

ALTAIR

Altair[®] FluxMotor[®] 2022.1

Synchronous Machines Permanent Magnets – Inner Rotor

Motor Factory – Test – Mechanics

General user information

Contents

1	<i>Mechanics – NVH – Working point – I - Ψ - N</i>	4
1.1	Overview	4
1.1.1	Positioning and objective	4
1.1.2	User inputs	4
1.1.3	Main outputs	5
1.2	Settings	5
1.3	Inputs	6
1.3.1	Introduction	6
1.3.2	Standard inputs	6
1.3.2.1	Line current / Current density	6
1.3.2.2	Control angle	6
1.3.2.3	Speed	6
1.3.3	Advanced input	7
1.3.3.1	Maximum engine order / No. Points per electrical period	7
1.3.3.2	Maximum mode / spatial order	7
1.3.3.3	Number of computations per tooth pitch	7
1.3.3.4	Displayed pressure range (dB)	7
1.3.3.5	Computation of forces on teeth	8
1.3.3.6	Mesh order	8
1.3.3.7	Airgap mesh coefficient	8
1.4	Main principles of computation	9
1.4.1	Introduction	9
1.4.2	Flow chart	10
1.5	Test results	11
1.5.1	Introduction	11
1.5.2	List of the main NVH results	11
1.6	Limitation of computations - Advice for use	13
2	<i>Mechanics – NVH – spectrogram – I - Ψ - N</i>	14
2.1	Overview	14
2.1.1	Positioning and objective	14
2.1.2	User inputs	14
2.1.3	Main outputs	15
2.2	Settings	15
2.3	Inputs	16
2.3.1	Introduction	16
2.3.2	Standard inputs	16
2.3.2.1	I- Ψ -N description	16
2.3.3	Advanced input	18
2.3.3.1	Maximum engine order / No. Points per electrical period	18
2.3.3.2	Maximum mode / spatial order	18
2.3.3.3	Number of computations per tooth pitch	18
2.3.3.4	Number of points for speed interpolation	18
2.3.3.5	Mesh order	18
2.3.3.6	Airgap mesh coefficient	19
2.4	Main principles of computation	20
2.4.1	Introduction	20

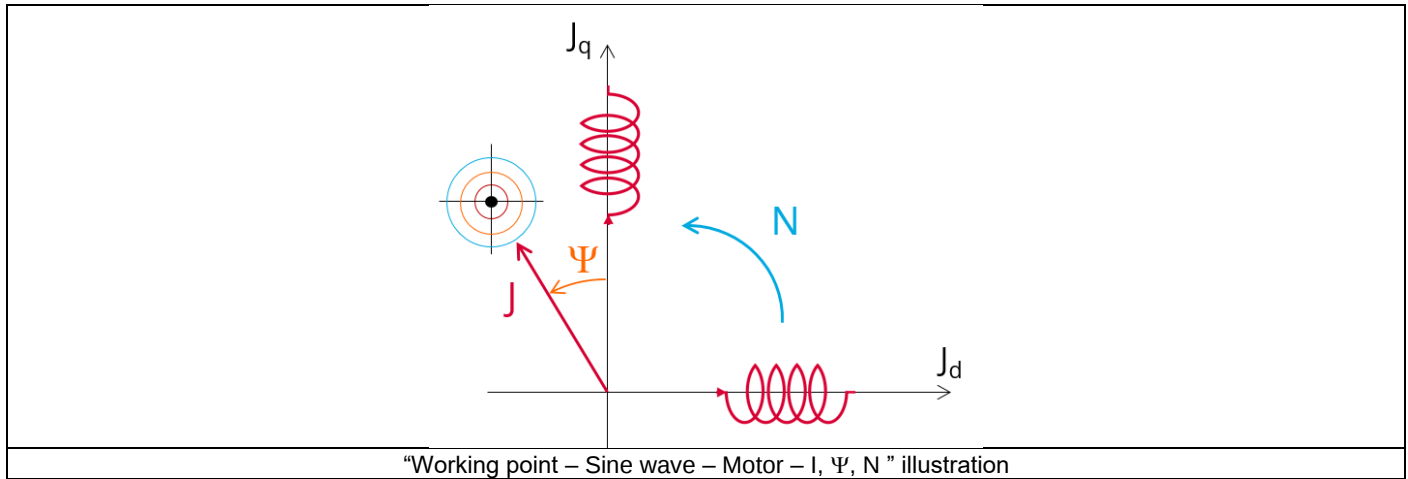
2.4.2	Flow chart	21
2.5	Test results	22
2.5.1	Introduction	22
2.5.2	List of the main NVH results	22
2.6	Limitation of computations - Advice for use	23
3	<i>mechanics – NVH – spectrogram – T - N</i>	24
3.1	Overview	24
3.1.1	Positioning and objective	24
3.1.2	User inputs	25
3.1.3	Main outputs	25
3.2	Settings	26
3.3	Inputs	26
3.3.1	Introduction	26
3.3.2	Standard inputs	26
3.3.2.1	Definition of the working point list	26
3.3.2.2	Maximum line current, rms / Current density	28
3.3.2.3	Maximum Line-Line voltage, rms	28
3.3.2.4	Command mode	28
3.3.2.5	Maximum speed	28
3.3.3	Advanced input	30
3.3.3.1	Maximum engine order / No. Points per electrical period	30
3.3.3.2	Maximum mode / spatial order	30
3.3.3.3	Number of computations per tooth pitch	30
3.3.3.4	Number of points for speed interpolation	30
3.3.3.5	Number of computations for Jd, Jq	30
3.3.3.6	Number of computations for speed	31
3.3.3.7	Number of computations for torque	31
3.3.3.8	Rotor initial position	32
3.3.3.9	Mesh order	32
3.3.3.10	Airgap mesh coefficient	32
3.4	Main principles of computation	33
3.4.1	Introduction	33
3.4.2	Flow chart	34
3.5	Test results	35
3.5.1	Introduction	35
3.5.2	List of NVH results	35
3.6	Limitation of computations - Advice for use	36

1 MECHANICS – NVH – WORKING POINT – I - Ψ - N

1.1 Overview

1.1.1 Positioning and objective

The aim of the test “Mechanics – NVH – Working point – I- Ψ -N” is to perform NVH analysis of the machine when operating at the targeted working point defined with the following inputs values I, Ψ , N (Magnitude of current, Control angle, Speed).



This test give data allowing NVH prediction in early electromagnetic and design stage.

The modal analysis of the stator mechanical structure, the radiated sound power and the magnetic forces applied on teeth are computed and displayed.

This test helps to answer the following question:

- Could the machine have any risks in connection with NVH? Yes / No.

The following table helps to classify the test “Mechanics – NVH – Working point – I- Ψ -N”.

Family	Mechanics
Package	NVH
Convention	#
Test	Working point - I - Ψ - N

Positioning of the test “Mechanics – NVH – Working point – I- Ψ -N”.

1.1.2 User inputs

The three main user input parameters are the supplied line current, the control angle and the speed. In addition, temperatures of winding and magnets must be set.

1.1.3 Main outputs

Test results are illustrated with data, graph and tables.

- 1) Tables of results
 - Machine performance - Working point defined with I- Ψ -N
- 2) Graphs, curves, and maps to illustrate NVH analysis results
 - Modal analysis
 - Radiation efficiency
 - Space-Time normal flux density in the airgap
 - Space-Time Maxwell pressure
 - Radiated sound power
 - Electromagnetic forces on teeth

1.2 Settings

Two buttons give access to the following setting definition:

- Temperature of active components: winding and magnets
- Definition of mechanical loss model parameters

For more details, please see the section Test area - Test settings.

1.3 Inputs

1.3.1 Introduction

The total number of inputs is equal to 10.

Among these inputs, 3 are standard inputs and 7 are advanced inputs.

1.3.2 Standard inputs

1.3.2.1 Line current / Current density

There are two common ways to define the electrical current.

Electrical current can be defined either by the current density in electric conductors or directly by indicating the value of the line current (the rms value is required).

When the choice of current definition mode is “Current”, the rms value of the line current supplied to the machine: “**Line current, rms**” (*Line current, rms value*) must be provided.

When the choice of current definition mode is “Density”, the rms value of the current density in electric conductors “**Current density, rms**” (*Current density in conductors, rms value*) must be provided.

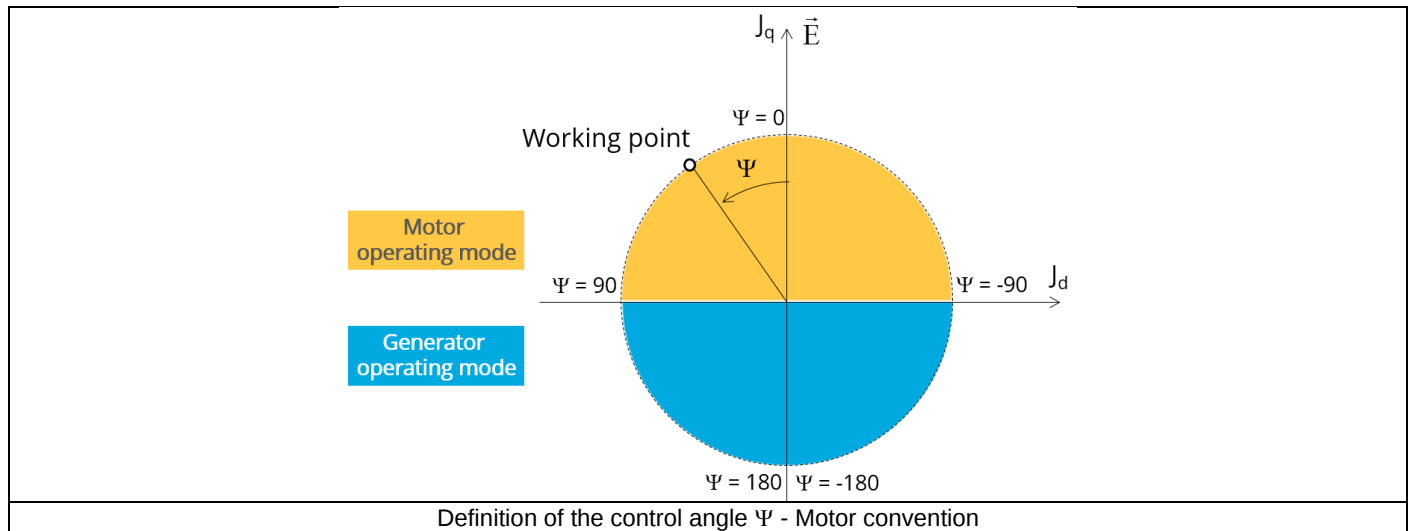
Note: The number of parallel paths and the winding connection are automatically considered in the results.

1.3.2.2 Control angle

Considering the vector diagram shown below, the “**Control angle**” is the angle between the electromotive force $\vec{E}$ and the electrical current ($\vec{J}$) ($\Psi = (\vec{E}, \vec{J})$).

The default value is 45 degrees. It is an electrical angle. It must be set in a range of -90 to 90 degrees.

This range of values covers all the possible working point in motor convention.



1.3.2.3 Speed

The imposed “**Speed**” (*Speed*) of the machine must be set.

1.3.3 Advanced input

1.3.3.1 Maximum engine order / No. Points per electrical period

Two kinds of inputs are possible:

Define the **Max. engine order** (*Maximum engine order*) or the **No. points / elec. Period** (*Number of points per electric period*).

When decomposing the Maxwell pressure, applied on the stator, to get its harmonic contributions, the “**max. engine order**” (*Maximum engine order*) is required to compute its decomposition in function of the time.

At a practical point of view, when the maximum engine order is equal to N, that leads to consider 2*N computation points over a complete rotation period of the rotor.

Note 1: The input “Engine order” is in connection with the frequency of vibration.

“Engine order” refers to a mechanical revolution period of the motor whereas frequency refers to the considered electrical period.

Obviously, both are linked with speed.

For instance, radiated sound power can be displayed either by considering frequency or engine order.

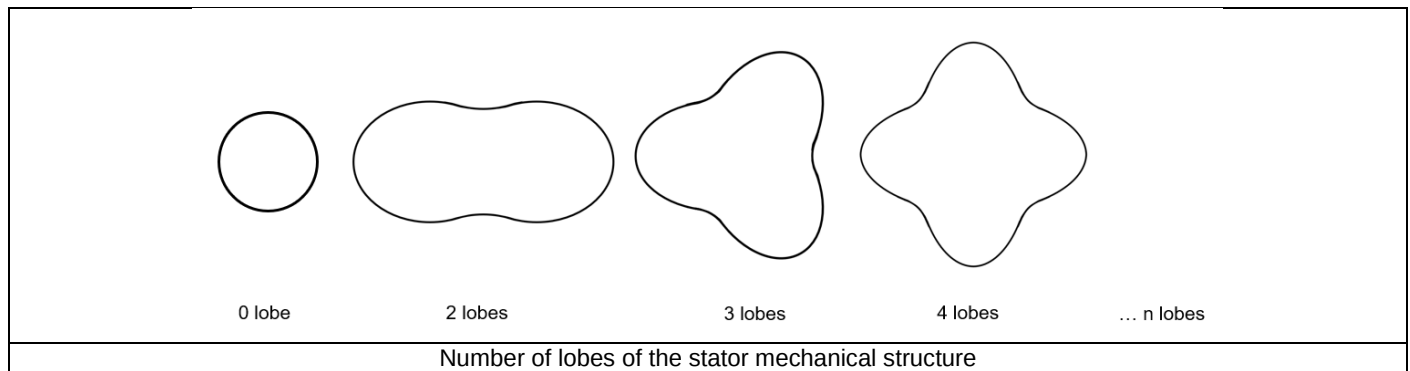
Note 2: There are two possibilities, either set an engine order or a number of points per electrical period.

For transient computations the minimum needed number of points per electrical period is 40.

So, when the engine order is not high enough to reach this constraint It is automatically modified to get 40 computation points per electrical period.

1.3.3.2 Maximum mode / spatial order

The “**max. mode / spatial order**” (*Maximum mode / spatial order*) input allows the user to define the number of modes to be considered for the acoustic structural analysis. If the user selects 25, it means that the highest number of lobes in the stator deformation will be equal to 25 lobes. All deformations corresponding to more than 25 lobes will be dismissed.



1.3.3.3 Number of computations per tooth pitch

The “**No. comp./tooth pitch**” (*Number of computations per tooth pitch*) allows to choose the number of Maxwell pressure evaluations per tooth. The more points selected, the more accurate the Maxwell pressure harmonic decomposition will be.

1.3.3.4 Displayed pressure range (dB)

The “**displayed pressure range (dB)**” (*Displayed Maxwell pressure range*) is only related to the displaying of results.

It allows to increase/decrease the range of non-zero contributions displayed in the Maxwell pressure harmonic decomposition map.

When one chooses a displayed pressure range equal to 50 dB, only the contributions within the range of 50 dB and below the maximum computed value is displayed.

