



# Simulación y Optimización de un Altavoz Electrodinámico Diseñado para Dispositivos Inteligentes

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30 de Julio de 2020



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DE MÁLAGA



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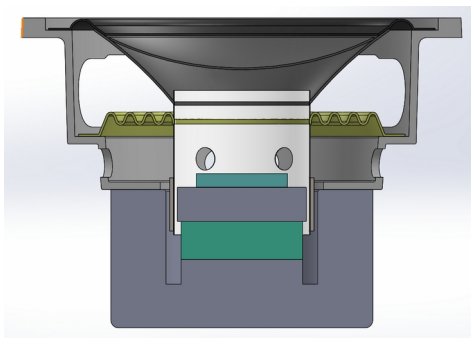
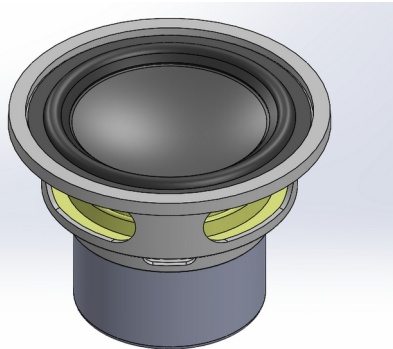


## Contenido

- Descripción general
- Fundamento teórico
- Geometría
- Materiales
- Ecuaciones e Interfaces Físicas
- Condiciones de Contorno
- Malla
- Estudios
- Resultados Obtenidos
- Conclusiones
- Referencias

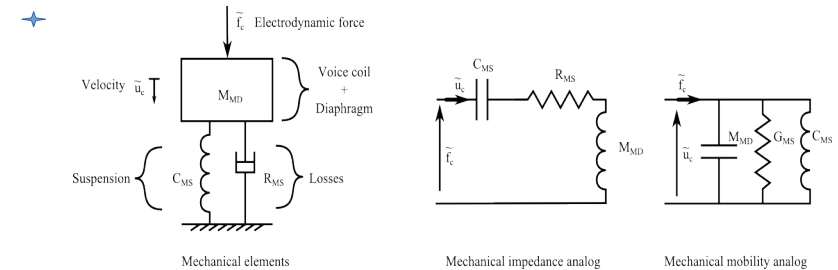
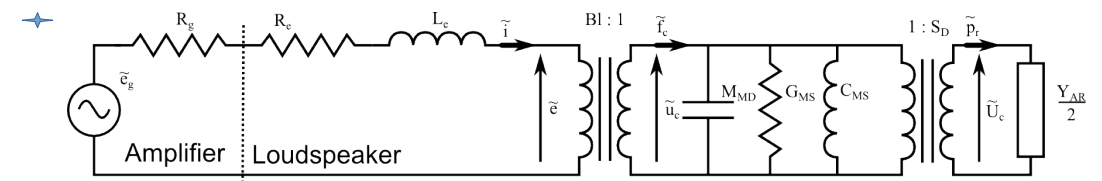
# Descripción general

- Altavoz electrodinámico 2 pulgadas
- Transformación electro-mecano-acústica
- Circuito magnético (conf. iniciales + optima)
- Anillo de cortocircuito
- No-linealidades:  $Bl(x)$ ;  $kms(x)$  [3]
- Respuesta en frecuencia acústica



