}\alpha}$ and the amount of tip relief $C_{\alpha\mathrm{a}}$, are provided. For root relief, length of root relief L_{Cf} and amount of root relief $C_{\alpha\mathrm{f}}$ are provided.

Based on the basic geometries of the ten gears in table 1 and the profile modification parameters in the table 7, twenty five test data sets (from `S23` to `S47`) for profile evaluation are simulated. In each test data set, one tooth is randomly selected from the specific gear, and the measurement data are simulated for both left and right flanks respectively. The profile points are simulated approximately in the middle of the facewidth, and starting below the root diameter and ending

Table 5: Combination of non-modified and modified helix

Test data ID	Gear ID	Combination of non-modified and modified helix			Nominal values of modified helix					
		End relief (Datum face)	Middle range	End relief (Non-datum face)	Slop	Crowning	End relief (Datum face)		End relief (Non-datum face)	
							Length of end relief	Amount of end relief	Length of end relief	Amount of end relief
S11	G1									
S12-S13	G2	Linear	Slope	Linear	0.02		22	-0.02	22	-0.02
S14	G3		Slope		0.01					
S15	G4		Slope + Crowning		0.035	0.04				
S16	G5		Crowning			0.03				
S17	G6									
S18	G7		Crowning			0.03				
S19	G8		Slope		0.02					
S20	G9		Slope + Crowning		0.025	0.04				
S21-S22	G10	Linear	Slope + Crowning	Linear	0.015		8	-0.02	8	-0.02

Table 6: Evaluation strategies of helix

Test data ID	**Gear ID**	**Combinations of non-modified and modified helix**			**Evaluation strategies**			
		End relief (Datum face)	**Middle range**	**End relief (Non-datum face)**	**End relief (Datum face)**		**End relief (Non-datum face)**	
					Amount of end relief	**Transition**	**Amount of end relief**	**Transition**
S11	G1							
S12	G2	Linear	Slope	Linear	4A	with_transition	4A	with_transition
S13	G2	Linear	Slope	Linear	4B	with_transition	4B	with_transition
S14	G3		Slope					
S15	G4		Slope+Crowning					
S16	G5		Crowning					
S17	G6							
S18	G7		Crowning					
S19	G8		Slope					
S20	G9		Slope + Crowning					
S21	G10	Linear	Slope	Linear	4A	with_transition	4A	with_transition
S22	G10	Linear	Slope	Linear	4B	with_transition	4B	with_transition

4A: Evaluation_VDI_2612B1_2018_4A
4B: Evaluation_VDI_2612B1_2018_4B
with_transition: evaluation of relief with transition range

near the tip diameter. The simulated measurement points are equally spaced along the length of roll. The diameters of the selected sphere stylus tip are listed in the table 4. The evaluation strategies of each test data are given in the table 8.

Table 7: Combination of non-modified and modified profile

Test data ID	Gear ID	Combination of non-modified and modified profile			Nominal values of modified profile					
		Root relief	Middle range	Tip relief	Slope	Crowning	Root relief		Tip relief	
							Length of root relief	Amount of root relief	Length of tip relief	Amount of tip relief
S23	G1									
S24-S27	G2		Crowning	Parabolic		0.02			183.67	-0.02
S28	G3		Slope	Linear	0.01				88.94	-0.01
S29	G3	Linear	Slope	Linear	0.01		83.84	-0.01	88.94	-0.01
S30	G4		Slope + Crowning		0.025	0.04				
S31-S32	G5			Parabolic					101.2	-0.015
S33	G5	Parabolic		Parabolic			98.48	-0.015	101.2	-0.015
S34	G5			Parabolic					101.2	-0.015
S35	G6									
S36	G6			Linear					158.3	-0.02
S37	G6	Linear		Linear			164.66	-0.02	158.3	-0.02
S38	G7		Crowning			0.02				
S39	G8		Crowning	Linear		0.02			218.2	-0.02
S40	G8	Linear	Crowning	Linear		0.02	233.26	-0.02	218.2	-0.02
S41-S42	G8		Crowning	Linear		0.02			218.2	-0.02
S43-S46	G9		Slope	Parabolic	0.02				1696.9	-0.08
S47	G10		Slope		0.015					

Table 8: Evaluation strategies of profile

Test data ID	Gear ID	Slope	Crowning	Regression of middle range	Root relief			Tip relief		
					Regression of root relief	Method of relief	Transition	Regression of tip relief	Method of relief	Transition
S23	G1	1A								
S24	G2	5A	6C	3B				3B	4A	with_tang_transition
S25	G2	5B	6A	3B				3B	4A	with_transition
S26	G2	5A	6C	3C				3C	4B	with_transition
S27	G2	5B	6A	3B				3B	4A	without_tang_transition
S28	G3			3A				3A	4A	with_transition
S29	G3			3A	3A	4B	with_transition	3A	4B	with_transition
S30	G4	1A	2A							
S31	G5			3A				3C	4A	with_transition
S32	G5			3A				3B	4A	without_tang_transition
S33	G5			3A	3B	4A	with_tang_transition	3B	4A	with_tang_transition
S34	G5			3A				3B	4B	with_transition
S35	G6	1A								
S36	G6			3A				3A	4B	with_transition
S37	G6			3A	3A	4A	with_transition	3A	4A	with_transition
S38	G7	1A	2A							
S39	G8	5A	6C	3C				3A	4A	with_transition
S40	G8	5B	6A	3B	3A	4A	with_transition	3A	4A	with_transition
S41	G8	5A	6C	3B				3A	4A	without_tang_transition
S42	G8	5B	6A	3C				3A	4B	with_transition
S43	G9			3A				3B	4B	with_tang_transition
S44	G9			3A				3C	4A	with_transition
S45	G9			3A				3B	4A	with_transition
S46	G9			3A				3B	4B	with_transition
S47	G10	1A								