Note that the absolute reference value P_{ref} (expressed in Pa), which corresponds to 0 dB, is indicated in the working point table.

Considering this referent value P_{ref} , one can compute any Maxwell pressure value P_{Pa} (expressed in Pa) from the ones expressed in Decibel P_{dB} .

The relations between these quantities are illustrated below:

$$P_{dB} = 20 \times \text{Log}_{10} \left(\frac{P_{Pa}}{P_{ref}} \right) \quad P_{Pa} = P_{ref} \times 10^{\frac{P_{dB}}{20}}$$

The default value is equal to 60. The range of possible values is [20;100].

1.3.3.5 Computation of forces on teeth

The “**computation of forces on teeth**” (*Additional analysis to compute the force on teeth*) allows to perform or not, the additional analysis which is the computation of force on teeth. Since this computation requires bigger memory and an additional computation time, this input allows to consider it as an additional option.

1.3.3.6 Mesh order

To get the results, the original computation is performed using a Finite Element Modeling.

Two levels of meshing can be considered for this finite element calculation: first order and second order.

This parameter influences the accuracy of results and the computation time.

By default, second order mesh is used.

1.3.3.7 Airgap mesh coefficient

The advanced user input “**Airgap mesh coefficient**” is a coefficient which adjusts the size of mesh elements inside the airgap. When the value of “**Airgap mesh coefficient**” decreases, the mesh elements get smaller, leading to a higher mesh density inside the airgap, increasing the computation accuracy.

The imposed Mesh Point (size of mesh elements touching points of the geometry), inside the Flux® software, is described as:

$$\text{MeshPoint} = (\text{airgap}) \times (\text{airgap mesh coefficient})$$

Airgap mesh coefficient is set to 1.5 by default.

The variation range of values for this parameter is [0.05; 2].

0.05 giving a very high mesh density and 2 giving a very coarse mesh density.

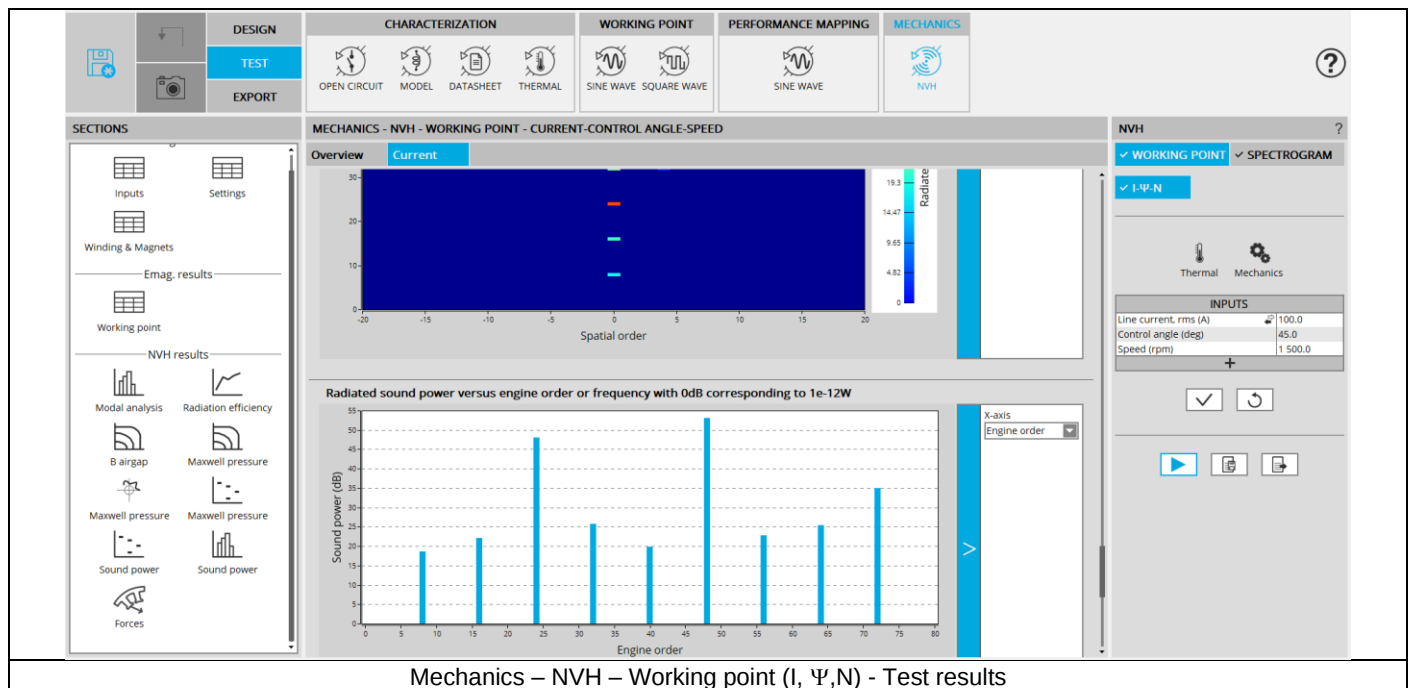
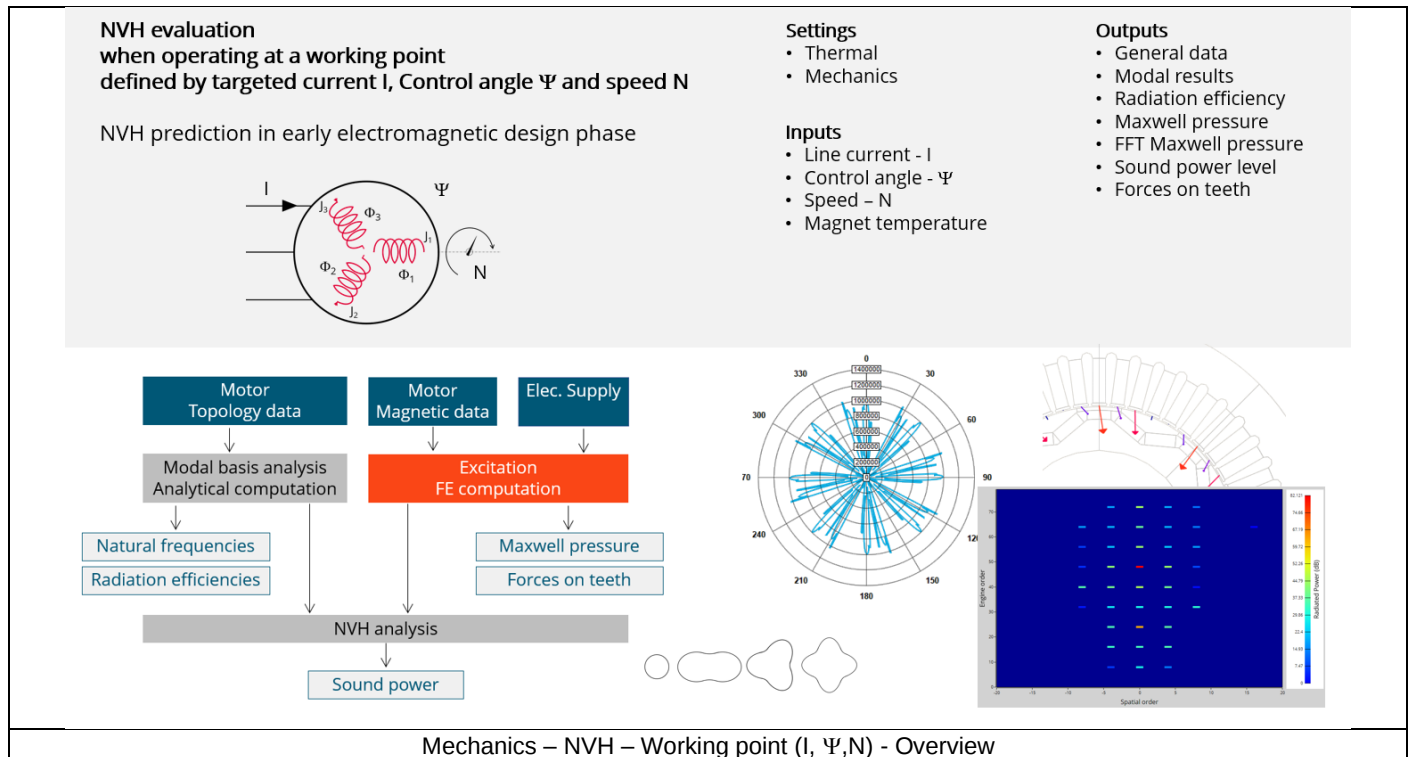
Caution:

Be aware, a very high mesh density does not always mean a better result quality. However, this always leads to a huge number of nodes in the corresponding finite element model. So, it means a need of huge numerical memory and increases the computation time considerably.

1.4 Main principles of computation

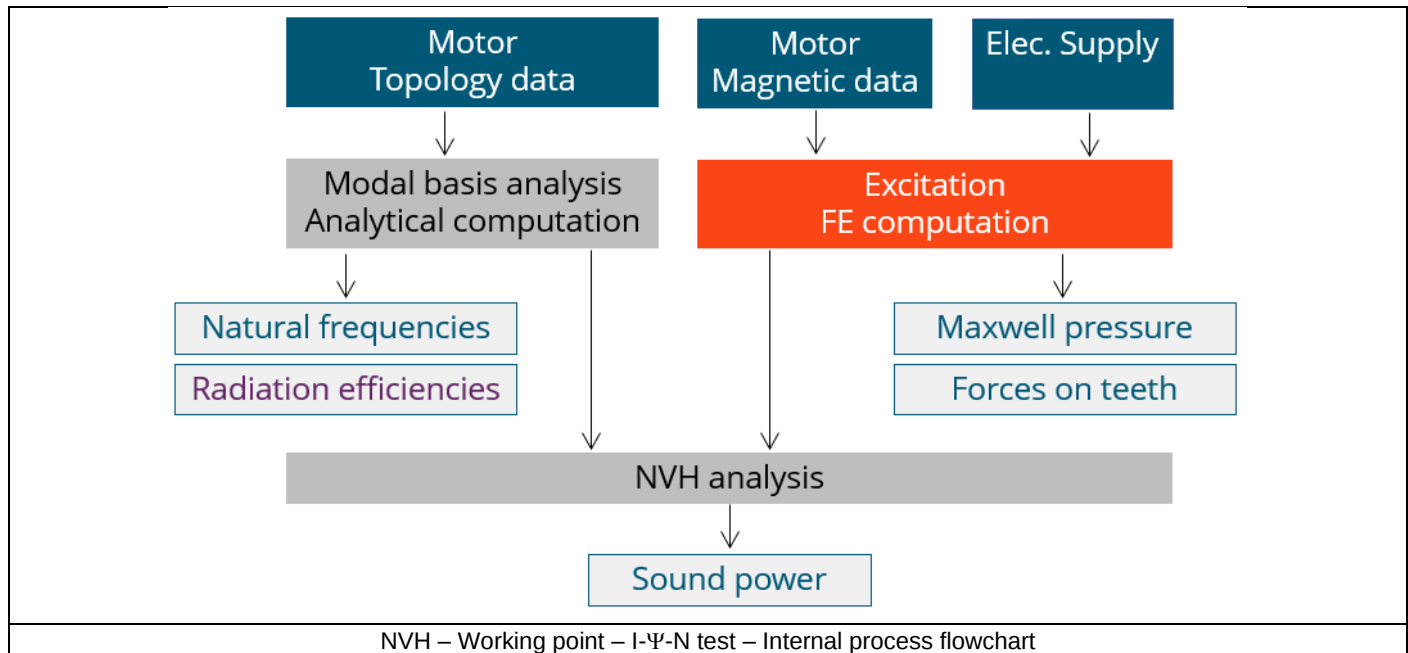
1.4.1 Introduction

Here are illustrations which give an overview of the test NVH – Working point (I, Ψ, N):



1.4.2 Flow chart

Here is the flowchart illustrating the internal process of the thermal test.



The inputs of the internal process are the parameters of:

- Motor topology data
- Motor magnetic data
- Electrical supply

The resulting NVH evaluation is based, first, on analytical computations allowing to characterize the modal analysis of the machine stator. Then, a time-space harmonic analysis of the Maxwell pressure computed in the airgap is performed. The Maxwell pressure is obtained from the normal flux density in the airgap computed in a 2D finite elements transient analysis.

Once this harmonic decomposition of the Maxwell pressure is performed, it is combined with the modal analysis of the machine to extract the acoustic power.

1.5 Test results

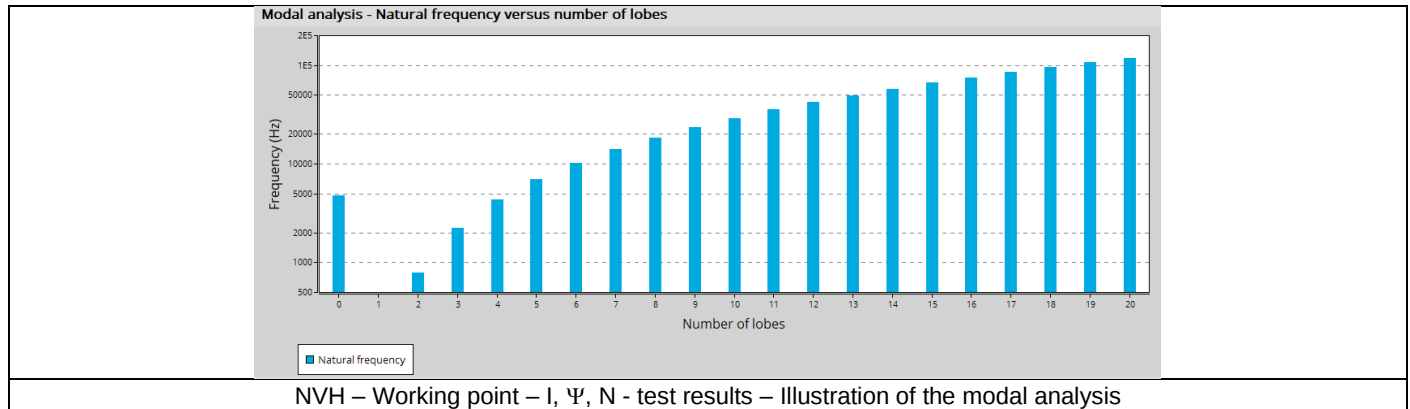
1.5.1 Introduction

Before analyzing the test results, take care of advice for use reminded in the section 1.6 (Limitation of computations - Advice for use)

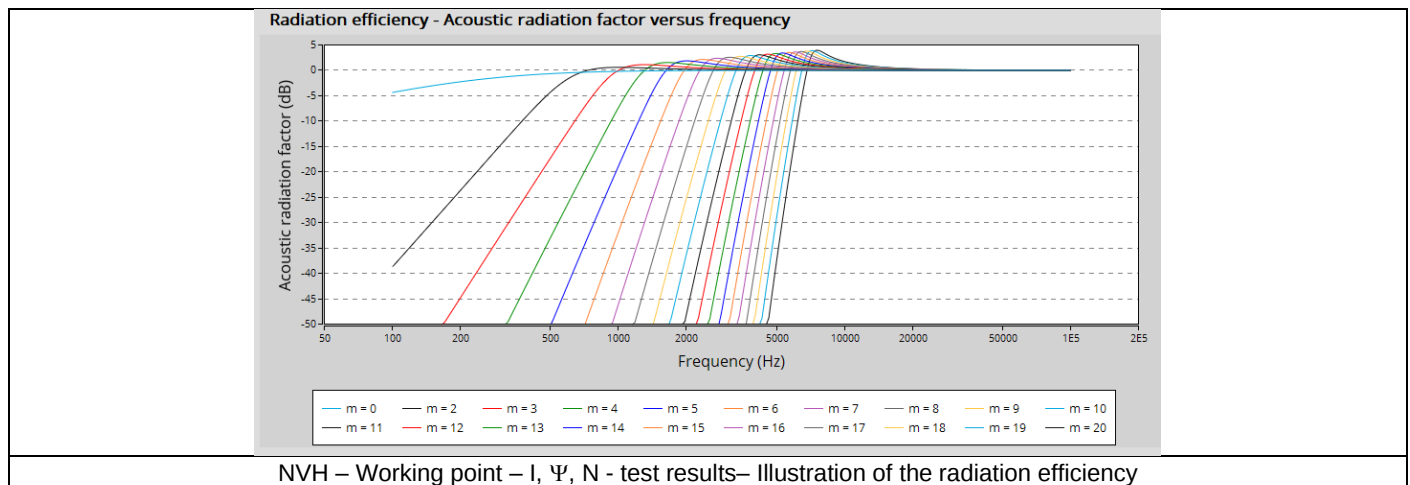
Electromagnetic results are computed and displayed to illustrate the considered working point at an electromagnetic point of view. The general data illustrate the machine performance. Information about NVH is listed like overall sound power. The magnitudes of forces on teeth (mean and maximum values) are displayed.