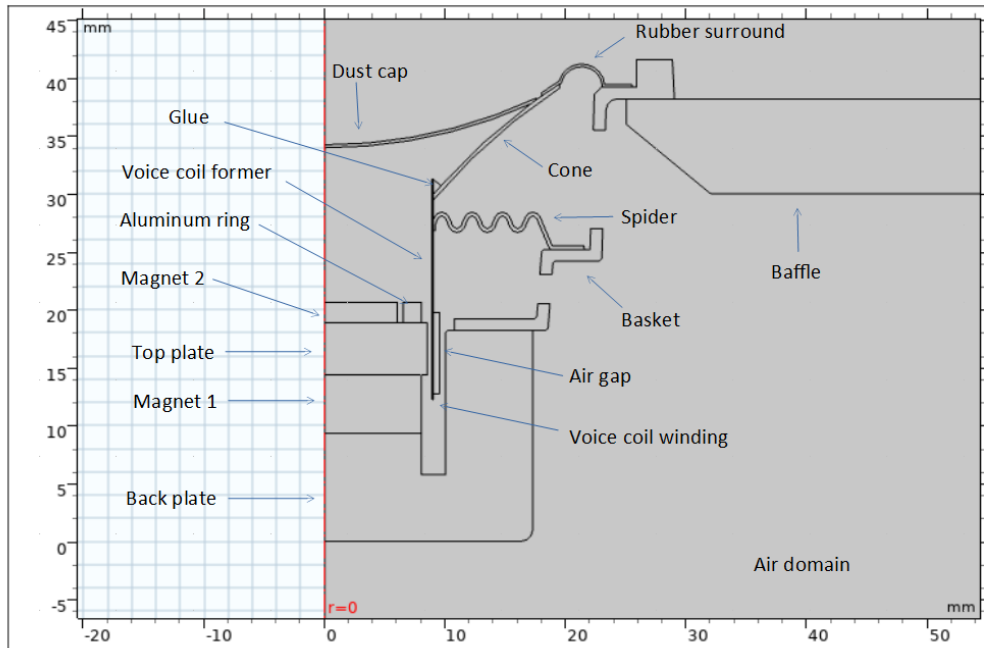
# Fundamento Teórico

- Funcionamiento básico [1]
- Sistema masa-resorte amortiguado
- Circuito equivalente simplificado

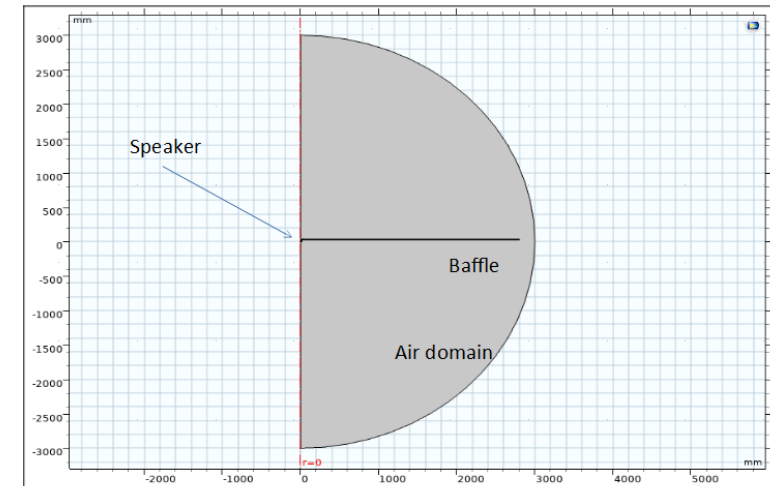


➤ dibujos[2]

# Geometría y Materiales

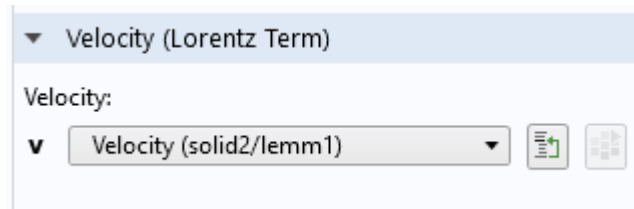
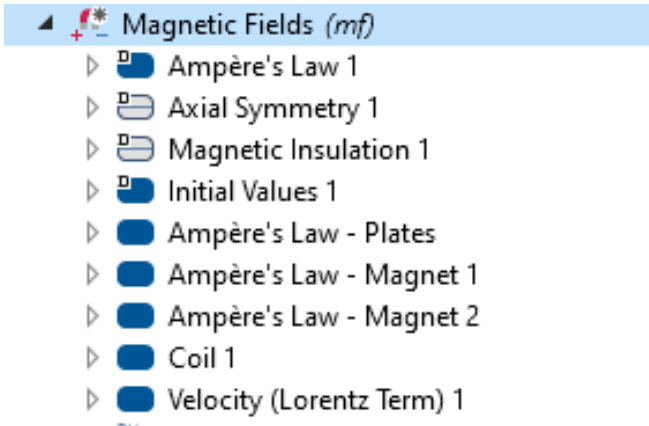