2.3 Result parameters

The following result parameters must be calculated by the test customer:

Table 9: Result parameter list

Evaluation	Parameter	
Pitch	Pitch single deviation	
	Pitch total deviation	
	Runout	
	Dimension over balls	Maximum
		Gap number 1 of maximum
		Gap number 2 of maximum
		Mean
		Minimum
		Gap number 1 of minimum
		Gap number 2 of minimum
	Tooth thickness	Maximum
		Tooth number of maximum
		Mean
		Minimum
		Tooth number of minimum
Helix	Total helix deviation	
	Helix slope deviation	
	Helix form deviation	
	Helix crowning (if needed)	
	End relief at datum face (if needed)	Length of end relief
		Amount of end relief
		Helix form deviation of end relief
	End relief at non-datum face (if needed)	Length of end relief
		Amount of end relief
		Helix form deviation of end relief
Profile	Total profile deviation	
	Profile slope deviation	
	Profile form deviation	
	Profile crowning (if needed)	
	Tip relief (if needed)	Length of tip relief
		Amount of tip relief
		Profile form deviation of tip relief
	Root relief (if needed)	Length of root relief
		Amount of root relief
		Profile form deviation of root relief

- For pitch evaluation, pitch single deviation and pitch total deviation must be calculated for both left and right flanks. For helix and profile evaluation, all the parameters must be calculated for both left and right flanks.
- If helix crowning modification is included, helix crowning must be calculated. If end relief at datum face and/or non-datum face are included, length of end relief, amount of end relief and form deviation of end relief must be calculated.

- If profile crowning modification is included, profile crowning must be calculated. If tip relief is included, length of tip relief, amount of tip relief and form deviation of tip relief must be calculated. If root relief is included, length of root relief, amount of root relief and form deviation of root relief must be calculated.
- The values refer to the unit mm (millimeter). Exceptions are the gap numbers for min/max values of dimension over balls and the tooth numbers for min/max values of tooth thickness.
- Section 4.3 shows the test result data structure.

3 Evaluation

The evaluation of the test data has to be done according to the the guidelines VDI/VDE 2612-1:2018 [5] and VDI/VDE 2613:2003 [2]. In many cases, different evaluation strategies are possible. This is indicated in the GDE files delivered to the customer by labels of the type

`Evaluation_VDI_2612B1_2018_*`

which are defined in VDI/VDE 2612-1:2018.

All simulated measurement points provided in the test data sets are 3D Cartesian coordinates of the center points of the stylus tip. From these coordinates the deviations to the nominal involute geometry must be calculated, where the deviations are measured in a transverse plane and tangentially to the base cylinder. Deviations to the required measuring plane or measuring cylinder must be corrected. For details see e.g. [6].

In case of profile evaluation, the deviations are calculated with respect to a reference involute. This is explained in VDI/VDE 2612-1:2018 [5]. If the reference involute is calculated by other means, e.g. by a recursive method, the results might slightly differ and the test could therefore fail.

For details on the evaluation of the data, please refer to the mentioned standard. Some information is also provided below, expecially in cases where these guidelines are not entirely clear.

3.1 Profile

The evaluation procedures and evaluation strategies for profile are described in VDI/VDE 2612-1:2018 [5]. For modified profile, additional supplements are described in the subsequent sections for special cases.

3.1.1 Total profile deviation

The total profile deviation F_α is determined by the nominal profile geometry with or without specific modifications (profile crowning and/or profile slope modification). Geometric specifications for profile modifications are defined in ISO 21771 [3]. In the following it is explained how the nominal profiles in case of profile crowning and profile slope modification are defined.

Profile crowning modification is defined with respect to the center of the length of roll of the usable flank and has a parabolic form passing through the points defined by $C_{\alpha,\mathrm{nom}}$. For this software test, the usable flank is always defined between the points E and a in figure 1. These points are defined in VDI/VDE 2612-1:2018 [5] as the end point of meshing (E) and the tip diameter (a). However, the relevant diameters for the evaluation are all given in the evaluation section of the GDE files containing the test data: E corresponds to `slope_profile_reference_start` and a corresponds to `slope_profile_reference_end`. (This means that for internal gears `slope_profile_reference_end` is smaller than `slope_profile_reference_start`).

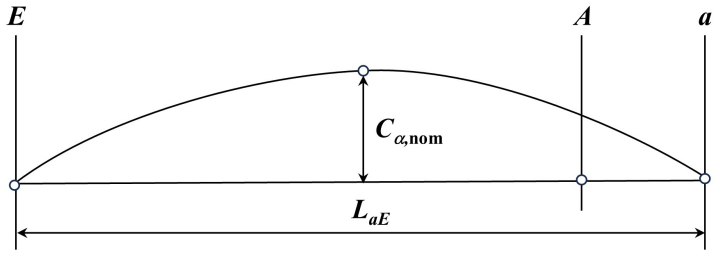

Figure 1: Nominal profile crowning without slope modification: The nominal profile is given by a parabola with horizontal chord at the x-positions E and a. The maximum deviation of the parabola from the chord is $C_{\alpha,\mathrm{nom}}$ in non-material direction.

Profile slope modification is a desired linear slope deviation from the involute over the whole width of the face [3]. As shown in figure 2, the amount $C_{\mathrm{H}\alpha,\mathrm{nom}}$ of the profile slope modification is specified over the whole width of the face between points E and a.