1.5.2 List of the main NVH results

- 1) Modal analysis – Natural frequency versus number of lobes: This graph displays the natural frequency corresponding to the n-lobe deformation.

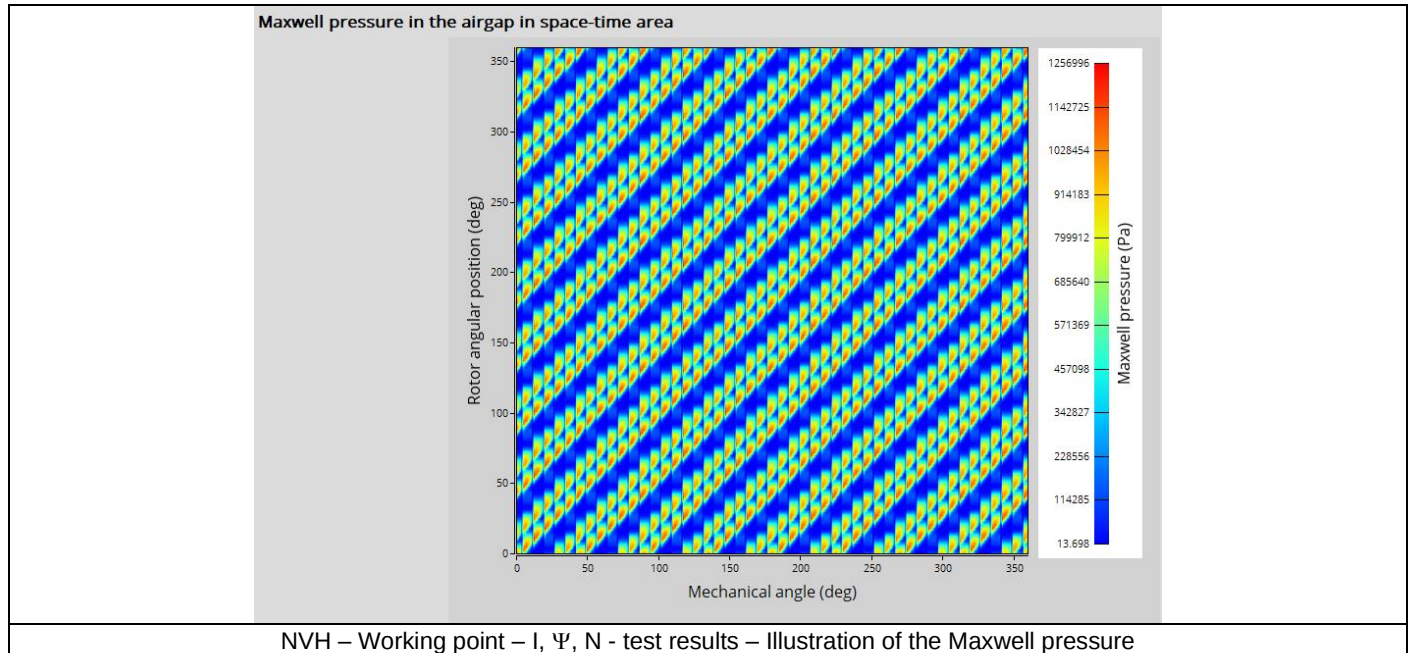


- 2) Radiation efficiency – Acoustic radiation factor versus frequency: This graph illustrates the capacity of the stator to convert vibration into noise.

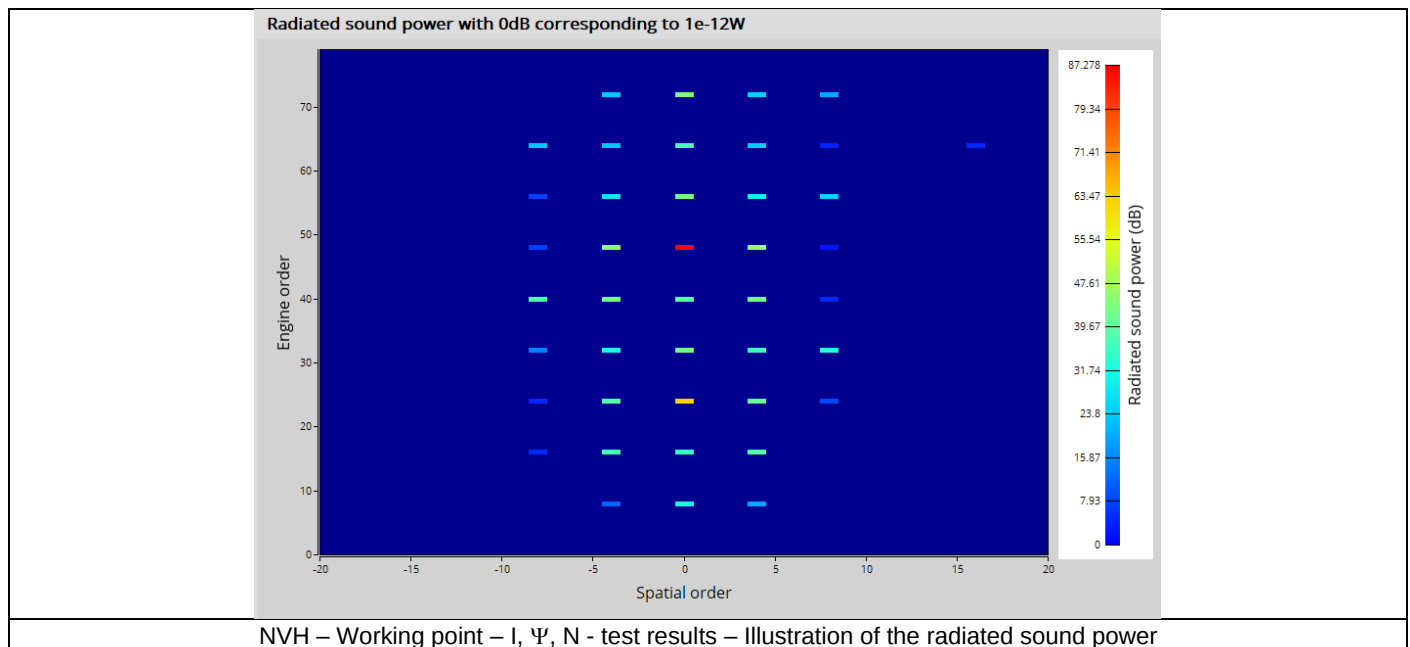


- 3) Normal flux density in the airgap in space-time area: This map is a time-space description of the flux density in the airgap.

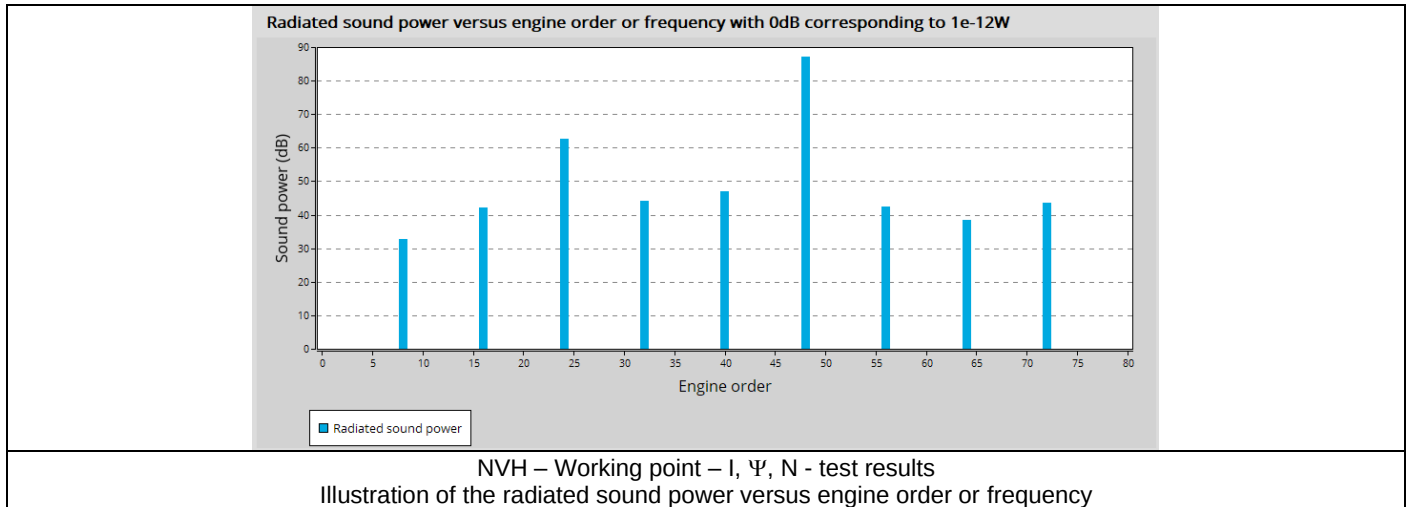
- 4) Maxwell pressure in the airgap in space-time area: This map is a time-space description of the normal Maxwell pressure in the airgap.



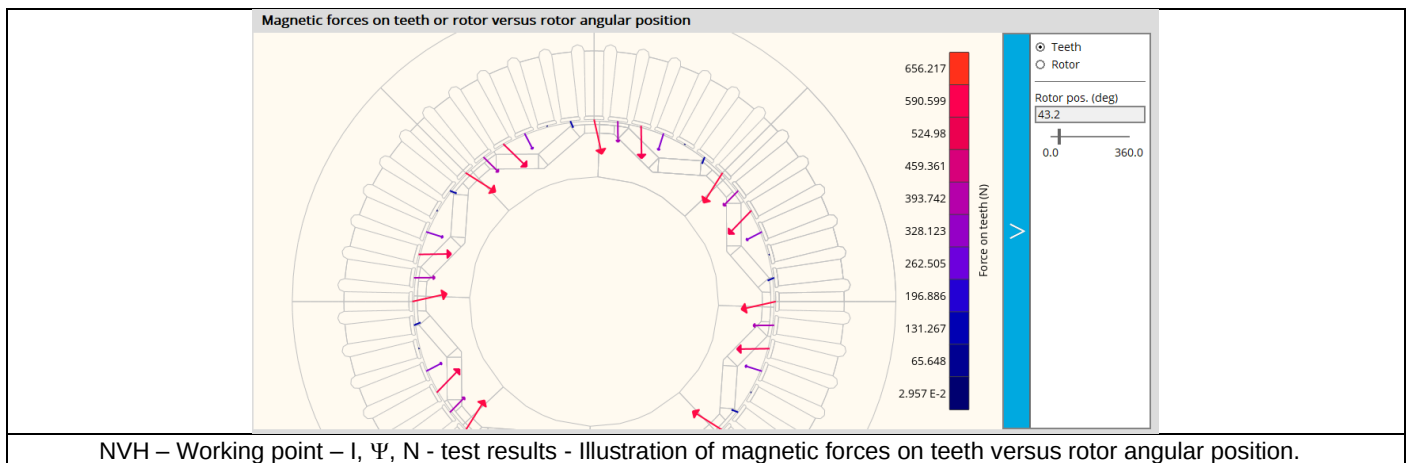
- 5) Maxwell pressure in the airgap versus rotor angular position: This curve displays the normal Maxwell pressure in the airgap for a given angular position of the rotor
- 6) Maxwell pressure space-time harmonic analysis: This map displays the magnitude of the harmonic decomposition for the magnetic excitation.
- 7) Radiated sound power with 0dB corresponding to E-12 W: This map displays the harmonic decomposition of the radiated sound power.



- 8) Radiated sound power versus engine order or frequency with 0dB c corresponding to E^{-12} W: This histogram shows the radiated sound power per engine order (or frequency) with a $1E^{-12}$ W as reference



- 9) Magnetic forces on teeth or rotor versus rotor angular position.



1.6 Limitation of computations - Advice for use

The modal analysis as well as the radiation efficiency are based on an analytical computation where the stator of the machine is considered as a vibrating cylinder.

The considered cylinder behavior is weighted by the additional masses like the fins or the winding and the subtractive masses like the slots and the cooling circuit holes.

This assumption allows to get fast evaluation of the behavior of machine in connection to NVH. In no way this can replace a mechanical Finite Element modeling and simulation.