- Materials
  - Aluminum - Basket (*mat3*)
  - Soft Iron (With Losses) - Plates (*mat5*)
  - CCAW 15% (*mat6*)
  - Air (*mat7*)
  - Spider (*mat8*)
  - Rubber surround (*mat12*)
  - Glue (*mat9*)
  - Cone - Paper (*mat10*)
  - Voice coil former (*mat11*)
  - Wood (pine) (*mat13*)
  - Dust cup (*mat14*)
  - N38H (Sintered NdFeB) (*mat15*)
  - Aluminum - Ring (*mat16*)



Materiales base de datos COMSOL y parametros materiales custom[4]

# Ecuaciones e Interfaces Físicas – Magnetic fields



**Estudio Estacionario:**

$$J = \sigma (E + v \times B)$$

**Estudio en Frecuencia:**

$$J = \sigma (E + v \times B) + j \omega D$$

**Estudio Estacionario:**

$$\nabla \times H = J$$

$$B = \nabla \times A$$

$$J = \sigma E$$

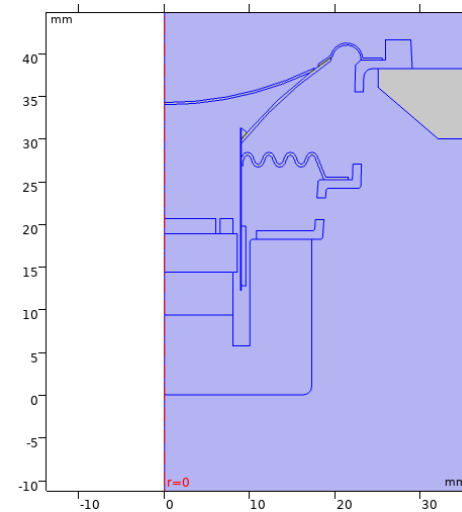
**Estudio en Frecuencia:**

$$\nabla \times H = J$$

$$B = \nabla \times A$$

$$J = \sigma E + j \omega D$$

$$E = -j \omega A$$



$$\nabla \times H = J + \frac{\delta D}{\delta t} \quad \text{Maxwell-Ampère's law}$$

$$\nabla \times E = - \left( \frac{\delta B}{\delta t} \right) \quad \text{Faraday's law}$$

$$\nabla \cdot D = \rho \quad \text{Gauss's law – Electric form}$$

$$\nabla \cdot B = 0 \quad \text{Gauss's law – Magnetic form}$$

- E – Intensidad del campo eléctrico
- D – Desplazamiento eléctrico
- H – Intensidad del campo magnético
- B – Densidad del flujo magnético
- J – Densidad de corriente
- $\rho$  – Densidad de carga eléctrica
- $\mu$  – Permeabilidad magnética
- $\epsilon$  – Permitividad eléctrica
- $\sigma$  – conductividad eléctrica
- A - Vector potencial magnético

$$B = \mu_0 \mu_r H = \mu H$$

$$D = \epsilon_0 \epsilon_r E = \epsilon E$$

# Ecuaciones e Interfaces Físicas - Pressure Acoustics, Frequency domain

- ▶ **Pressure Acoustics, Frequency Domain (acpr)**
  - ▶ Pressure Acoustics 1
  - ▶ Axial Symmetry 1
  - ▶ Sound Hard Boundary (Wall) 1
  - ▶ Initial Values 1
  - ▶ Normal Acceleration 1
  - ▶ Pointwise Constraint 1
  - ▶ Sound Hard Boundary - Open baffle
  - ▶ Sound Soft Boundary - External

▼ Normal Acceleration

Type:

Acceleration

Acceleration:

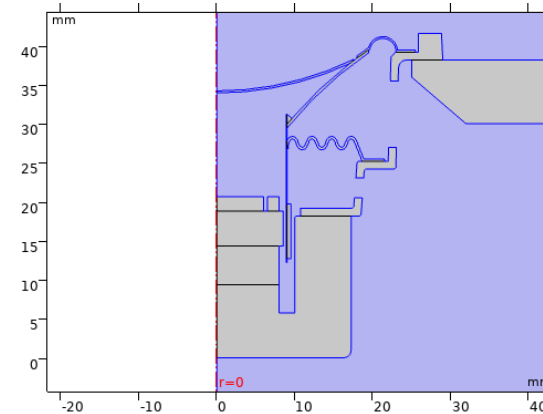
**a0** Acceleration (solid2/lemm1)

**Estudio en Frecuencia:**

$$\nabla \cdot \left( -\left(\frac{1}{\rho_c}\right) (\nabla p_t - q_d) \right) - k_{eq}^2 \frac{p_t}{\rho_c} = Q_m$$

2D – axial simétrico

$$p_t = p + p_b \quad k_{eq}^2 = \left(\frac{\omega}{c_c}\right)^2 - k_m^2$$



- p – Presión total
- ρ – Densidad total
- u – Campo velocidad
- s – Entropía
- M y F – fuentes
- c- Velocidad del sonido

$$\frac{\delta \rho}{\delta t} + \nabla \cdot (\rho u) = M \quad \text{Continuity equation}$$

$$\frac{\delta \rho}{\delta t} + (u \nabla) u = -\left(\frac{1}{\rho}\right) \nabla p + F \quad \text{Euler's equation}$$

$$\frac{\delta s}{\delta t} + \nabla \cdot (su) = 0 \quad \text{Entropy equation}$$

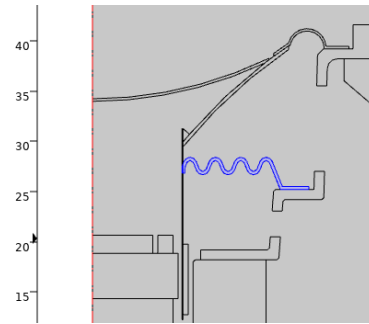
Ec. de ondas de presión en un medio sin pérdidas:

$$\frac{1}{\rho c^2} \frac{\delta^2 p}{\delta t^2} + \nabla \cdot \left( -\left(\frac{1}{\rho}\right) (\nabla p - q_d) \right) = Q_m$$

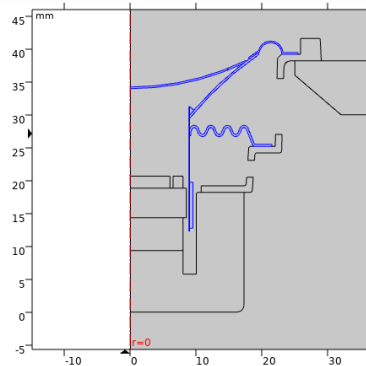
$$\frac{\delta^2 p}{\delta t^2} = c^2 \nabla^2 p \quad \text{Ecuaciones de ondas}$$

# Ecuaciones e Interfaces Físicas – Solid mechanics

- ▶ **Solid Mechanics - Kms Spider (solid)**
  - ▶ Linear Elastic Material 1
  - ▶ Axial Symmetry 1
  - ▶ Free 1
  - ▶ Initial Values 1
  - ▶ Fixed Constraint 1
  - ▶ Prescribed Displacement - Kms evaluation
  - ▶ Boundary Load - Kms evaluation
  - ▶ Equation View