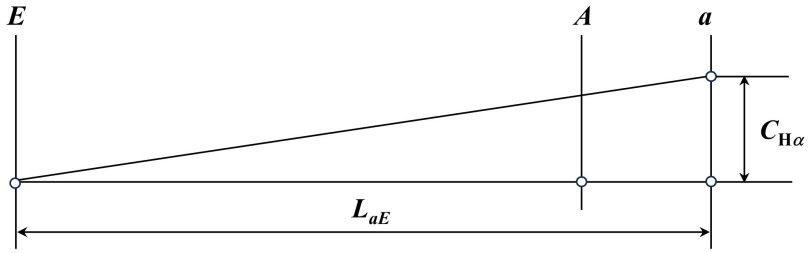

Figure 2: Profile slope modification: The nominal profile is given by a linear function with gradient $C_{\mathrm{H}\alpha,\mathrm{nom}}/L_{aE}$. The gradient is positive, if in direction of increasing length of roll the deviations from the involute to the non-material side are also increasing. (Note that for internal gears the length of roll is increasing from a to E.)

Finally, the combination of profile slope modification and profile crowning is a superposition of both modifications as shown in figure 3.

For profiles without relief, F_α is obtained by the minimal possible distance of two nominal profiles shifted in y-direction against each other, such that all deviations points on the material side inside the regression range L_α and all deviations points on the non-material side inside the range L_{aE} are between the two shifted nominal profiles. If the profile has tip and/or root reliefs, points on the material side are considered in the middle range $L_{\alpha\mathrm{m}}$, while on the non-material side additionally the points indicating surplus material in the transition ranges must be considered. Details can be found in VDI/VDE 2612-1:2018 [5].

3.1.2 Profile slope deviation

The profile slope deviation $f_{\mathrm{H}\alpha}$ is determined by the regression element and the reference length. These information is provided by the evaluation parameters as explained in Section 4.2.

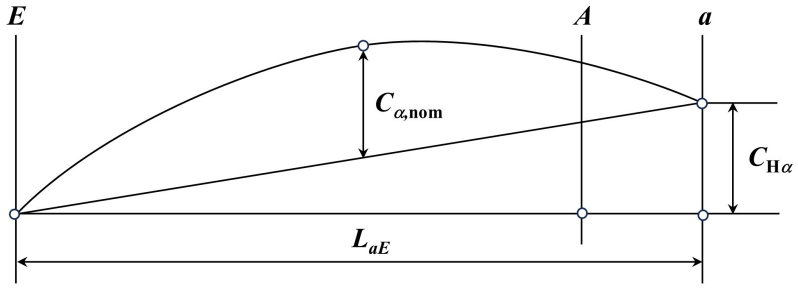

Figure 3: Combination of profile slope modification and profile crowning: The chord to the nominal parabola at the x-positions E and a has gradient $C_{\mathrm{H}\alpha,\mathrm{nom}}/L_{aE}$ and the maximum deviation of the parabola from the chord is $C_{\alpha,\mathrm{nom}}$ in non-material direction.

3.1.3 Profile form deviation

The profile form deviation $f_{\mathrm{f}\alpha}$ is calculated from the distances (residuals) of the measured deviations to the regression line, i.e. the least squares line or parabola. The form deviation is given by the maximum absolute value of all residuals inside a specified range. Here, a distinction must be made between material and non-material side. For profiles without reliefs, the residuals to points which are on the material side of the regression line (i.e. negative residuals) are considered only in the regression range L_α, while residuals to points on the non-material side (i.e. positive residuals) are considered in the complete range L_{aE}. If the profile includes tip and/or root reliefs, the residuals to the material side (negative residuals) are considered in the middle range $L_{\alpha\mathrm{m}}$, while the residuals to the non-material side (positive residuals) must be considered also in the neighboring transition range(s). This is explained in detail in VDI/VDE 2612-1:2018 [5].

3.1.4 Profile crowning

The profile crowning C_α is the largest distance between the regression parabola and a certain chord to this parabola. The chord to the regression parabola is determined by its reference range, such as L_{aE}, L_{AE} or $L_{\alpha\mathrm{m}}$. Start and end of this reference range is given in the GDE files with the test data by `crowning_profile_reference_start` and `crowning_profile_reference_end` as explained in Section 4.2. More details can be found in the VDI/VDE 2612-1:2018 [5].

3.1.5 Tip and root reliefs

If the profile has tip and/or root reliefs, the deviations are evaluated in separate ranges and with varied regression elements (such as line, parabola, and chord of parabola). For tip relief, three additional parameters must be calculated: length of tip relief $L_{\mathrm{C}\alpha\mathrm{a}}$, amount of tip relief $C_{\alpha\mathrm{a}}$, and profile form deviation of tip relief $f_{\mathrm{f}\alpha\mathrm{a}}$. For root relief, length of root relief $L_{\mathrm{C}\alpha\mathrm{f}}$, amount of root relief $C_{\alpha\mathrm{f}}$, and profile form deviation of root relief $f_{\mathrm{f}\alpha\mathrm{f}}$ must be calculated.

For evaluations with transition range between middle range and relief, the length of the relief $L_{\mathrm{C}\alpha\mathrm{a}}$ is evaluated by the distance in direction of x-axis between the intersection points P_1 and P_2 (or P_3, which has the same x-value). The amount of the relief $C_{\alpha\mathrm{a}}$ is evaluated by y-distance between the points P_1 and P_3, or P_2 and P_3, depending on the evaluation strategy.