Among possible reasons for deviations of results can be the following ones:

- The limits of the analytical model are reached or overpassed
- Unusual topology and/or dimensions of the teeth/slots
- Complexity of the stator-frame structure when it is composed with several components for instance
- The ratio between the total length of the frame L_{frame} and the stack length of the machine L_{stk} in any case, this ratio must be lower than 1.5:

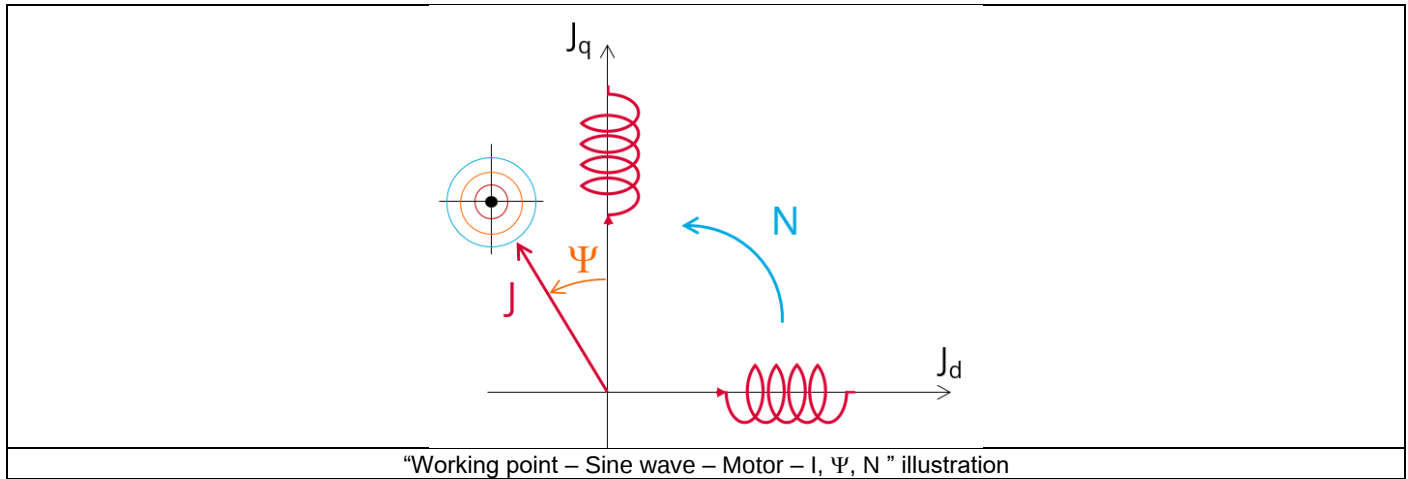
$$\frac{L_{Frame}}{L_{Stk}} \leq 1.5$$

2 MECHANICS – NVH – SPECTROGRAM – I - Ψ - N

2.1 Overview

2.1.1 Positioning and objective

The aim of the test “Mechanics – NVH – Spectrogram – I- Ψ -N” is to perform NVH analysis on the machine when operating at a set of targeted working points defined with the following inputs values I, Ψ , N (Magnitude of current, Control angle, Speed).



This test give data allowing NVH prediction in early electromagnetic and design stage.

The modal analysis of the stator mechanical structure, the radiated sound power spectrogram per engine order versus speed and the resulting overall weighted radiated sound power versus speed are computed and displayed.

These results allow to see if there are any problems linked with NVH over the considered speed range.

And finally, this test helps to answer the following question:

- Could the machine have any risks in connection with NVH? Yes / No.

The following table helps to classify the test “Mechanics – NVH – Spectrogram – I- Ψ -N”.

Family	Mechanics
Package	NVH
Convention	#
Test	Spectrogram - I - Ψ - N

Positioning of the test “Mechanics – NVH – Spectrogram – I- Ψ -N”

2.1.2 User inputs

A list of working points must be defined in a file. They are described with the four following input parameters:

- The supplied line current, or current density (rms value),
- The control angle
- The speed
- The magnet temperature.

In addition, temperatures of winding must be set.

2.1.3 Main outputs

Test results are illustrated with data, graphs, and tables.

- 1) Curves to give an overview of the electromagnetic behavior of the machine versus speed
 - Power
 - Mechanical torque
 - Line current
 - Control angle
 - Magnet temperature
- 2) Graphs, curves, and maps to illustrate NVH analysis results
 - Modal analysis
 - Radiation efficiency
 - Radiated sound power spectrogram in speed-engine order area
 - Radiated sound power spectrogram in speed-frequency area
 - Overall weighted radiated sound power versus speed

2.2 Settings

Two buttons give access to the following setting definition:

- Temperature of active components: winding and magnets
- Definition of mechanical loss model parameters

For more details, please see the section Test area - Test settings.

2.3 Inputs

2.3.1 Introduction

The total number of inputs is equal to 7.

Among these inputs, 1 is a standard input and 6 are advanced inputs.

Note that the standard input corresponds to a table to be filled with a set of working point described as indicated in the following section.

2.3.2 Standard inputs

2.3.2.1 I-Ψ-N description

The “**I-Ψ-N description**” allows to define several working points.

The description must be defined by clicking on the button “Set values”.

Then, two ways are possible to fill in the table: either filling the table line per line or by importing an Excel file in which all the working points to be considered are defined.

Each working point is described by the following data:

- The line current, or current density (rms value)
- The control angle
- The speed
- The magnet temperature

Note 1: There must be at least two working points.

Note 2: The speed column must contain increasing speeds.

1) Line current

There are two common ways to define the electrical current.

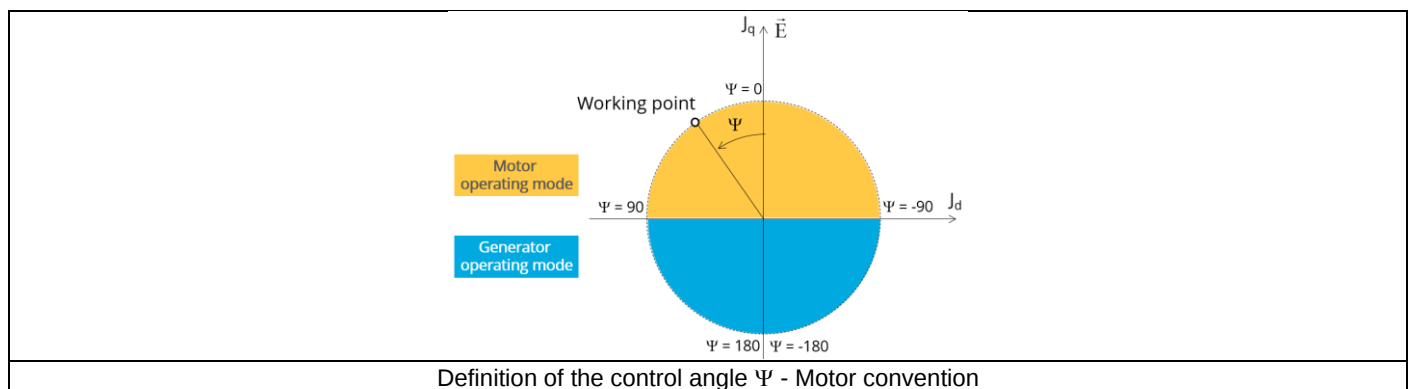
The rms value of the line current supplied to the machine: “**Line current, rms**” (*Line current, rms value*) must be provided.

Note: The number of parallel paths and the winding connection are automatically considered in the results.

2) Control angle

Considering the vector diagram shown below, the “**Control angle**” is the angle between the electromotive force E and the electrical current (J) ($\Psi = (E, J)$). It is an electrical angle. It must be set in a range of -90 to 90 degrees.

This range of values covers all the possible working point in motor convention.



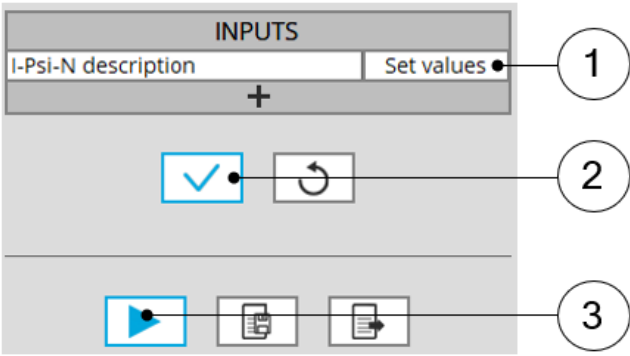
3) Speed

The imposed “**Speed**” (*Speed*) of the machine must be set. The speed column must contain increasing speeds.

4) Magnet temperature

The magnet temperature which is expected for each considered worked point must be set.

5) Process to define the list of working points



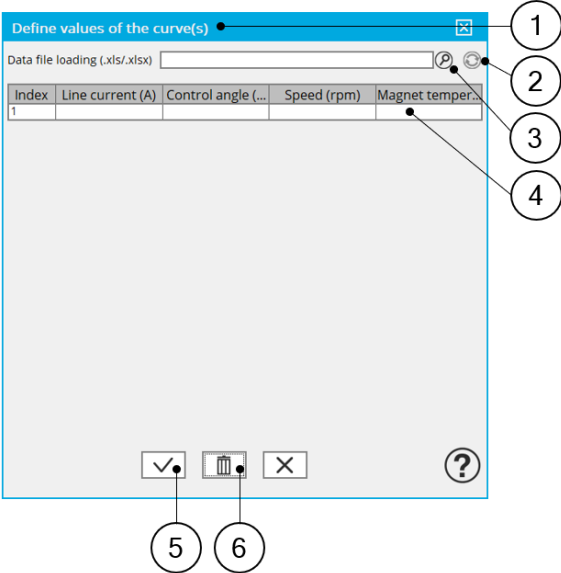
1

2

3

List of working points to be defined

1	Click on the button “Set values” of the field “ I, Ψ, N description” to define the working points in a dialog box. Refer to the next illustration which shows how to fill the working point table.
2	Button to validate the user input data
3	Button to run the computations



1

2

3

4

5

6

Dialog box to define the list of working points

1	Dialog box opened after having clicked on the button “Set values” in the field “Cycle description”
2	Browse the folder to select an Excel file which is described the duty cycle
3	Button to refresh the table data when the considered Excel file has been modified
4	Fields to be filled with data to describe the duty cycle to be considered

I-Psi-N input				
Label	Current	Control angle	Speed	Magnet temperature
Units	A	deg	rpm	°C
Values	100	0	1000	100
	120	0	6000	115
	135	0	13000	136
	150	0	25000	170
	160	0	40000	220

Excel file template to define the list of working points

2.3.3 Advanced input

2.3.3.1 Maximum engine order / No. Points per electrical period

Two kinds of inputs are possible:

Define the **Max. engine order** (*Maximum engine order*) or the **No. points / elec. Period** (*Number of points per electric period*).

When decomposing the Maxwell pressure, applied on the stator, to get its harmonic contributions, the “**max. engine order**” (*Maximum engine order*) is required to compute its decomposition in function of the time.

At a practical point of view, when the maximum engine order is equal to N, that leads to consider $2*N$ computation points over a complete rotation period of the rotor.

Note 1: The input “Engine order” is in connection with the frequency of vibration.

“Engine order” refers to a mechanical revolution period of the motor when frequency refers to the considered electrical period.

Obviously, both are linked with speed.

For instance, radiated sound power can be displayed either by considering frequency or engine order.

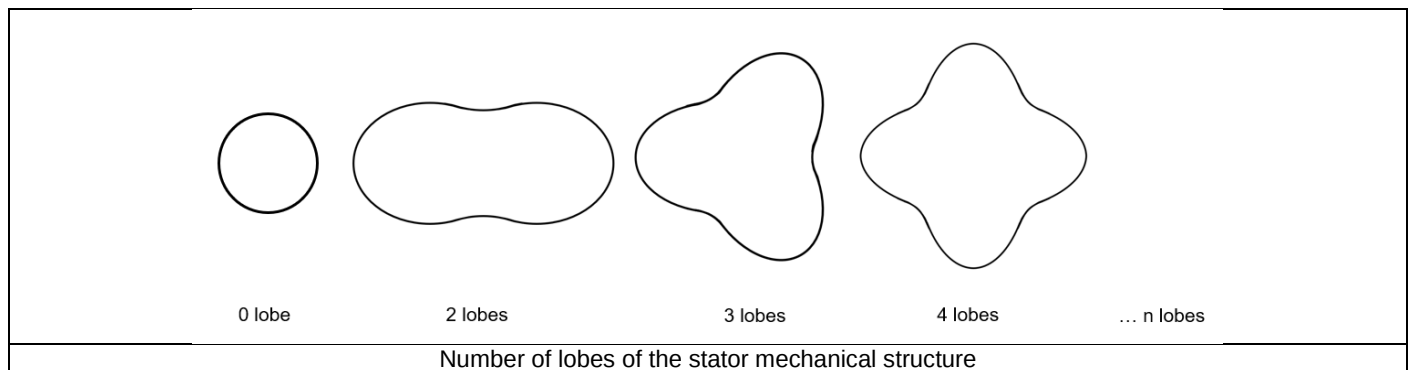
Note 2: There are two possibilities, either set an engine order or a number of points per electrical period.

For transient computations the minimum needed number of points per electrical period is 40.

So, when the engine order is not high enough to reach this constraint It is automatically modified to get 40 computation points per electrical period.

2.3.3.2 Maximum mode / spatial order

The “**max. mode / spatial order**” (*Maximum mode / spatial order*) input allows the user to define the number of modes to be considered for the acoustic structural analysis. If the user selects 25, it means that the highest number of lobes in the stator deformation will be equal to 25 lobes. All deformations corresponding to more than 25 lobes will be dismissed.



2.3.3.3 Number of computations per tooth pitch

The “**No. comp./tooth pitch**” (*Number of computations per tooth pitch*) allows to choose the number of Maxwell pressure evaluations per tooth. The more points selected, the more accurate the Maxwell pressure harmonic decomposition will be.

2.3.3.4 Number of points for speed interpolation

The “**No. points for speed interpolation**” (*Number of points for speed interpolation*) allows to manage the computation of the radiated sound power per engine order. It allows to manage the data interpolation between the speeds indicated as inputs. Thanks to that, the curves “Radiated sound power per engine order versus speed” and “weighted radiated sound power versus speed” can have a better discretization which leads to a better displaying of the local peaks.

The default value is equal to 100. The range of possible values is [50,300]

2.3.3.5 Mesh order

To get the results, the original computation is performed using a Finite Element Modeling.

Two levels of meshing can be considered for this finite element calculation: first order and second order.

This parameter influences the accuracy of results and the computation time.

By default, second order mesh is used.

2.3.3.6 Airgap mesh coefficient

The advanced user input “**Airgap mesh coefficient**” is a coefficient which adjusts the size of mesh elements inside the airgap. When the value of “**Airgap mesh coefficient**” decreases, the mesh elements get smaller, leading to a higher mesh density inside the airgap, increasing the computation accuracy.

The imposed Mesh Point (size of mesh elements touching points of the geometry), inside the Flux® software, is described as:

$$\text{MeshPoint} = (\text{airgap}) \times (\text{airgap mesh coefficient})$$

Airgap mesh coefficient is set to 1.5 by default.

The variation range of values for this parameter is [0.05; 2].

0.05 giving a very high mesh density and 2 giving a very coarse mesh density.

