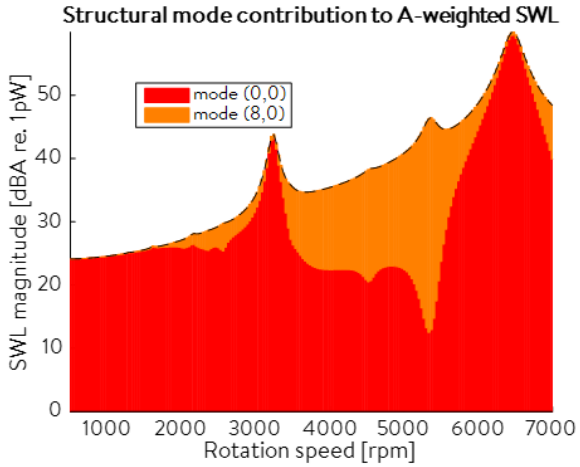
Vibro-acoustic design of electrical machines using MANATEE software
Interior Permanent Magnet Synchronous Machine tutorial

The first project consists in running the IPMSM in open circuit, without faults:

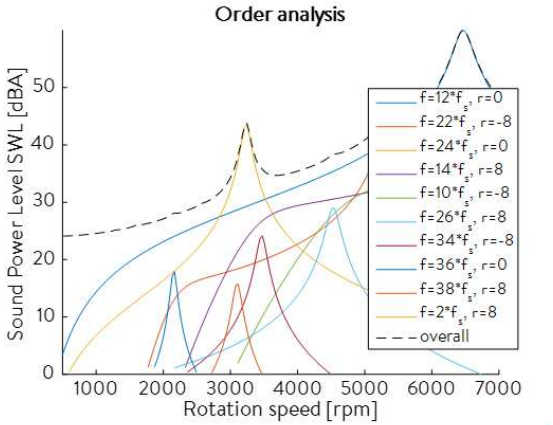
run_MANATEE('tuto_BPMSM_001')

One can see the structural mode contribution to overall noise:



The wavenumber 0 (pulsating radial excitation) is very present, which is common in electric motor for automotive electrical powertrain.

The frequency of the excitations can be found using MANATEE order tracking analysis:



How can we further explain the origin of pulsating (r=0) forces at 12f/24f ? Using MANATEE built in command:

```
>> find_harmonic_PMSM_open_circuit(0,12,4,48,1)
u min for l*2p+0*Zs=8
v min for l*2p+0*Zs=8