For evaluations with transition range, length and height of the reliefs are determined by the points P_1, P_2 and P_3. These points are defined as follows:

- Point P_1 (boundary point between middle range and relief range) results as intersection of the line of the middle range with the line of the relief range.
- Point P_2 results as intersection of the line of the middle range with the boundary of the evaluation range.
- Point P_3 results as intersection of the line of the relief range with the boundary of the evaluation range.

Figure 4 shows these intersection points P_1, P_2, and P_3 for both tip and root relief in case of linear regression elements for all three ranges.

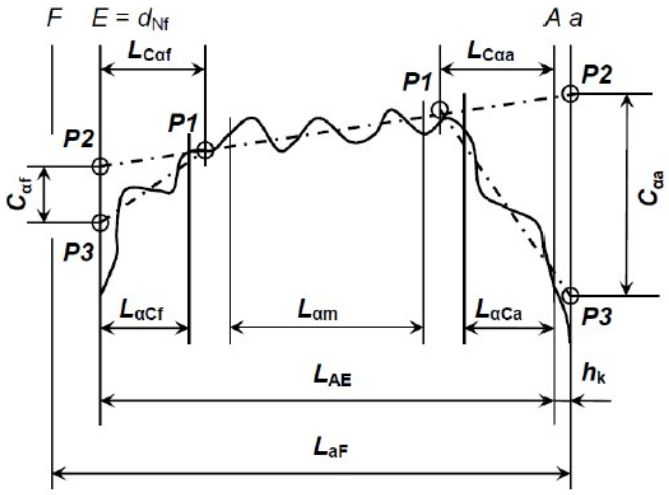

Figure 4: Definition of $C_{\alpha a}$, $L_{c\alpha a}$, and $C_{\alpha f}$, $L_{c\alpha f}$ at the tip and root relief using the points P_1, P_2 and P_3 determined by regression lines [5].

The profile form deviations of tip and root relief are determined individually for each relief range. For the non-material side the evaluation of the residuals is extended from the regression range to the neighboring transition range, while deviations showing a lack of material are only considered in the regression range. To determine the form deviation of the tip relief $f_{f\alpha a}$, the evaluation is extended to a (d_a) for the non-material side. Details can be found in the VDI/VDE 2612-1:2018 [5].

Below, some special cases are described based on the example of a tip relief. These can be applied analogously to root reliefs and helix reliefs.

The points P_2 or P_3 are defined as intersection points of the extended regression lines with the boundary of the evaluation range, resulting in only one single intersection point.

The point P_1 is defined as intersection point of the lines (regression lines or chords) of the middle range and the relief range. If both lines are straight lines, only one intersection point is obtained. (The case of parallel lines with no intersection point can be ruled out as extremely unlikely in the case of real measurement data.) However, if the regression element of the middle range and/or the relief range is a parabola, it is possible to have either no intersection points or two. (The case of exactly one intersection point can be ruled out as extremely unlikely in the case of real measurement data.)

If there are two intersection points as shown in figure 5, there is no rule which intersection point must be selected as P_1. To handle this unclear case in the software test, the intersection point in the transition range must be selected as P_1. The test data are designed such that, if two

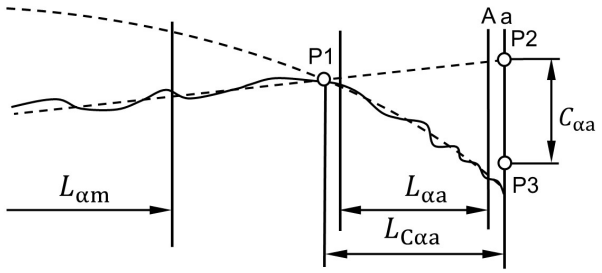

Figure 5: The picture shows the case of two intersection points of the regression line of the middle range with the regression parabola of the relief range. One intersection point in in the transition range and defines the point P_1, while the second intersection point is not visible in the picture.

intersection points exist, only one of them is in the transition range and defines the point P_1 while the other one is outside the transition range.

If there is no intersection point as shown in figure 6, the point P_1 is undefined. In such a case, the length of tip relief $L_{C\alpha a}$ cannot be evaluated. In the GDE file with the test results calculated by the customer this must be represented by "NaN" as result for $L_{C\alpha a}$. If the field is empty of contains a number, the test will fail.

The calculation of the amount of tip relief $C_{\alpha a}$ is dependent on the selected evaluation strategy. It is either given as the distance in the direction of y-axis either between the points P_2 and P_3 or between the points P_1 and P_3, labeled as `Evaluation_VDI_2612B1_2018_4A` and `Evaluation_VDI_2612B1_2018_4B`, respectively. Details are given in VDI/VDE 2612-1:2018 [5]. If the strategy `Evaluation_VDI_2612B1_2018_4A` is used, there is always a numerical value of $C_{\alpha a}$. However, if `Evaluation_VDI_2612B1_2018_4B` is used, there is only a result for $C_{\alpha a}$ if P_1 is defined. If there is no intersection point, no result for $C_{\alpha a}$ can be determined which has to be represented as "NaN" in the GDE file. An example extracted from a GDE file with evaluation parameter and test results can be found below.

```
<gde:evaluation>
  <gde:evaluation_parameters>
    <gde:profile_evaluation flank="both" position="0.0">
      [...]
      <gde:tip_relief_evaluation
        type_regression="Evaluation_VDI_2612B1_2018_3B"
        type_regression_middle_zone="Evaluation_VDI_2612B1_2018_3A"
        method_relief="Evaluation_VDI_2612B1_2018_4B">
        [...]
      </gde:tip_relief_evaluation>
    </gde:profile_evaluation>
  </gde:evaluation_parameters>
  <gde:evaluation_results>
    <gde:profile_results tooth="[...]" flank="[...]" position="0.0">
      [...]
      <gde:tip_relief_actual>
        <gde:relief_length_actual>NaN</gde:relief_length_actual>
        <gde:relief_depth_actual>NaN</gde:relief_depth_actual>
        <gde:relief_form_actual>[...]</gde:relief_form_actual>
      </gde:tip_relief_actual>
    </gde:profile_results>
  </gde:evaluation_results>
</gde:evaluation>
```