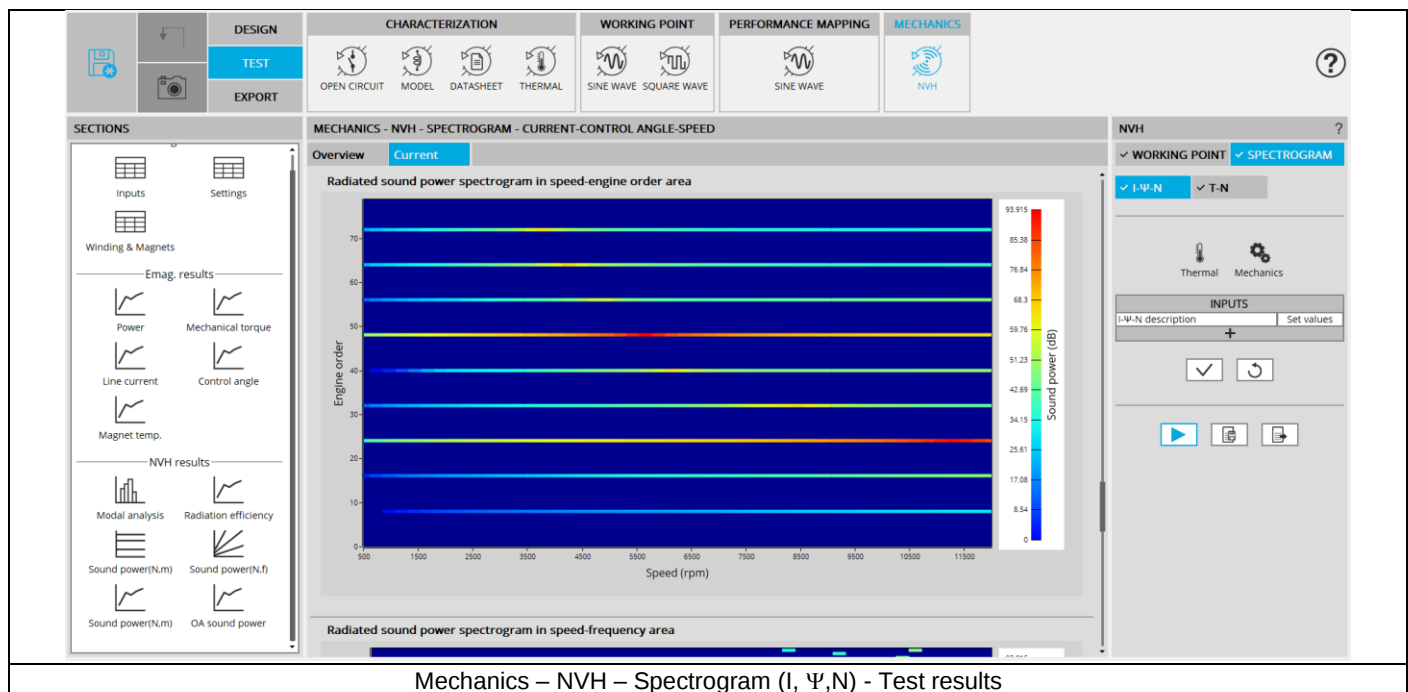
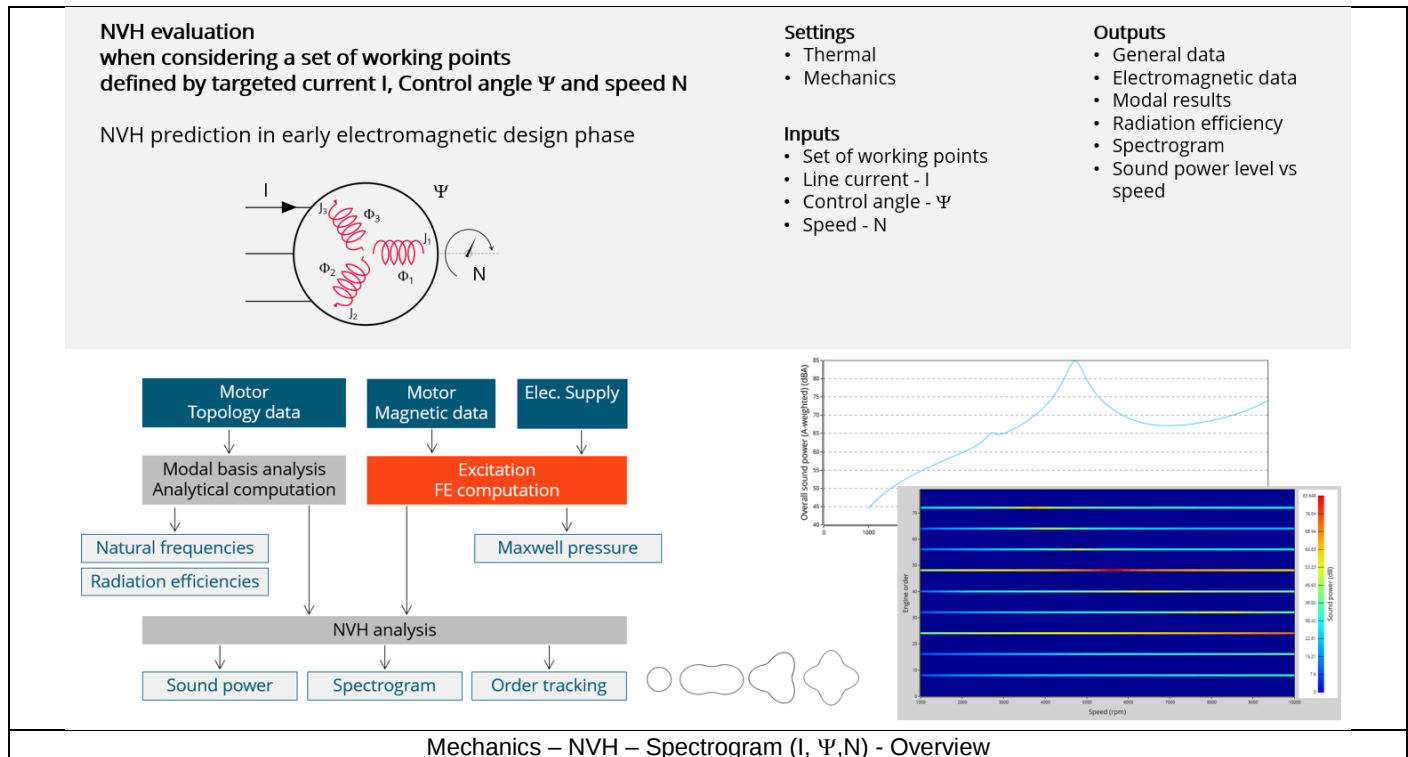
Caution:

Be aware, a very high mesh density does not always mean a better result quality. However, this always leads to a huge number of nodes in the corresponding finite element model. So, it means a need of huge numerical memory and increases the computation time considerably.

2.4 Main principles of computation

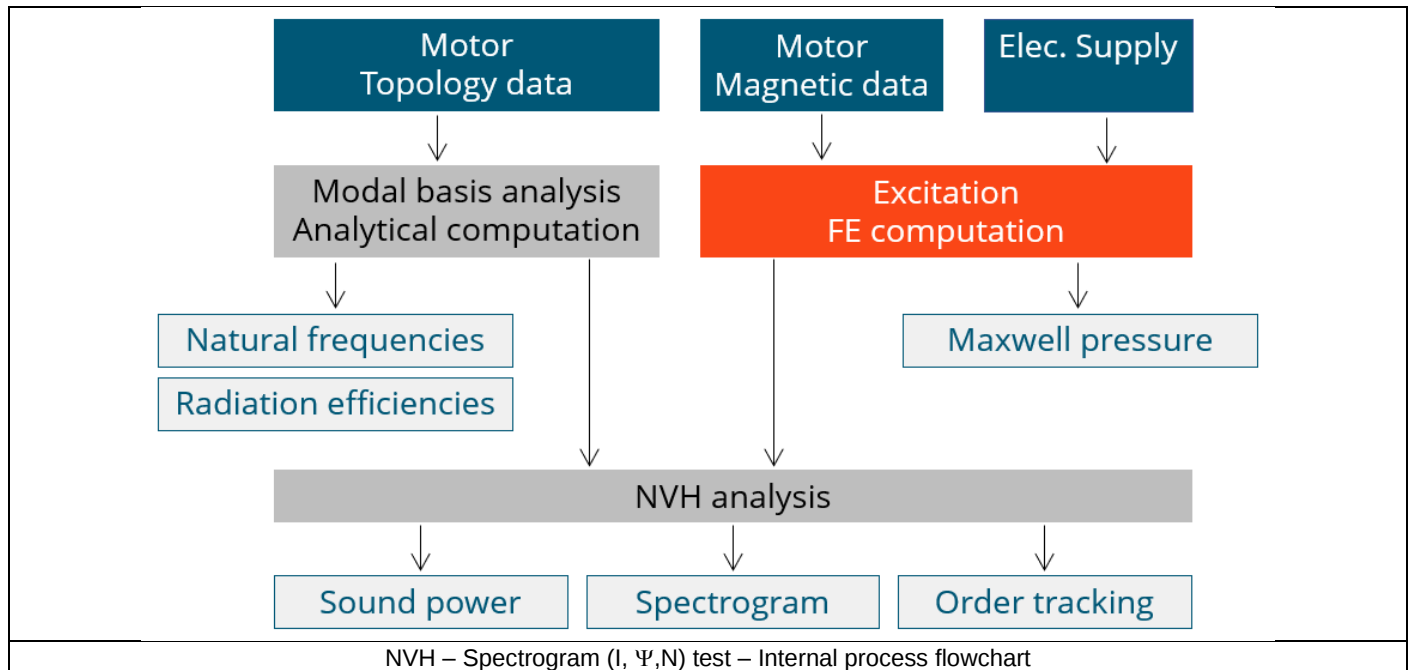
2.4.1 Introduction

Here are illustrations which give an overview of the test NVH – Spectrogram (I, Ψ, N):



2.4.2 Flow chart

Here is the flowchart illustrating the internal process of the thermal test.



The inputs of the internal process are the parameters of:

- Motor topology data
- Motor magnetic data
- Electrical supply

For each points of the I-Ψ-N description, the process described in the previous test is performed. Once it is done, interpolations between the targeted working points are made to produce a high-quality order tracking/ spectrogram graph.

2.5 Test results

2.5.1 Introduction

Before analyzing the test results, take care of advices for use reminded in the section 2.6 (Limitation of computations - Advice for use).

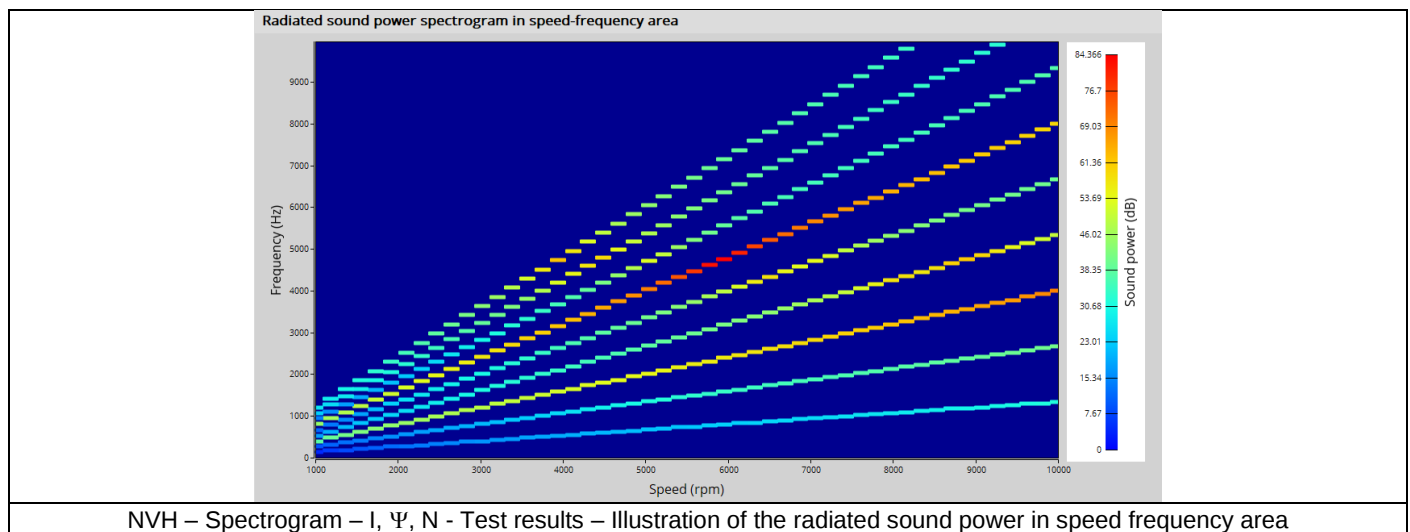
Electromagnetic results are computed and displayed to illustrate and to characterize the considered working points at an electromagnetic point of view.

Data like Mechanical torque, Power, Line current and control angle are displayed versus the speed.

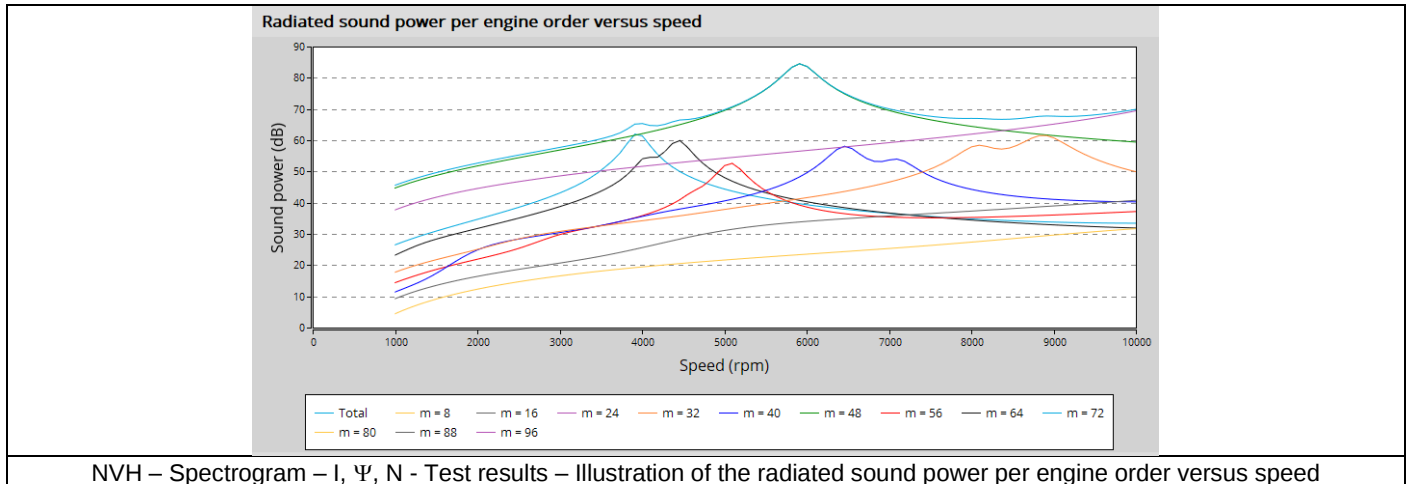
Accordingly, the user inputs a list of several working points which is considered to compute the spectrogram. Each working point is computed by means of Finite Element computations with electromagnetic transient application.