Force wave in stator frame {f=12fs, r=0} is created by the product of flux waves B1=P1.F1 and B2=P2.F2 such as:
B1={0,0}.{11fs,11p} and B2={0,-Zs}.{fs,p}
B1={0,0}.{fs,p} and B2={0,-Zs}.{13fs,13p}
B1={0,0}.{9fs,9p} and B2={0,-Zs}.{3fs,3p}
B1={0,0}.{7fs,7p} and B2={0,-Zs}.{5fs,5p}
B1={0,0}.{3fs,3p} and B2={0,-Zs}.{15fs,15p}
B1={0,0}.{5fs,5p} and B2={0,-Zs}.{17fs,17p}
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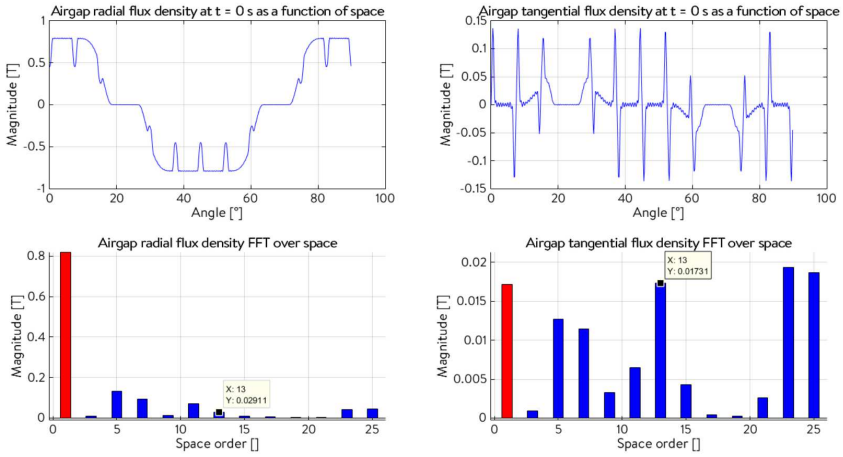
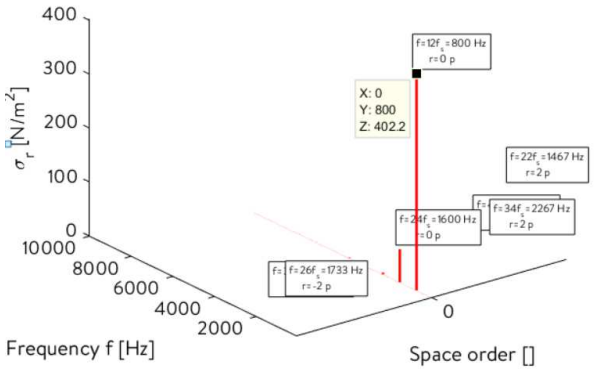
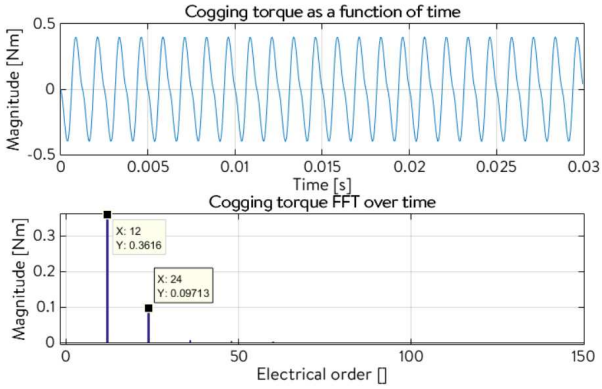
The 13p & 11p rotor mmf space harmonics and stator slotting are involved in 12f excitation in open circuit:



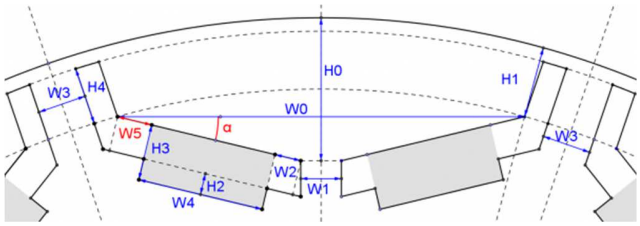
The associated radial force is at 400 N/m2



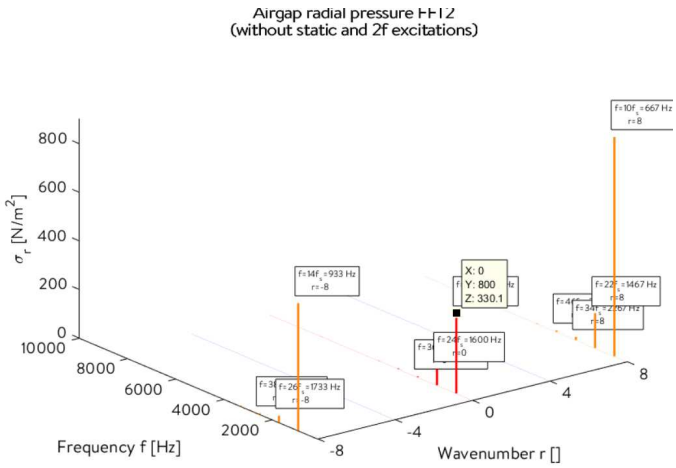
This radial pulsating force is the same giving cogging torque:



Can we change the magnitude by playing on magnet geometry ?