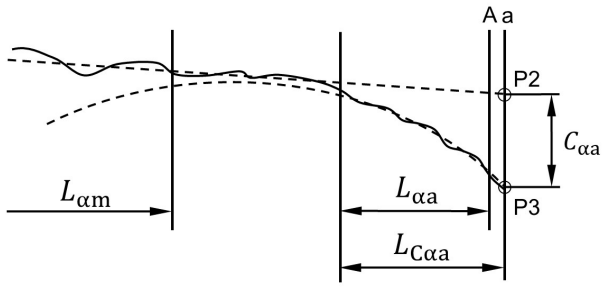

Figure 6: No intersection point P_1 between the regression line of the middle range and the regression parabola of the relief range.

Tip reliefs can also be determined by evaluation without transition range and with a nominally specified tip relief length. In such a case the nominal value must be given as result for the length of tip relief. The nominal length is obtained as the distance in x-direction between the given `relief_datum_diameter` specified in the geometry section of the GDE file and the border of the evaluation range (tip diameter).

If the evaluation strategy of tip relief is without transition range, the tip relief can be evaluated with or without tangential transition. If the tip relief is evaluated with tangential transition, the intersection point P_1 is the point of transition between the regression elements for middle range and tip relief. Both length and amount of tip relief can be calculated. If the tip relief is evaluated without tangential transition range, it is not clearly defined in VDI/VDE 2612-1:2018 [5] how to evaluate the amount of tip relief in case of evaluation strategy `Evaluation_VDI_2612B1_2018_4B`. To avoid these ambiguities, the test data contains only test cases in which evaluation without tangent transition (and no transition range) is combined with the strategy `Evaluation_VDI_2612B1_2018_4A`. In such a case, the amount of tip relief is determined in the direction of the y-axis between points P_2 and P_3.

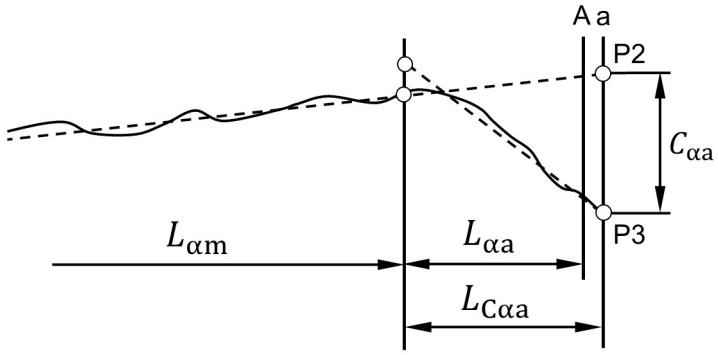

Figure 7: Evaluation of relief through regression without tangential transition.

3.2 Helix

The evaluation procedures and evaluation strategies for helix deviations are described in VDI/VDE 2612-1:2018 [5]. The specifics mentioned in Section 3.1 for evaluation profile deviations apply analogously to helix deviations.

3.3 Pitch

The measurands for pitch deviations, i.e. single pitch deviation and total pitch deviation, are determined following VDI/VDE 2613:2003 [2]. Pitch deviations are evaluated on both left and right flanks in a transverse plane of the gear, i.e. $z = 0$. According to ISO 1328-1:2013, the nominal pitch is defined on the measuring diameter by the arc length. The z-axis position and the diameter of reference circle are provided in the test data.

Runout, dimension over balls and tooth thickness are determined using the pitch measurement points. The evaluation methods follow VDI/VDE 2613:2003 [2]. Additionally, the corresponding z-axis position and the diameter of reference circle are provided in the test data. For dimension over balls, the maximum, mean and minimum values together with the corresponding two gap numbers used to determine the maximum or minimum dimension over balls have to be evaluated. Similarly, for tooth thickness, the maximum, mean and minimum values along with the corresponding tooth number used to determine the maximum or minimum tooth thickness must be evaluated.

4 Data structure of the test data

The individual test data sets inside the xml file provided by the TraCIM server follow the Gear Data Exchange Format (GDE format) specified in VDI/VDE 2610 [1] in version 3.3.

Each GDE file includes the two sections `gde_creating_systems` and `gear_data`. The section `gde_creating_systems` records the version of test data, while the section `gear_data` includes the gear-specific data like nominal geometry, evaluation parameters and simulated measurement points. The following items in `gear_data` are used in the test data sets:

- `gear_id`: The ID of one of the ten basic gears (G1–G10)
- `section_identification`: Test data ID (S01–S47) and evaluation type (pitch, helix or profile)
- `section_geometry`: Nominal geometry of the gear
  - `basic_data`: Basic geometry of the gear
  - `modification` (if needed): Modification geometry of tooth flank in profile or helix direction
- `section_inspection`:
  - `measurement_results`: Coordinates of the simulated measurement points
  - `evaluation`:
    - `evaluation_parameters`: Specified parameters for evaluation
  - `output_parameters`: Parameters required to be calculated