2.5.2 List of the main NVH results

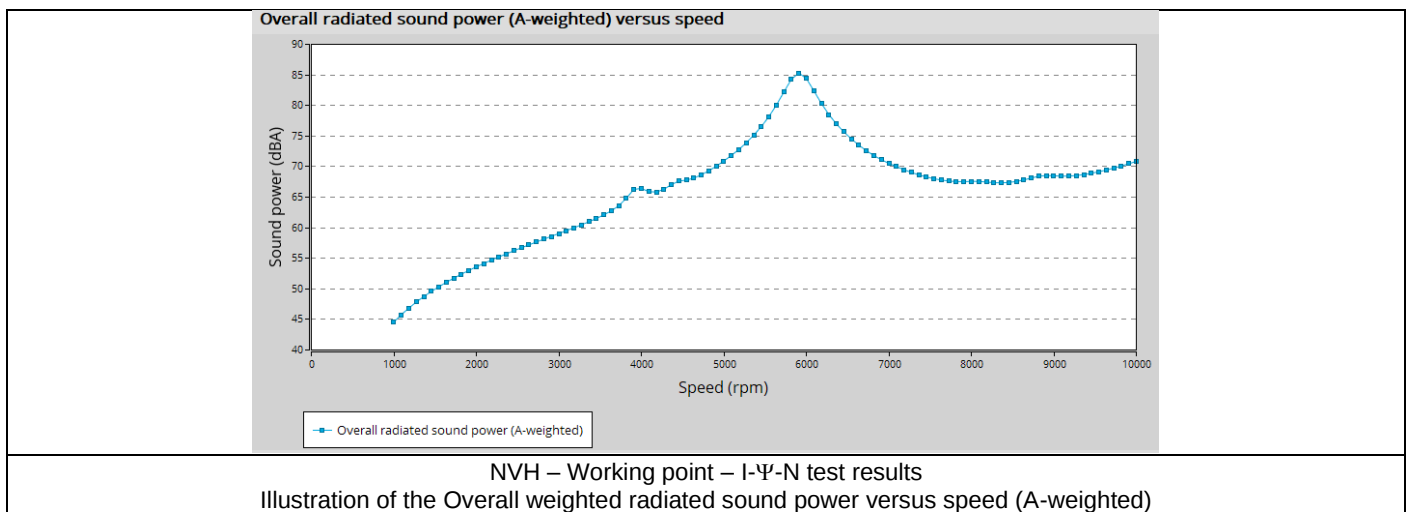
- 1) Modal analysis – Natural frequency versus number of lobes: This graph displays the natural frequency corresponding to the n-lobe deformation.
- 2) Radiation efficiency – Acoustic radiation factor versus frequency: This graph illustrates the capacity of the stator to convert vibration into noise.
- 3) Radiated sound power spectrogram in speed-engine order area: This spectrogram displays the radiated sound power in an engine order/speed area. Only the relevant engine orders are displayed (the multiples of the number of poles of the engine).
- 4) Radiated sound power spectrogram in speed frequency area: This spectrogram displays the radiated sound power in a frequency/speed area. Only the relevant engine orders are displayed (the multiples of the number of poles of the engine).



- 5) Radiated sound power per engine order versus speed: This graph displays the radiated sound power per engine order as well as the total radiated sound power.



- 6) Overall weighted radiated sound power versus speed: This graph displays the radiated sound power weighted for the human ear (A-weighted).



2.6 Limitation of computations - Advice for use

The modal analysis as well as the radiation efficiency are based on an analytical computation where the stator of the machine is considered as a vibrating cylinder.

The considered cylinder behavior is weighted by the additional masses like the fins or the winding and the subtractive masses like the slots and the cooling circuit holes.

This assumption allows to get fast evaluation of the behavior of machine in connection to NVH. In no way this can replace a mechanical Finite Element modeling and simulation.

Among possible reasons for deviations of results can be the following ones:

- The limits of the analytical model are reached or overpassed
- Unusual topology and/or dimensions of the teeth/slots
- Complexity of the stator-frame structure when it is composed with several components for instance
- The ratio between the total length of the frame L_{Frame} and the stack length of the machine L_{stk} in any case, this ratio must be lower than 1.5:

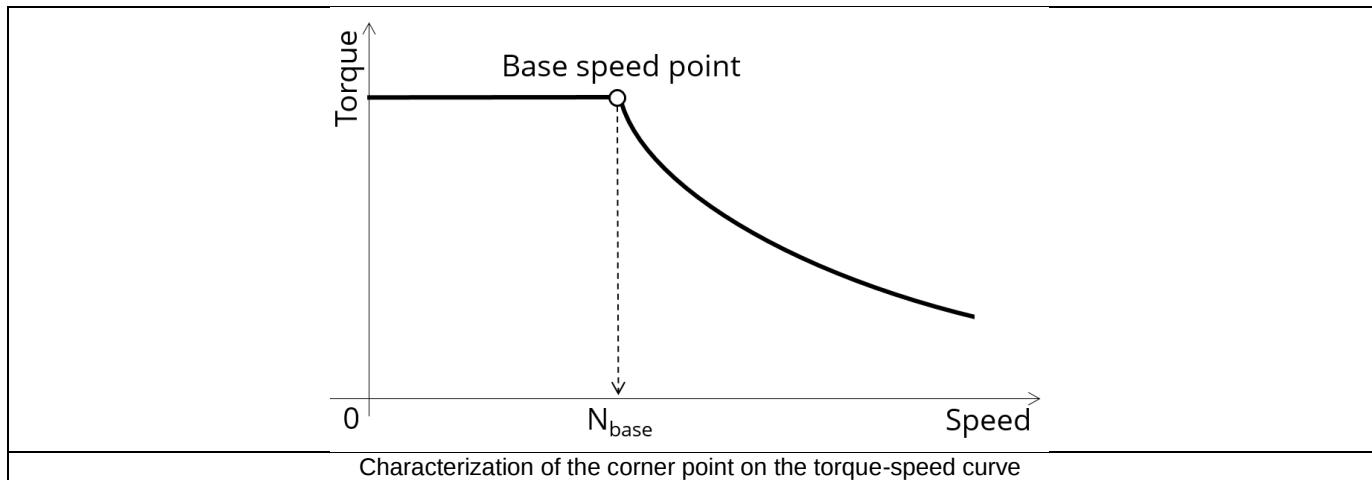
$$\frac{L_{Frame}}{L_{stk}} \leq 1.5$$

3 MECHANICS – NVH – SPECTROGRAM – T - N

3.1 Overview

3.1.1 Positioning and objective

The aim of the test “**Mechanics – NVH – Spectrogram – T-N**” is to perform NVH analysis on the machine when operating at a set of targeted working points defined with the following inputs values T, N (Mechanical torque and Speed).



Input parameters like the maximum “Line-Line voltage”, the maximum “line current” and the desired “Maximum speed” of the machine are considered.

Two types of command modes are available: The Maximum Torque Per Volt command mode (MTPV) and the Maximum Torque Per Amps command mode (MTPA).

Input parameters allow to define torque-speed envelope in the framework of which the targeted working points can be selected.

By default, the NVH evaluation is computed by considering working points on the torque-speed envelope.

But, one can define a list of working points located anywhere under (or on) the torque-speed envelope.

This test give data allowing NVH prediction in early electromagnetic and design stage.

The modal analysis of the stator mechanical structure, the radiated sound power spectrogram per engine order and versus speed and the resulting overall weighted radiated sound power versus speed are computed and displayed.

These results allow to see if there are any problem linked with NVH overall the considered speed range.

And finally, this test helps to answer the following question:

- Could the machine have any risks in connection with NVH? Yes / No.

The following table helps to classify the test “Mechanics – NVH – Spectrogram – T-N”.

Family	Mechanics
Package	NVH
Convention	#
Test	Spectrogram - T- N

Positioning of the test “Mechanics – NVH – Spectrogram – T-N”

3.1.2 User inputs

A list of working points must be defined in a file. They are described with the four following input parameters:

- Selection type of working point set
- Maximum line current (or density),
- Maximum Line-Line voltage
- Command mode
- Maximum speed.

In addition, temperatures of winding must be set.

3.1.3 Main outputs

Test results are illustrated with data, graphs, and tables.

- 1) Curves to give an overview of the electromagnetic behavior of the machine versus speed
 - Mechanical torque
 - Power
 - Line current
 - Control angle
- 2) Graphs, curves, and maps to illustrate NVH analysis results
 - Modal analysis
 - Radiation efficiency
 - Radiated sound power spectrogram in speed-engine order area
 - Radiated sound power spectrogram in speed-frequency area
 - Overall weighted radiated sound power versus speed

3.2 Settings

Three buttons give access to the following setting definition:

- Temperature of active components: winding and magnets
- Definition of the power electronics parameters
- Definition of mechanical loss model parameters

For more details, please see the section Test area - Test settings.

3.3 Inputs

3.3.1 Introduction

The total number of inputs is equal to 16.
Among these inputs, 5 are standard inputs and 11 are advanced inputs.

The aim is to define a list of working points characterized with the torque and the speed.
To know the framework in which the working points can be selected, the torque-speed envelope is computed considering the four inputs data: the maximum line current, the maximum line-line voltage, the command mode and the maximum speed to be considered.

By default, the list of working points is built with points on the torque-speed envelope.
But, one can define a list of working points located anywhere under (or on) the torque-speed envelope.
Please refer to the section: Definition of the working point list.

3.3.2 Standard inputs

3.3.2.1 Definition of the working point list

1) Overview

By default, the list of working points is automatically built by considering seven points on the machine torque-speed envelope. The torque-speed envelope depends on the four following input parameters:

- Max. line current, rms
- Max. Line-Line voltage, rms
- Command mode
- Maximum speed

It is also possible to define our own working point list by filling in a table with the targeted speeds and torques.

INPUTS

Torque speed envelope

Max. line current, rms (A)

Max. Line-Line voltage, rms (V)

Command mode

Maximum speed (rpm)

Auto

100.0

300.0

MTPV

12 000.0

+

✓

↺

1

INPUTS

User working point list

Max. line current, rms (A)

Max. Line-Line voltage, rms (V)

Command mode

Maximum speed (rpm)

Set values

100.0

300.0

MTPV

12 000.0

+

✓

↺

2

Two ways for defining the working point list

1

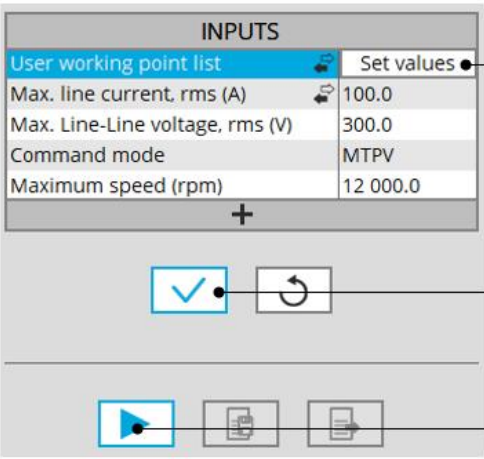
Automatic mode: working points are automatically considered on the torque-speed envelope

2

We can define our own working point list by filling in a table with the targeted speeds and torques

2) Process to define the working point list

Two ways are possible to define the list of working points: either filling the table line per line or by importing an Excel file in which all the working points to be considered are defined.



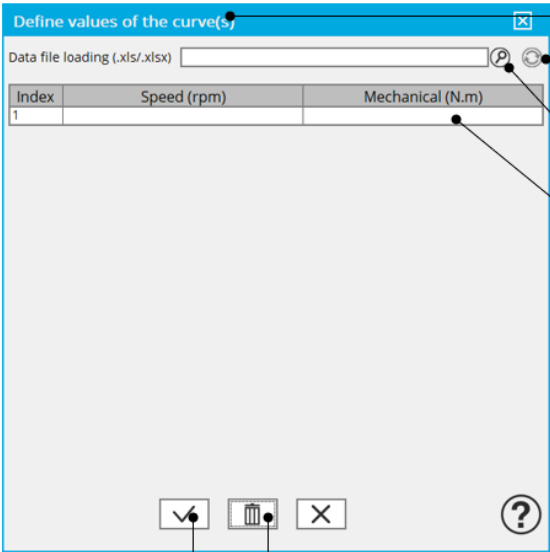
INPUTS	
User working point list	Set values
Max. line current, rms (A)	100.0
Max. Line-Line voltage, rms (V)	300.0
Command mode	MTPV
Maximum speed (rpm)	12 000.0

Buttons: [Checkmark] [Refresh] [Play]

1: Set values button
2: Validation button
3: Run button

List of working points to be defined

1	Click on the button “Set values” of the field “User working point list” to define the working points in a dialog box. Refer to the next illustration which shows how to fill the working point table.
2	Button to validate the user input data
3	Button to run the computations



Define values of the curve(s)

Data file loading (.xls/.xlsx)

Index	Speed (rpm)	Mechanical (N.m)
1		

Buttons: [Checkmark] [Trash] [X] [Help]

1: Title bar
2: File loading field
3: Table
4: Refresh button
5: Validation button
6: Help icon

Dialog box to define the list of working points

1	Dialog box opened after having clicked on the button “Set values” in the field “Cycle description”
2	Browse the folder to select an Excel file which is described the duty cycle
3	Button to refresh the table data when the considered Excel file has been modified
4	Fields to be filled with data to describe the duty cycle to be considered

	T-N input		
	Label	Speed	Mech. torque
	Units	rpm	N.m
	Values	500	150
		1000	140
		1010	130
		2000	130
		3000	140
		3500	115
		4000	95
		5000	85
		5500	65
Excel file template to define the list of working points with speed and torque data			

3.3.2.2 Maximum line current, rms / Current density

There are two common ways to define the maximum line current.

Electrical current can be defined either by the current density in electric conductors or directly by indicating the value of the line current (the rms value is required).

When the choice of current definition mode is “current”, the rms value of the maximum line current supplied to the machine: **“Max. line current, rms”** (*Maximum line current, rms value*) must be provided.

When the choice of current definition mode is “density”, the rms value of the maximum current density in electric conductors **“Max. Current density, rms”** (*Maximum current density in conductors, rms value*) must be provided.

Note: The number of parallel paths and the winding connection are automatically considered in the results.

3.3.2.3 Maximum Line-Line voltage, rms

The rms value of the maximum line-line voltage supplying to the machine: **“Max. Line-Line voltage, rms”** (*Maximum Line-Line voltage, rms value*) must be provided.

Note: The number of parallel paths and the winding connection are automatically considered in the results

3.3.2.4 Command mode

For any applied command mode, the process consists of computing the torque-speed envelope.

Note: For additional information on this topic, please see the section dedicated to command modes (Performance mapping – efficiency map)

3.3.2.5 Maximum speed

The computation and analysis of the torque-speed curves are performed over a given speed range.

The maximum allowed value for the « **Maximum speed** » corresponds to 53000 rad/s - about 506000 rpm.