- ▶ **Solid Mechanics 2 (solid2)**
  - ▶ Linear Elastic Material 1
  - ▶ Axial Symmetry 1
  - ▶ Free 1
  - ▶ Initial Values 1
  - ▶ Fixed Constraint 1
  - ▶ Boundary Load - Acoustic coupling
  - ▶ Body Load - Lorentz force
  - ▶ Equation View



$$\rho \frac{\delta^2 u}{\delta t^2} = \nabla_x \sigma + f_v \quad \text{Newton's law}$$

$$\rho_0 \frac{\delta^2 u}{\delta t^2} = \nabla_x (FS) + F_v \quad \text{Consol notation}$$

**Estudio Estacionario:**

$$0 = \nabla_x (FS)^T + F_v; F = I + \nabla u$$

**Estudio en Frecuencia:**

$$-\rho \omega^2 u = \nabla (FS)^T + F_v e^{(j\phi)}; F = I + \nabla u, -ik_z = \lambda$$

$\rho$  – Densidad de masa

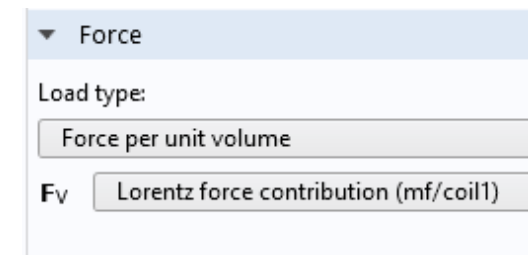
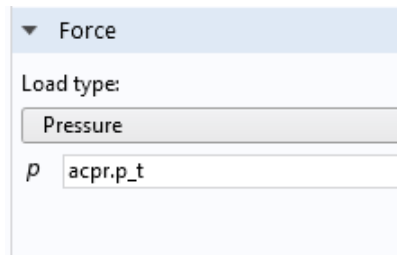
$\sigma$  – Tensor tensiones Cauchy

$f_v$  – Fuerza cuerpo por unidad de volumen deformado

$F$  - Gradiente de deformación

$S$  - Segundo tensor de tensión Piola-Kirchoff

$F_v$  – Fuerza cuerpo respecto a volumen no deformado



# Condiciones de contorno - Magnetic Fields

## Placas de hierro dulce

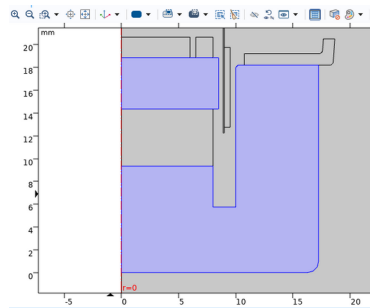
▼ Constitutive Relation B-H

Magnetization model:  
B-H curve

$$\mathbf{B} = f(\|\mathbf{H}\|) \frac{\mathbf{H}}{\|\mathbf{H}\|}$$

Magnetic field norm:  
||H|| From material

Magnetic coenergy density:  
 $W'_m$  From material



## Imán 1 - NdFeB

▼ Constitutive Relation B-H

Magnetization model:  
Remanent flux density

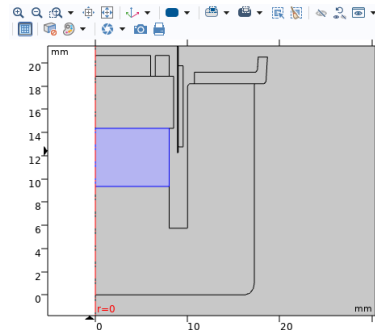
$$\mathbf{B} = \mu_0 \mu_{rec} \mathbf{H} + \mathbf{B}_r, \quad \mathbf{B}_r = \|\mathbf{B}_r\| \frac{\mathbf{e}}{\|\mathbf{e}\|}$$

Recoil permeability:  
 $\mu_{rec}$  From material

Remanent flux density norm:  
||B<sub>r</sub>|| From material

Remanent flux direction:

0	r	
0	phi	1
1	z	



## Imán 2 - NdFeB

▼ Constitutive Relation B-H

Magnetization model:  
Remanent flux density

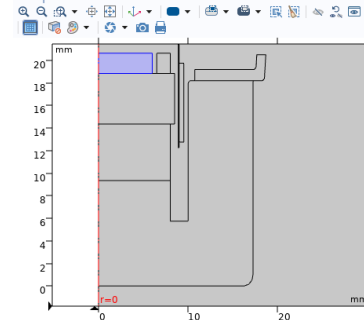
$$\mathbf{B} = \mu_0 \mu_{rec} \mathbf{H} + \mathbf{B}_r, \quad \mathbf{B}_r = \|\mathbf{B}_r\| \frac{\mathbf{e}}{\|\mathbf{e}\|}$$

Recoil permeability:  
 $\mu_{rec}$  From material

Remanent flux density norm:  
||B<sub>r</sub>|| From material

Remanent flux direction:

0	r	
0	phi	1
-1	z	



## Coil

Conductor model:  
Homogenized multi-turn

Coil group

Coil excitation:  
Voltage

Coil voltage:  
 $V_{coil}$  linper(V0) V

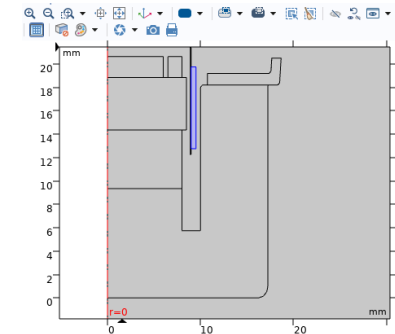
▼ Homogenized Multi-Turn Conductor

Number of turns:  
N N0

Coil wire conductivity:  
 $\sigma_{coil}$  35[S\*m/mm^2] S/m

Coil wire cross-section area:  
American wire gauge (Brown & Sharpe)