In `basic_data`, the basic geometry of one of the gears listed in Table 1 is provided. Below is an example of the data structure for the `basic_data`, extracted from the test data for gear G1.

```
<gde:basic_data>
  <gde:kind_of_gear>software_gauge</gde:kind_of_gear>
  <gde:external_internal>external</gde:external_internal>
  <gde:number_of_teeth>18.0</gde:number_of_teeth>
  <gde:normal_module>12.0</gde:normal_module>
  <gde:pressure_angle flank="both">20.0</gde:pressure_angle>
  <gde:helix_angle direction="straight" flank="both">0.0</gde:helix_angle>
  <gde:facewidth>100.0</gde:facewidth>
```

```
  <gde:profile_shift_coefficient>0.0</gde:profile_shift_coefficient>
  <gde:tip_diameter>240.0</gde:tip_diameter>
  <gde:tip_form_diameter>239.0</gde:tip_form_diameter>
  <gde:root_diameter>203.0</gde:root_diameter>
  <gde:root_active_diameter>208.0</gde:root_active_diameter>
</gde:basic_data>
```

Furthermore, the nominal values for modifications listed in Tables 5 and 7 are given in the sections `profile_modification` and `helix_modification`, respectively, under the section `modification`. The nominal values for profile modification listed in table 7 are given in the following elements:

- `profile_slope` (if needed): Nominal slope modification with respect to the complete evaluation range from E to a
- `profile_crowning` (if needed): Nominal crowning with respect to the complete evaluation range from E to a
- `tip_relief` (if needed)
  - `relief_datum_diameter`: Nominal start of tip relief
  - `relief_depth`: Nominal depth of tip relief
- `root_relief` (if needed):
  - `relief_datum_diameter`: Nominal start of root relief
  - `relief_depth`: Nominal depth of root relief

The nominal values for helix modification listed in table 5 are given in the following elements:

- `helix_slope` (if needed): Nominal slope modification with respect to the complete tooth width
- `helix_crowning` (if needed): Nominal crowning with respect to the complete tooth width
- `end_relief_datum_face` (if needed):
  - `relief_length`: Nominal length of relief
  - `relief_depth`: Nominal depth of relief
- `end_relief_non_datum_face` (if needed):
  - `relief_length`: Nominal length of relief
  - `relief_depth`: Nominal depth of relief

The section `section_inspection` of the test data consists of three parts: `measurement_results`, `evaluation`, and `output_parameters`. Each test data corresponds to a specific type of measurement, i.e pitch, helix or profile measurement. The contents of each part vary depending on the type of measurement, which are described in sections 4.1, 4.2 and 4.3.

4.1 Simulated measurement data

The simulated measurement points are provided in `measurement_points` under `measurement_results`. The coordinates of each measurement points are stored in `measurement_pointset`. The type (profile, helix, or pitch) of the measurement is identified by the attribute `type` of the `measurement_pointset`.

Profile points are given for both left and right flanks of one tooth. Beside the coordinates of the measurement points, the additional attributes `tooth` for the tooth number, `position` for the (nominal) z-position of the points and `measuring_balldia` for the stylus sphere diameter are given.

The data structure for the helix points is analogous to that for profile points. Instead of `position` the attribute `diameter` is added to record the diameter of the V-cylinder on which the helix points were generated.

For pitch, one point on every tooth on both left and right flanks are provided. Therefore, there are $2 \cdot$ `number_of_teeth` knots `measurement_pointset` under `measurement_points`, identified by the attributes `tooth` and `flank`. Additionally, the diameter of the V-cylinder and the z-position where pitch points were generated are specified.

Below are the data structure for the three different types of measurement, as well as their corresponding attributes.

```
<gde:measurement_pointset type="profile" tooth="[...]" flank="[...]"
    position="0.0" measuring_balldia="[...]">

<gde:measurement_pointset type="helix" tooth="[...]" flank="[...]"
    diameter="[...]" measuring_balldia="[...]">

<gde:measurement_pointset type="pitch" tooth="[...]" flank="[...]"
    position="0.0" diameter="[...]" measuring_balldia="[...]">
```

4.2 Evaluation parameters

4.2.1 Profile

The evaluation parameters for profile are identical for both left and right flanks and are given in the section `profile_evaluation` under the section `evaluation_parameters`. The regression range L_α for linear or parabolic regression is specified by

- `profile_evaluation_start`: start of regression range, and
- `profile_evaluation_end`: end of regression range.

The guideline VDI/VDE 2612-1 [5] documents various evaluation strategies for both non-modified and modified profiles, most of which are categorized with labels. These labels start with the term "`Evaluation_VDI_2612B1_2018`", followed by a number and a letter. Further specifications can be found in [5]. If a measurand can be evaluated using several methods or a combination of methods, the details regarding the evaluation range are specified in the GDE files in order to clearly distinguish among them.

For the evaluation of profile slope deviation, the reference start and end diameters of the profile are specified in the following elements under the section `slope_evaluation_profile`, which is the subsection of `profile_evaluation`:

- `slope_profile_reference_start`: reference start diameter for determination of profile slope deviation;

- `slope_profile_reference_end`: reference end diameter for determination of profile slope deviation.

Additionally, if the evaluation strategy for profile slope deviation is required, it is provided as attribute `method_without_relief_profile` or `method_relief_profile` of the element `slope_evaluation_profile`. The following satrtegies are defined in VDI/VDE 2612-1 [5].