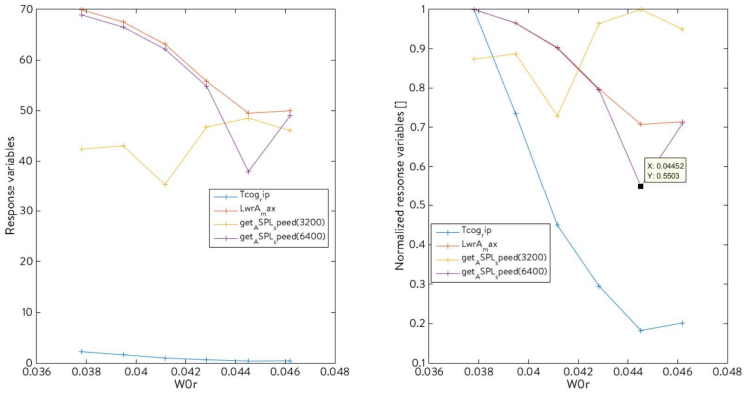


Let's quickly change H0 by +10%



Now the amplitude of the radial force at 12f has reduced so this parameter has an effect on both radial & tangential pulsating forces. We can therefore run a sensitivity study on the magnet width on noise & cogging torque:

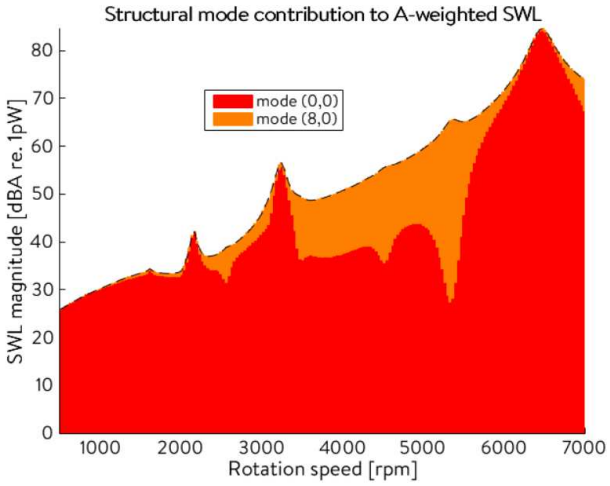
run_MANATEE('tuto_BPMSM_015')



There is a correlation between noise (driven by radial ripple) & cogging torque (tangential ripple) in open circuit case which is normal for IPMSM, but this correlation does not hold at full load.

Let's include the load by activating armature field in full load case following id/iq curve:

run_MANATEE('tuto_BPMSM_13')

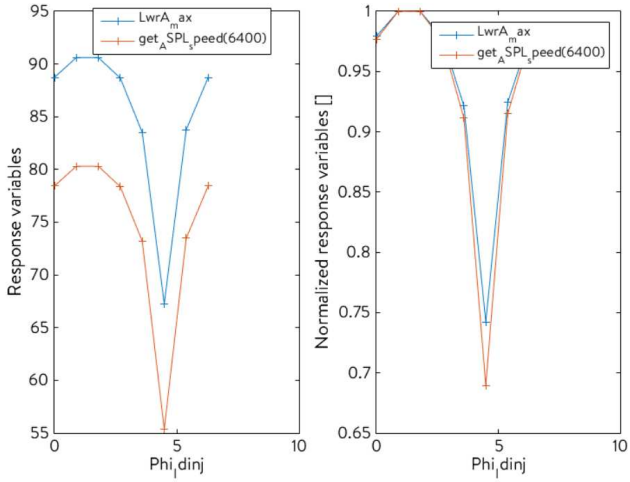


Noise level is increased but armature field does not bring new excitation frequencies. How armature field is creating 12f and 24f r=0 forces ?

```
>> find_harmonic_PMSM_partial_load(0,12,4,48,1)
u min for 1*2p+0*Zs=8
v min for 1*2p+0*Zs=8
u min for 1*2p+0*Zs=8
v min for 1*2p+0*Zs=8
Force wave in stator frame {f=12fs, r=0} is created by the product of flux waves B1=P1.F1 and B2=P2.F2 such as:
B1={0,0}.{11fs,11p} and B2={0,0}.{fs,-11p}
B1={0,0}.{13fs,13p} and B2={0,0}.{fs,13p}
B1={0,0}.{11fs,11p} and B2={0,-Zs}.{fs,p}
B1={0,-Zs}.{13fs,13p} and B2={0,0}.{fs,p}
B1={0,Zs}.{11fs,11p} and B2={0,0}.{fs,-23p}
B1={0,-2Zs}.{13fs,13p} and B2={0,0}.{fs,-11p}
B1={0,0}.{11fs,11p} and B2={0,-2Zs}.{fs,13p}
B1={0,0}.{13fs,13p} and B2={0,-Zs}.{fs,25p}
B1={0,0}.{11fs,11p} and B2={0,-3Zs}.{fs,25p}
```

One can see that 13p=Zs+p and 11p=Zs-p stator mmf stepped harmonics create pulsating forces but they cannot be cancelled with coil pitch optimization.