Note 1: The maximum speed is considered build the following outputs:

- Radiated sound power spectrograms versus engine order or frequency
- Overall radiated sound power per engine order versus speed
- Overall weighted radiated sound power versus speed

Note 2: As a function of the maximum speed value, following different cases must be considered:

Case 1: The maximum speed is lower than the base speed N_{base} (corner point speed of the torque-speed curve) $N_{max} < N_{base}$.

In that case, whatever is the command mode (MTPA or MTPV), the behavior of the machine will be studied over the speed range $[0, N_{max}]$.

That allows the user to precisely choose the range of speed to be considered for computing and displaying the torque-speed curve and especially maps like efficiency map.

Case 2: The maximum speed is greater than the base speed (corner point speed) $N_{\max} > N_{\text{base}}$.

The relevance of the maximum speed given by the user is analyzed to evaluate if it is reachable by the machine.

If the user maximum speed is unreachable by the machine, the correction of this value is automatically performed.

The resulting new maximum speed is linked to a limit torque. This limit torque is obtained by applying a reduction coefficient to the base point torque.

Note 3: For additional information on this topic, please see the section dedicated to command modes (Performance mapping – efficiency map)

3.3.3 Advanced input

3.3.3.1 Maximum engine order / No. Points per electrical period

Two kinds of inputs are possible:

Define the **Max. engine order** (*Maximum engine order*) or the **No. points / elec. Period** (*Number of points per electric period*).

When decomposing the Maxwell pressure, applied on the stator, to get its harmonic contributions, the “**max. engine order**” (*Maximum engine order*) is required to compute its decomposition in function of the time.

At a practical point of view, when the maximum engine order is equal to N, that leads to consider $2 \times N$ computation points over a complete rotation period of the rotor.

Note 1: The input “Engine order” is in connection with the frequency of vibration we want to be able to compute.

“Engine order” refers to a mechanical revolution period of the motor when frequency refers to the considered electrical period.

Obviously, both are linked with speed.

For instance, radiated sound power can be displayed either by considering frequency or engine order.

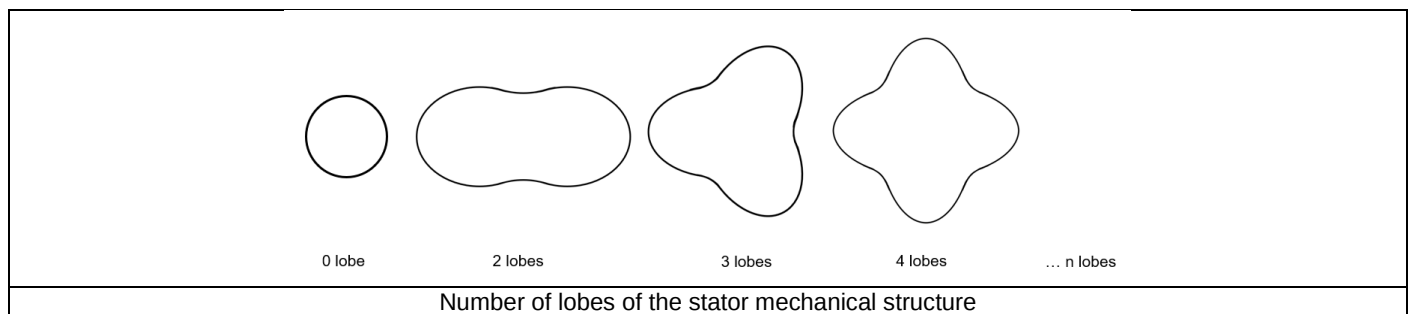
Note 2: There are two possibilities, either set an engine order or a number of points per electrical period.

For transient computations the minimum needed number of points per electrical period is 40.

So, when the engine order is not high enough to reach this constraint It is automatically modified to get 40 computation points per electrical period.

3.3.3.2 Maximum mode / spatial order

The “**max. mode / spatial order**” (*Maximum mode / spatial order*) input allows the user to define the number of modes to be considered for the acoustic structural analysis. If the user selects 25, it means that the highest number of lobes in the stator deformation will be equal to 25 lobes. All deformations corresponding to more than 25 lobes will be dismissed.



3.3.3.3 Number of computations per tooth pitch

The “**No. comp./tooth pitch**” (*Number of computations per tooth pitch*) allows to choose the number of Maxwell pressure evaluations per tooth. The more points selected, the more accurate the Maxwell pressure harmonic decomposition will be.

3.3.3.4 Number of points for speed interpolation

The “**No. points for speed interpolation**” (*Number of points for speed interpolation*) allows to manage the computation of the radiated sound power per engine order. It allows to manage the data interpolation between the speeds indicated as inputs. Thanks to that, the curves “Radiated sound power per engine order versus speed” and “weighted radiated sound power versus speed” can have a better discretization which leads to a better displaying of the local peaks.

The default value is equal to 100. The range of possible values is [50,300]

3.3.3.5 Number of computations for Jd,Jq

The “**No. comp. for Jd,Jq**” (*Number of computations for D-axis and Q-axis currents*) has the same definition than in the test “Performance mapping – Sine wave – Motor - Efficiency maps.

First, it is needed to compute the D-axis and Q-axis flux linkage in the $J_d - J_q$ plane.

To get maps in the $J_d - J_q$ plane, a grid is defined. The number of computation points along the d-axis and q-axis can be defined with the user input « **No. Comp. for Jd, Jq** » (*Number of computations for D-axis and Q-axis currents*).

The default value is equal to 5. This default value provides a good compromise between accuracy and computation time. The minimum allowed value is 5.

3.3.3.6 Number of computations for speed

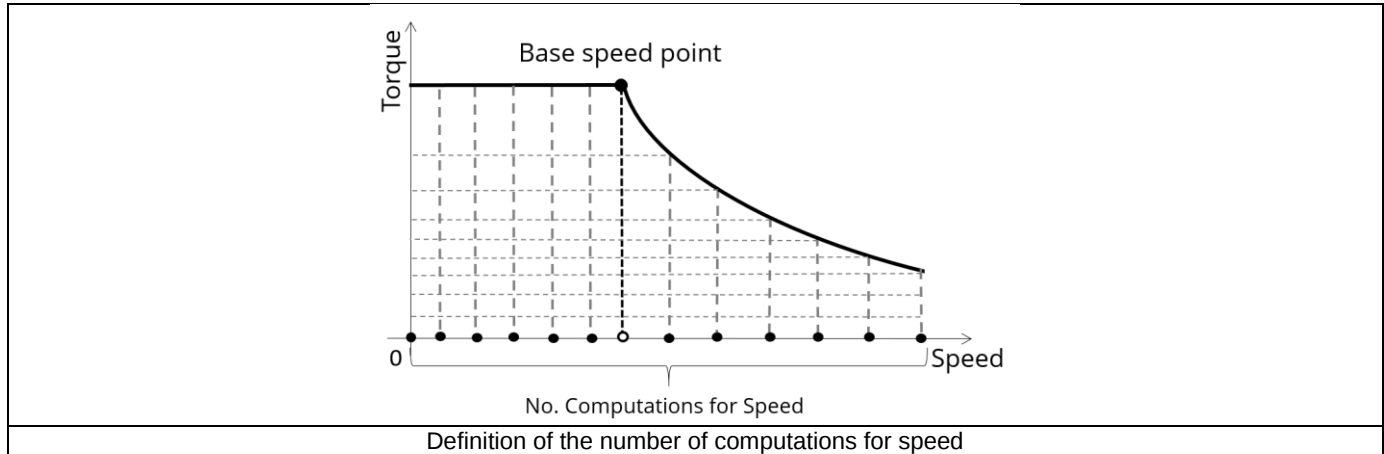
The “**No. comp. for speed**” (*Number of computations for speed*) has the same definition than in the test “Performance mapping – Sine wave – Motor - Efficiency maps.

The “**No. comp. for speed**” (*Number of computations for speed*) corresponds to the number of points to be considered in the speed range from 0 to the maximum speed.

Half of these points are distributed from 0 to the base speed. The remaining points are distributed from the base speed to the maximum speed.

In both cases, base speed is considered as an additional point.

Note: If the user input parameter “**No. comp. for speed**” is an odd number, one discretization point is automatically removed.



The default value is equal to 15, the minimum allowed value is 5. The maximum recommended value is 40.

Note: Increasing the number of computations can improve the convergence of the optimization used to define the torque-speed curve and the efficiency map. However, that also means longer computation time.

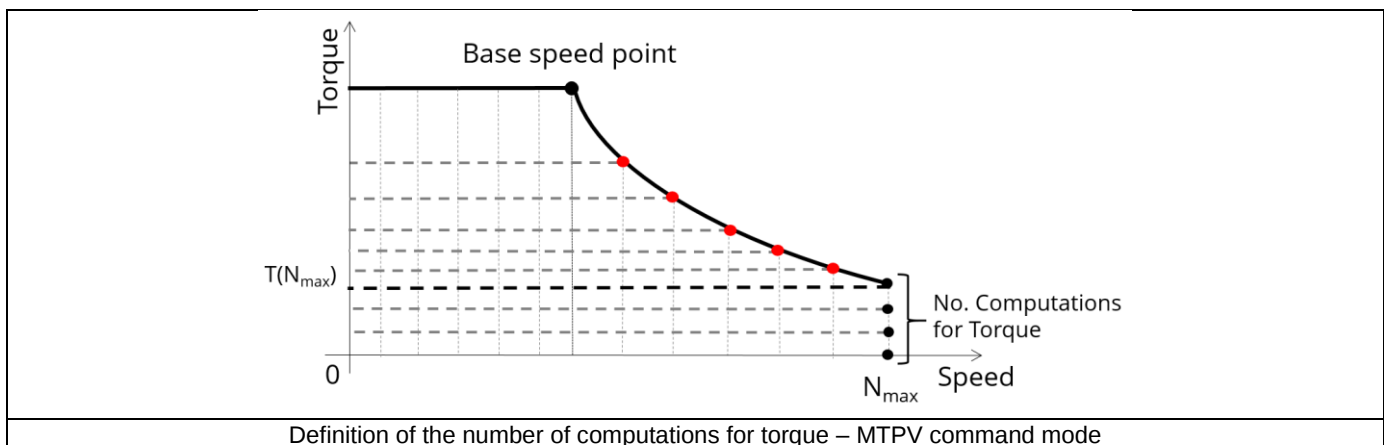
3.3.3.7 Number of computations for torque

The “**No. comp. for torque**” (*Number of computations for torque*) has the same definition than in the test “Performance mapping – Sine wave – Motor - Efficiency maps.

For the speed range $[N_{\text{base}}; N_{\text{max}}]$, the number of computations for torque is imposed by the number of computations for speed in the speed range $[N_{\text{base}}; N_{\text{max}}]$ (Red points in the image shown below).

The advanced user input parameter “**No. comp. for torque**” allows to finalize the grid within the torque range $[0, T(N_{\text{max}})]$ at the maximum speed (Black points in the image shown below).

The default value is equal to 7. The minimum allowed value is 3. The maximum recommended value is 20.



3.3.3.8 Rotor initial position

By default, the “**Rotor initial position**” is set to “**Auto**”.

When the “**Rotor initial position mode**” is set to “**Auto**”, the initial position of the rotor is automatically defined by an internal process of FluxMotor®.

The resulting relative angular position corresponds to the alignment between the axis of the stator phase 1 (reference phase) and the direct axis of the rotor north pole.

When the “**Rotor initial position**” is set to “User input” (i.e. toggle button on the right), the initial position of the rotor considered for computation must be set by the user in the field « **Rotor initial position** ». The default value is equal to 0. The range of possible values is [-360, 360].

For more details, please refer to the document: MotorFactory_2022.1_SMPM_IOR_3PH_Test_Introduction – section “Rotor and stator relative position”.

3.3.3.9 Mesh order

To get the results, the original computation is performed using a Finite Element Modeling (inside Flux® software).

Two levels of meshing can be considered for this finite element calculation: first order and second order.

This parameter influences the accuracy of results and the computation time.

By default, second order mesh is used.

3.3.3.10 Airgap mesh coefficient

The advanced user input “**Airgap mesh coefficient**” is a coefficient which adjusts the size of mesh elements inside the airgap. When the value of “**Airgap mesh coefficient**” decreases, the mesh elements get smaller, leading to a higher mesh density inside the airgap, increasing the computation accuracy.

The imposed Mesh Point (size of mesh elements touching points of the geometry), inside the Flux® software, is described as:

$$\text{MeshPoint} = (\text{airgap}) \times (\text{airgap mesh coefficient})$$

Airgap mesh coefficient is set to 1.5 by default.

The variation range of values for this parameter is [0.05; 2].

0.05 giving a very high mesh density and 2 giving a very coarse mesh density.

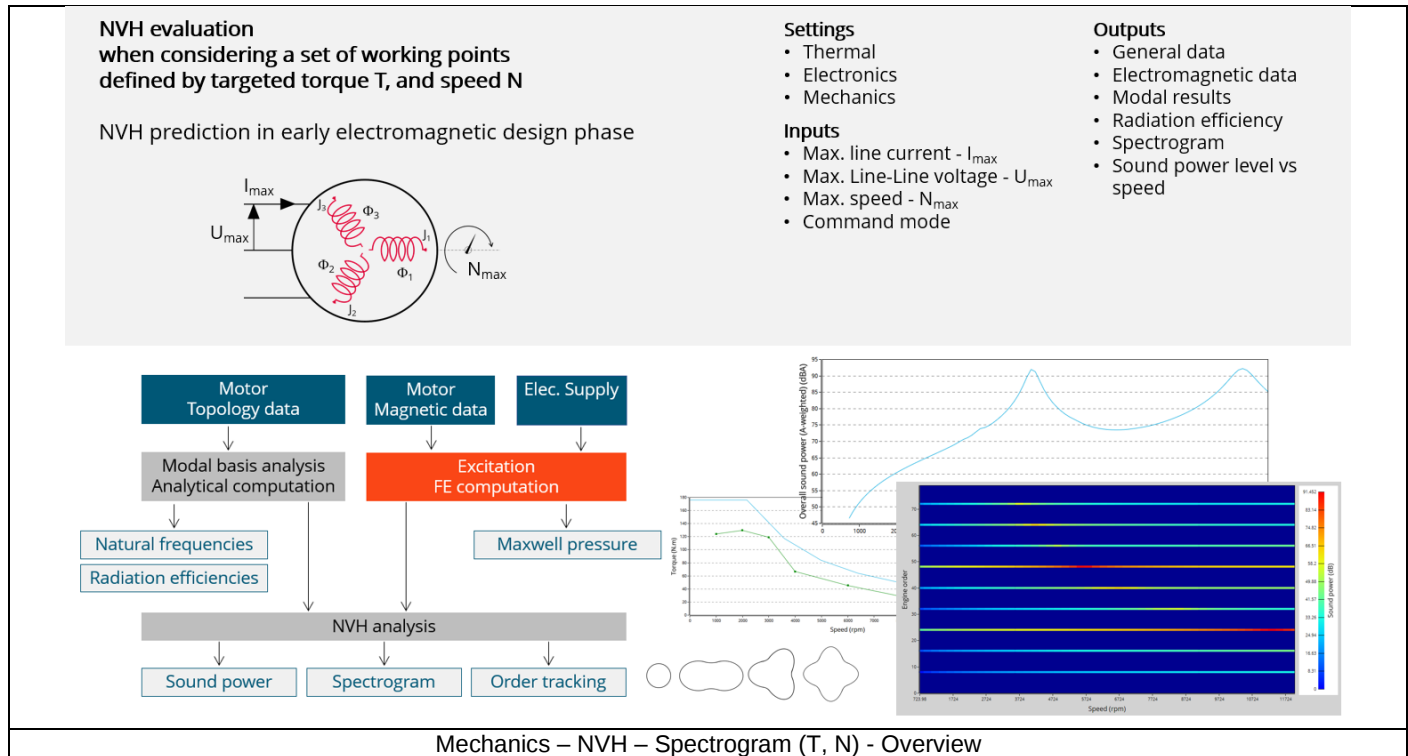
Caution:

Be aware, a very high mesh density does not always mean a better result quality. However, this always leads to a huge number of nodes in the corresponding finite element model. So, it means a need of huge numerical memory and increases the computation time considerably.