- `method_without_relief_profile` (if needed): evaluation method for profile without relief
  - `Evaluation_VDI_2612B1_2018_1A`
  - `Evaluation_VDI_2612B1_2018_1B`
- `method_relief_profile` (if needed): evaluation method for profile with relief
  - `Evaluation_VDI_2612B1_2018_5A`
  - `Evaluation_VDI_2612B1_2018_5B`

The data structure for the evaluation parameters for profile crowning is analogous to those for profile slope deviation. The reference diameters used to determine the profile crowning, i.e. the two diameters where the chord to the regression parabola is taken, are specified in the following elements under the section `crowning_evaluation_profile`:

- `crowning_profile_reference_start`: reference start for determination of profile crowning;
- `crowning_profile_reference_end`: reference end for determination of profile crowning.

(It should be noted that these values are not used to define the nominal crowning as needed to calculate the total deviation.)

The corresponding evaluation strategy is provided as an attribute of `crowning_evaluation_profile` using the labels from VDI/VDE 2612-1 [5].

- `method_without_relief_profile` (if needed): evaluation method for profile without relief
  - `Evaluation_VDI_2612B1_2018_2A`
  - `Evaluation_VDI_2612B1_2018_2B`
- `method_relief_profile` (if needed): evaluation method for profile with relief
  - `Evaluation_VDI_2612B1_2018_6A`
  - `Evaluation_VDI_2612B1_2018_6B`
  - `Evaluation_VDI_2612B1_2018_6C`

If the profile has a tip relief, the following evaluation parameters are provided under the section `tip_relief_evaluation`:

- `relief_evaluation_start`: start of relief regression range;
- `relief_evaluation_end`: end of relief regression range.

The selected evaluation strategies are given as attributes using the labels from VDI/VDE 2612-1 [5]. The type of the regression (i.e. linear, parabolic, or chord to parabola) lines for the tip relief range and the middle range are given in the `type_regression` and `type_regression_middle_zone`, respectively. The attribute `method_relief` specifies the method used for determining the amount of the tip relief. If the tip relief is evaluated without transition range, the attribute `form_relief` specifies if there must be a tangent transition between the regression lines of the two ranges or not.

- `type_regression`: type for regression of tip relief range
- `type_regression_middle_zone`: type for regression of middle range
- `method_relief`: evaluation method for the amount of the tip relief
  - `Evaluation_VDI_2612B1_2018_4A`
  - `Evaluation_VDI_2612B1_2018_4B`
  - `Evaluation_VDI_2612B1_2018_4C`
  - `Evaluation_VDI_2612B1_2018_4D`
- `form_relief` (if needed): evaluation of tip relief without transition range
  - `without_tang_transition`
  - `with_tang_transition`

The regression lines used in the `type_regression` and `type_regression_middle_zone` can be

- `Evaluation_VDI_2612B1_2018_3A`: (extended) regression line;
- `Evaluation_VDI_2612B1_2018_3B`: (extended) regression parabola;
- `Evaluation_VDI_2612B1_2018_3C`: (extended) chord of the regression parabola.

If profile has a root relief, the evaluation parameters and evaluation strategies are provided in the `root_relief_evaluation` under the `profile_evaluation`. The data structure for root relief is analogous to that for tip relief. The only difference from tip relief is that the attribute `method_relief` excludes `Evaluation_VDI_2612B1_2018_4C` and `Evaluation_VDI_2612B1_2018_4D`.

4.2.2 Helix

The evaluation parameters are provided in the section `helix_evaluation` under the section `evaluation_parameters`, whose data structure is analogous to that for profile. The regression range L_β is specified in the following elements under the `helix_evaluation`:

- `helix_evaluation_start`: start of regression range;
- `helix_evaluation_end`: end of regression range.

For evaluation of helix slope deviation, the reference start and end of the helix are specified in the following elements under the `slope_evaluation_helix`, which is the subsection of `helix_evaluation`:

- `slope_helix_reference_start`: reference start for determination of helix slope deviation;
- `slope_helix_reference_end`: reference end for determination of helix slope deviation.

For evaluation of helix crowning, the reference start and end of the helix are specified in the following elements under the `crowning_evaluation_helix`, which is the subsection of `helix_evaluation`:

- `crowning_helix_reference_start`: reference start for determination of helix crowning;
- `crowning_helix_reference_end`: reference end for determination of helix crowning.

The corresponding evaluation strategy is only provided when the helix has a relief as an attribute of `crowning_evaluation_helix`,i.e.

- `method_relief_helix` (if needed): evaluation method for helix with relief
  - `Evaluation_VDI_2612B1_2018_7A`
  - `Evaluation_VDI_2612B1_2018_7B`

If helix has an end relief at either datum face or non-datum face, the evaluation parameters are provided in the following elements under the `end_relief_datum_face_evaluation` and/or `end_relief_non_datum_face_evaluation`:

- `relief_evaluation_start`: start of relief regression range;
- `relief_evaluation_end`: end of relief regression range.

Furthermore, the selected evaluation strategies are presented as attributes using the labels from VDI/VDE 2612-1 [5], and the details are consistent with those used for root relief.

4.2.3 Pitch

The evaluation parameters for pitch are provided in the `pitch_evaluation` under the `evaluation_parameters`. In this section, the element `reference_diameter` is provided, as well as attributes `flank` and `position`.

Additionally, the evaluation parameters for runout, tooth thickness and dimension over balls are also provided in the `runout_evaluation`, `tooth_thickness_evaluation`, and `size_over_balls_evaluation`, respectively. Corresponding attribute such as `position` is also specified.