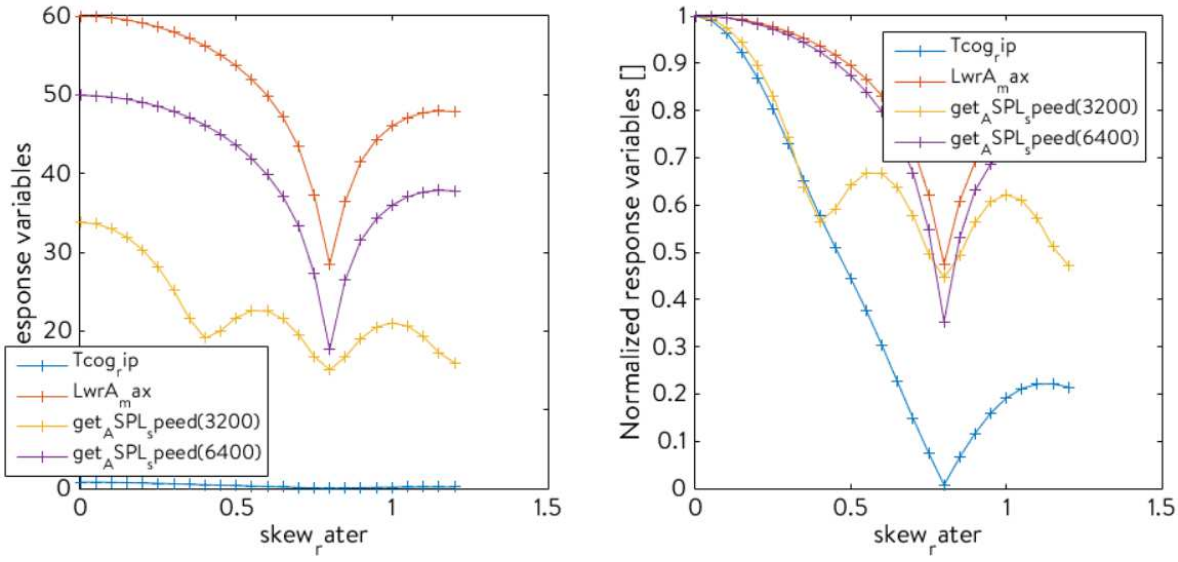
However we can try reducing noise by harmonic current injection, for instance at 12f in DQ frame along d-axis with 0.5A magnitude (to be compared to 250A fundamental). Running a sensitivity study on harmonic current angle, one can find:



The noise due to 12f and the overall noise at variable speed is efficiently reduced. A more accurate sensitivity should be run on both magnitude and phase.

Alternative techniques include notching of the rotor or skewing the rotor. In open circuit to study the effect of the step skew rotor angle on noise and cogging:

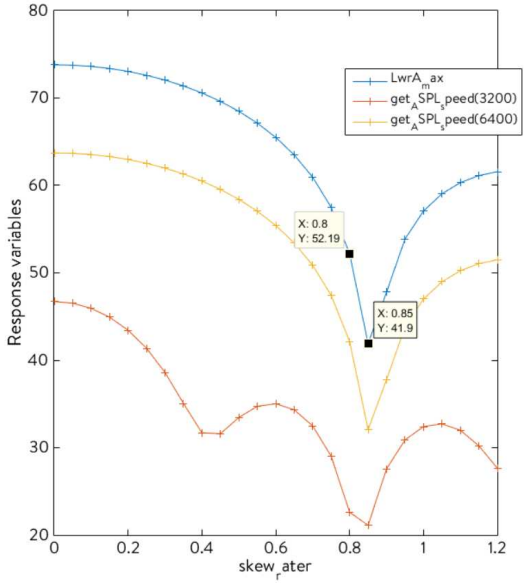
run_MANATEE('tuto_BPMSM_05')



Optimal skew is (4/5) of one stator slot pitch as expected by theory.