3.4 Main principles of computation

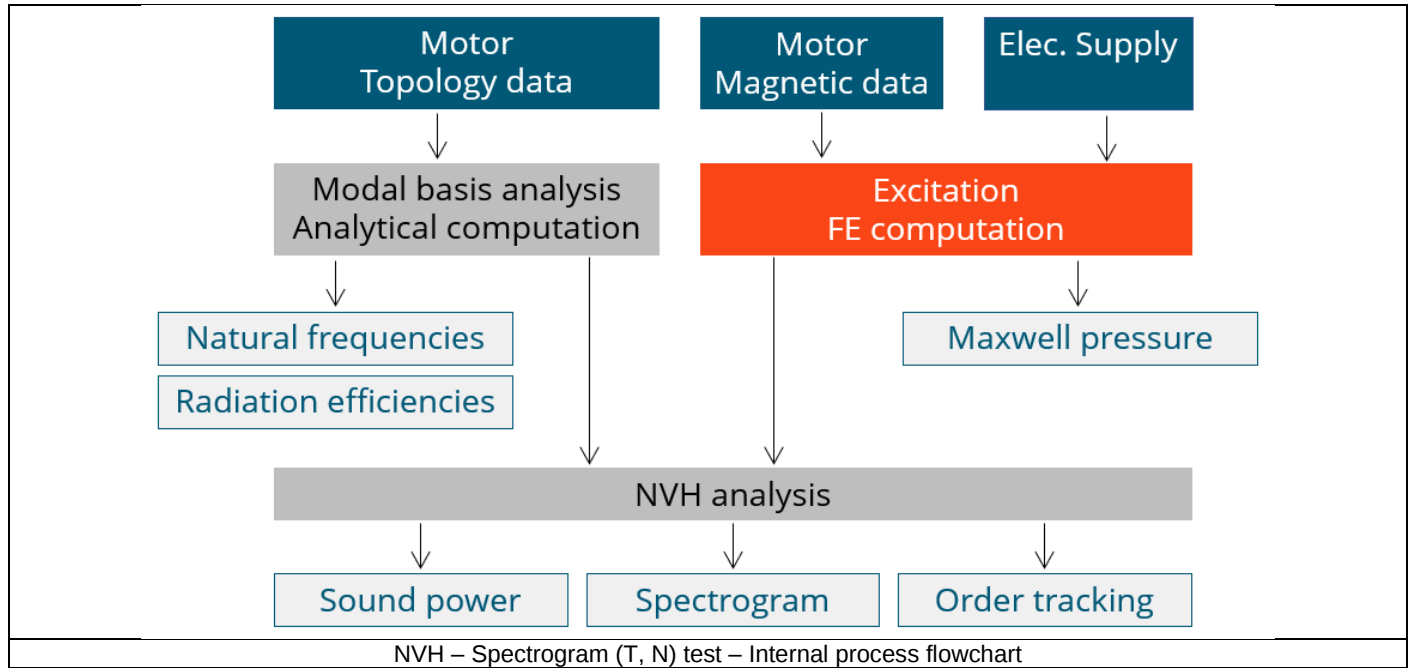
3.4.1 Introduction

Here are illustrations which give an overview of the test NVH – Spectrogram (T, N):



3.4.2 Flow chart

Here is the flowchart illustrating the internal process of the thermal test.



The inputs of the internal process are the parameters of:

- Motor topology data
- Motor magnetic data
- Electrical supply

When the user chooses the torque-speed envelope mode, the software computes the envelope similarly to the performance mapping – efficiency map test. Then, seven points are selected on the envelope over which the previous test is applied.

When the user chooses the user working point list mode, the software computes current and control angle maps similarly to the performance mapping – efficiency map test and interpolates the torque-speed data to create a current/control-angle/speed working point list. The previous test is then used once again.

3.5 Test results

3.5.1 Introduction

Before analyzing the test results, take care of advices for use reminded in the section 3.6 (Limitation of computations - Advice for use).

Electromagnetic results are computed and displayed to illustrate and to characterize the considered working points at an electromagnetic point of view.

Data like Mechanical torque, Power, Line current and control angle are displayed versus the speed.

Accordingly, the user inputs a list of several working points which is considered to compute the spectrogram. Each working point is computed by means of Finite Element computations with electromagnetic transient application.

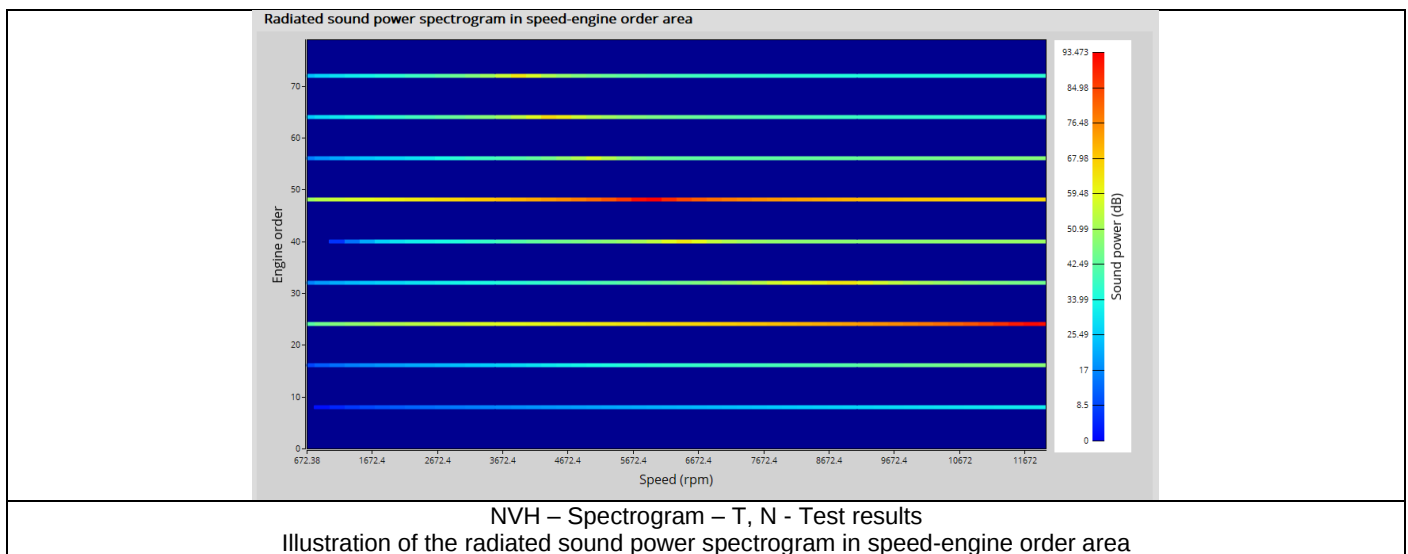
Note: For the displaying of the mechanical torque – speed curve, three curves are always displayed:

- The torque-speed envelope,
- The user's serial of working points computed by means of Park model and by using Finite Element modelling and simulation with magnetostatics application.
- The user's serial of working points computed by means Finite Element modelling and simulation with transient application.

The difference in results which could appear between these two last curves illustrates the impact of the computation method of the two last approaches. In particular, the way to consider or not losses like Joule losses in magnet, iron losses, and the process to compute them.

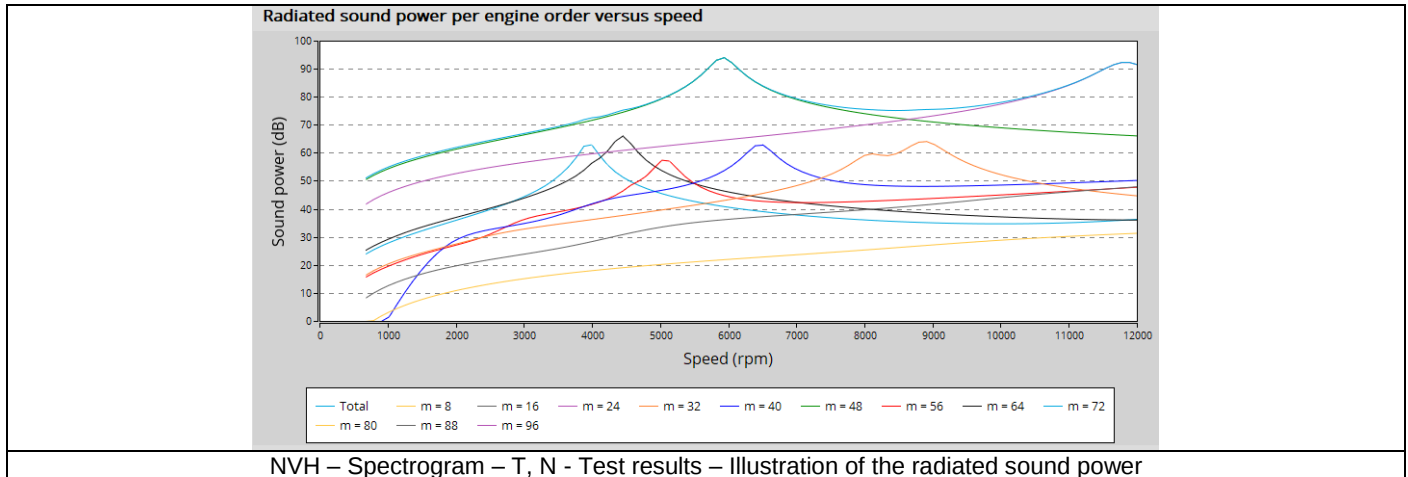
3.5.2 List of NVH results

- 1) Modal analysis – Natural frequency versus number of lobes: This graph displays the natural frequency corresponding to the n-lobe deformation.
- 2) Radiation efficiency – Acoustic radiation factor versus frequency: This graph illustrates the capacity of the stator to convert vibration into noise.
- 3) Radiated sound power spectrogram in speed-engine order area: This spectrogram displays the radiated sound power in an engine order/speed area. Only the relevant engine orders are displayed (the multiples of the number of poles of the engine).

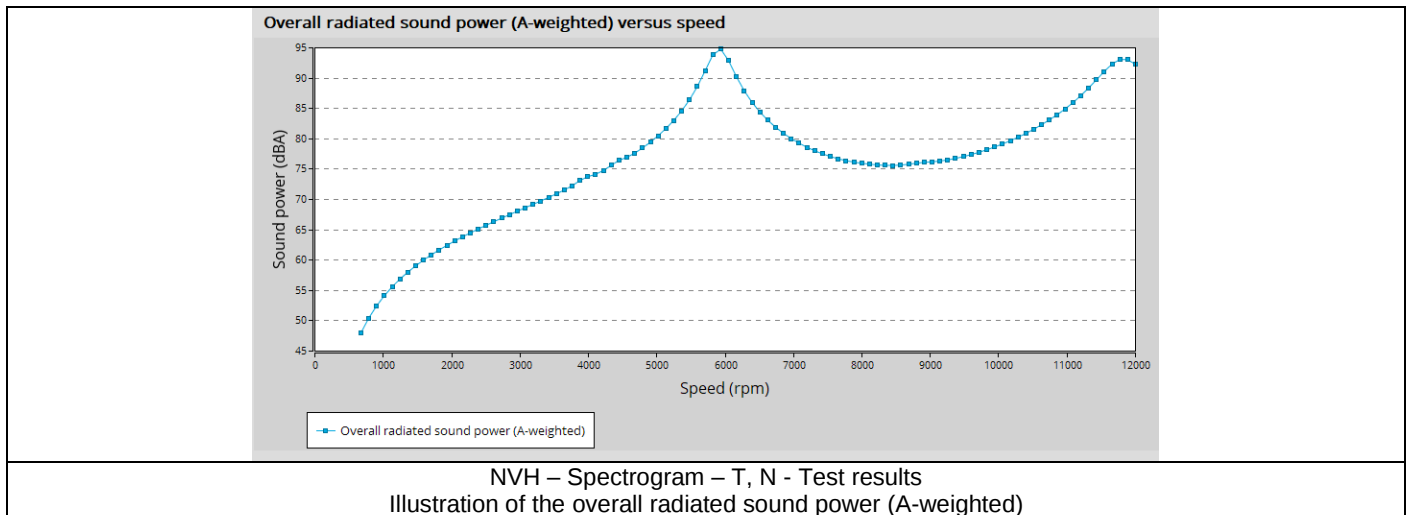


- 4) Radiated sound power spectrogram in speed frequency area: This spectrogram displays the radiated sound power in a frequency/speed area. Only the relevant engine orders are displayed (the multiples of the number of poles of the engine).

- 5) Radiated sound power per engine order versus speed: This graph displays the radiated sound power per engine order as well as the total radiated sound power.



- 6) Overall weighted radiated sound power versus speed: This graph displays the radiated sound power weighted for the human ear (A-weighted).



3.6 Limitation of computations - Advice for use

The modal analysis as well as the radiation efficiency are based on an analytical computation where the stator of the machine is considered as a vibrating cylinder.

The considered cylinder behavior is weighted by the additional masses like the fins or the winding and the subtractive masses like the slots and the cooling circuit holes.

This assumption allows to get fast evaluation of the behavior of machine in connection to NVH. In no way this can replace a mechanical Finite Element modeling and simulation.

Among possible reasons for deviations of results can be the following ones:

- The limits of the analytical model are reached or overpassed
- Unusual topology and/or dimensions of the teeth/slots
- Complexity of the stator-frame structure when it is composed with several components for instance
- The ratio between the total length of the frame L_{frame} and the stack length of the machine L_{stk} in any case, this ratio must be lower than 1.5:

$$\frac{L_{Frame}}{L_{stk}} \leq 1.5$$