Below is the data structure of evaluation parameters for pitch measurement.

```
<gde:evaluation_parameters>
  <gde:pitch_evaluation flank="both" position="0.0">
    <gde:reference_diameter>[...]</gde:reference_diameter>
  </gde:pitch_evaluation>
  <gde:runout_evaluation position="0.0">
    <gde:evaluation_balldia>[...]</gde:evaluation_balldia>
  </gde:runout_evaluation>
  <gde:tooth_thickness_evaluation position="0.0">
    <gde:reference_diameter>[...]</gde:reference_diameter>
  </gde:tooth_thickness_evaluation>
  <gde:size_over_balls_evaluation position="0.0"/>
<gde:evaluation_parameters>
```

4.3 Evaluation results

The measurands required to be calculated are listed in the section `output_paramters` under the `section_inspection`. The customer has to create GDE files with the corresponding evaluation results stored in the section `evaluation_results`. In the end, a single xml file containing the 47 GDE files together with some adminstry data as explained in Section 1.5.2 must be submitted to the TraCIM server.

4.3.1 Profile

The profile evaluation results for both left and right flanks must be stored in the section `profile_results` under `evaluation_results`, identified by the attribute `flank`. Additionally, the evaluated tooth number and z-position must also be provided in the attributes of `profile_results`.

```
<gde:evaluation_results>
  <gde:profile_results tooth="[...]" flank="left" position="0.0">
    [...]
  </gde:profile_results>
  <gde:profile_results tooth="[...]" flank="right" position="0.0">
    [...]
  </gde:profile_results>
</gde:evaluation_results>
```

The evaluation results of each flank must be provided in the following elements:

- `total_actual`: total profile deviation
- `slope_to_design_actual`: profile slope deviation
- `form_actual`: profile form deviation
- `crowning_actual` (if needed): profile crowning
- `tip_relief_actual` (if needed)
  - `relief_length_actual`: length of tip relief
  - `relief_depth_actual`: amount of tip relief
  - `relief_form_actual`: profile form deviation of tip relief
- `root_relief_actual` (if needed)
  - `relief_length_actual`: length of root relief
  - `relief_depth_actual`: amount of root relief
  - `relief_form_actual`: profile form deviation of root relief

4.3.2 Helix

The helix evaluation results for both left and right flanks must be stored in the section `helix_results` under `evaluation_results`, identified by the attribute `flank`. Additionally, the evaluated tooth number and diameter must also be provided in the attributes of `helix_results`.

```
<gde:evaluation_results>
  <gde:helix_results tooth="[...]" flank="left" diameter="[...]">
    [...]
  </gde:helix_results>
  <gde:helix_results tooth="[...]" flank="right" diameter="[...]">
    [...]
  </gde:helix_results>
</gde:evaluation_results>
```

The evaluation results of each flank are given in the following elements:

- `total_actual`: total helix deviation
- `slope_to_design_actual`: helix slope deviation

- `form_actual`: helix form deviation
- `crowning_actual` (if needed): helix crowning
- `end_relief_datum_face_actual` (if needed)
  - `relief_length_actual`: length of end relief at datum face
  - `relief_depth_actual`: amount of end relief at datum face
  - `relief_form_actual`: helix form deviation of end relief at datum face
- `end_relief_non_datum_face_actual` (if needed)
  - `relief_length_actual`: length of end relief at non-datum face
  - `relief_depth_actual`: amount of end relief at non-datum face
  - `relief_form_actual`: helix form deviation of end relief at non-datum face

4.3.3 Pitch

The pitch results for both left and right flanks must be stored in the section `pitch_results` under `evaluation_results`, identified by the attribute `flank`. Additionally, the position should be specified as an attribute of `pitch_results`. The evaluation results for runout must be stored inside `runout_results`, with the position provided as an attribute `position`. Furthermore, the evaluation results for tooth thickness and dimension over balls must be provided inside `size_results`.

```
<gde:evaluation_results>
  <gde:size_results position="0.0">
    <gde:tooth_thickness_actual>[...]</gde:tooth_thickness_actual>
    <gde:size_over_balls_actual ball_diameter="[...]">
      [...]
    </gde:size_over_balls_actual>
  </gde:size_results>
  <gde:pitch_results flank="left" position="0.0">[...]</gde:pitch_results>
  <gde:pitch_results flank="right" position="0.0">[...]</gde:pitch_results>
  <gde:runout_results position="0.0">[...]</gde:runout_results>
</gde:evaluation_results>
```

The detail evaluation results of pitch measurement are given in the following elements:

- `pitch_results`
  - `pitch_total_actual`
  - `pitch_single_actual`
- `runout_results`
  - `runout_actual`
- `tooth_thickness_actual`
  - `tooth_thickness_mean`
  - `tooth_thickness_max`
  - `tooth_number_max`
  - `tooth_thickness_min`
  - `tooth_number_min`

- size_over_balls_actual
  - size_over_balls_mean
  - size_over_balls_max
  - gap_number_1_max
  - gap_number_2_max
  - size_over_balls_min
  - gap_number_1_min
  - gap_number_2_min

References

[1] VDI/VDE 2610:2021-03. Exchange format for gear data - Gear Data Exchange Format (GDE Format) - Definition. 2007.

[2] VDI/VDE 2613:2003-12. Pitch and runout testing on gearings - Cylindrical gears, whormwheels, bevel gears. 2003.

[3] ISO 21771:2007-09. Gears - Cylindrical involute gears and gear pairs - Concepts and geometry. 2007.

[4] ISO 1328-1:2013-09. Cylindrical gears - iso system of flank tolerance classification - part 1: Definitions and allowable values of deviations relevant to flanks of gear teeth. 2013.

[5] VDI/VDE 2612 Part 1:2018-11. Measurement and testing of gears - evaluation of profile and helix measurements on cylindrical gears with involute profile. 2018.

[6] Frank Härtig and Martin Stein. 3d Involute Gear Evaluation – Part I: Workpiece Coordinates. *Measurement*, 134:569–573, 2019.