At partial load following specific Id/Iq curve:

run_MANATEE('tuto_BPMSM_07')



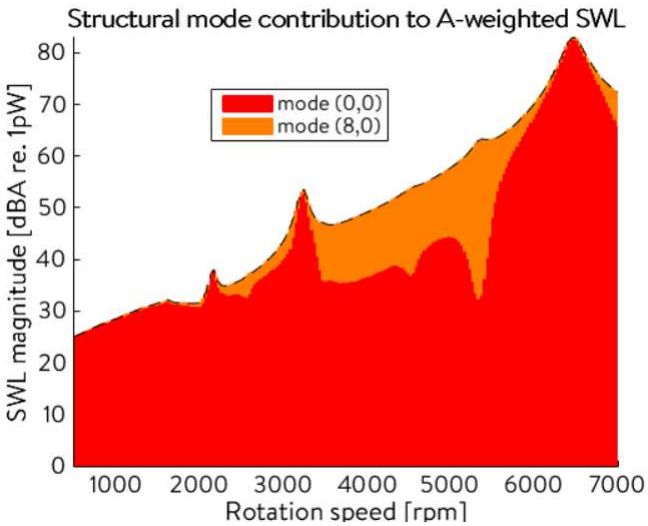
The optimal skew is larger than 4/5 stator slot pitch due to armature field effect.

What is more interesting is too find the best compromise between skew, torque ripple, noise and torque reduction; This study can be automatically carried in the skew optimizer environment of MANATEE which is based on the calculation of flux tables

run_MANATEE('tuto_BPMSM_19')

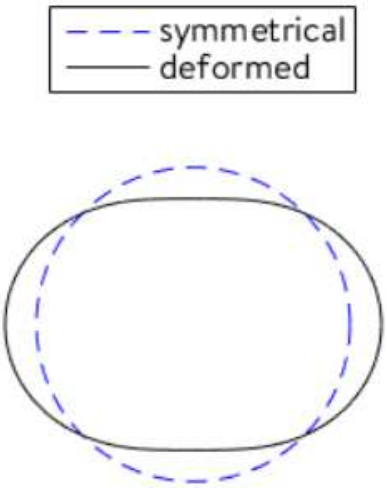
Let's now investigate fault simulations (demagnetization, pole misplacement etc) : for that we need to switch to permeance mmf model instead of subdomain model. Let's check that PMMF model gives similar results as subdomain model:

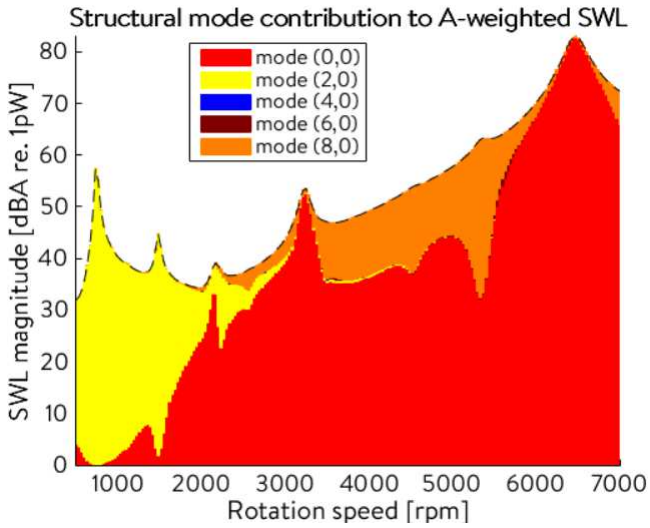
run_MANATEE('tuto_BPMSM_04')



One can see that results are very similar to SDM model. Then uneven airgap or eccentricities can be be modelled. Case of an oval stator in open circuit:

run_MANATEE('tuto_BPMSM_18')





The oval stator modulates pulsating forces and introduces new resonances.

All these examples can be extended to quickly analyze the response of a full CAD model under Optistruct or Ansys.