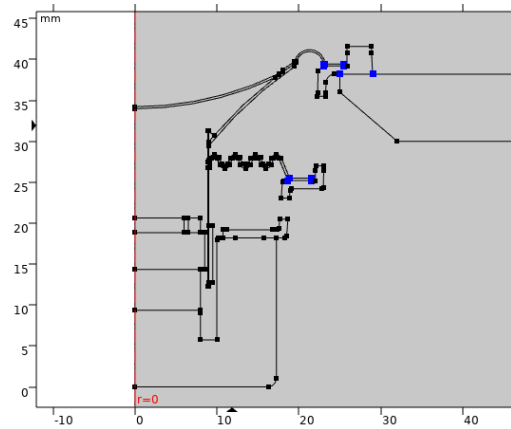
AWG 32



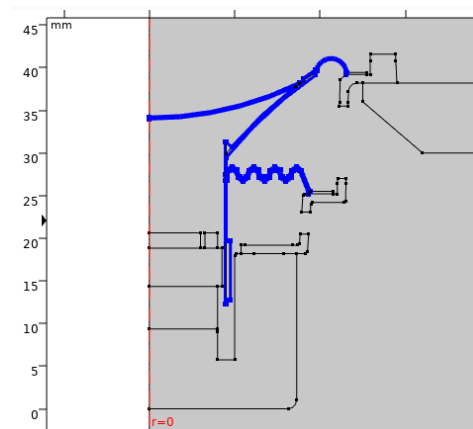


# Condiciones de contorno - Pressure Acoustics, Frequency domain

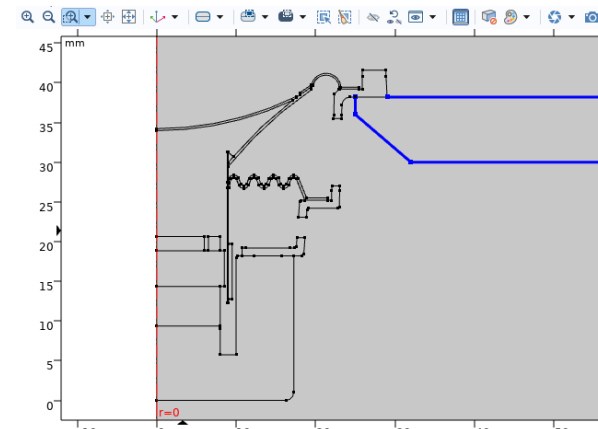
Pointwise constraint



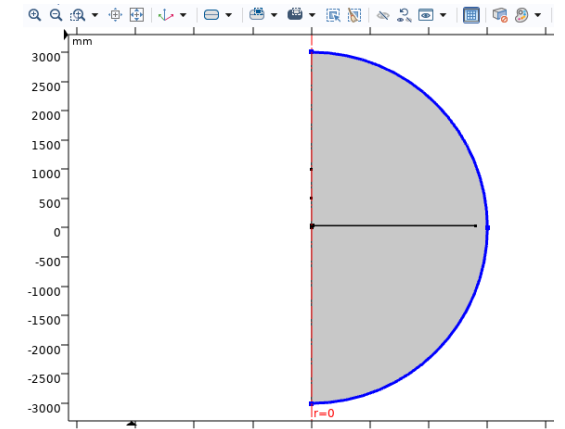
Normal Acceleration



Sound Hard Boundary



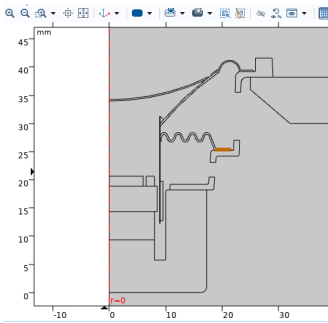
Sound Soft Boundary



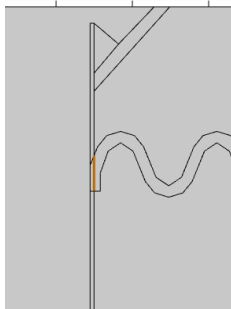
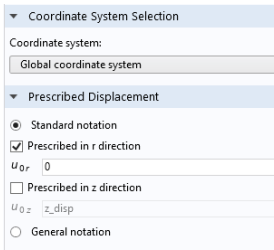
# Condiciones de contorno – Solid mechanics

## Solid Mechanics – kms spider

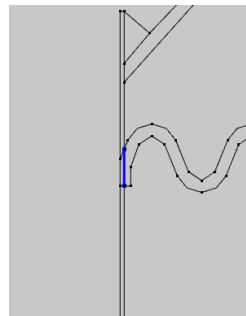
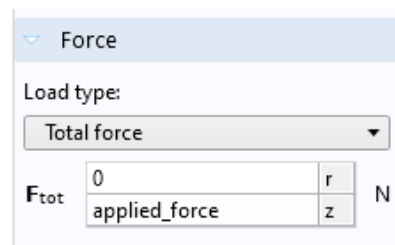
### Fixed constraint



### Prescribed displacement

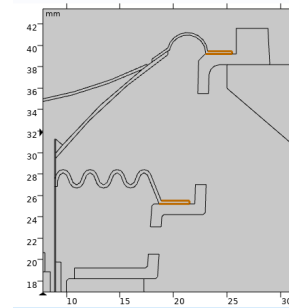


### Boundary Load – kms estimation

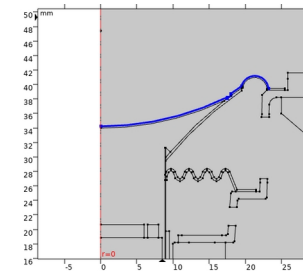
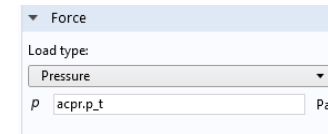


## Solid Mechanics 2

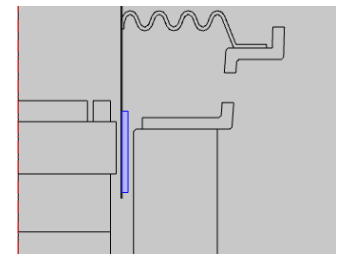
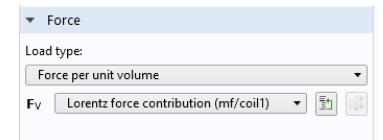
### Fixed constraint



### Boundary law – acoustic coupling

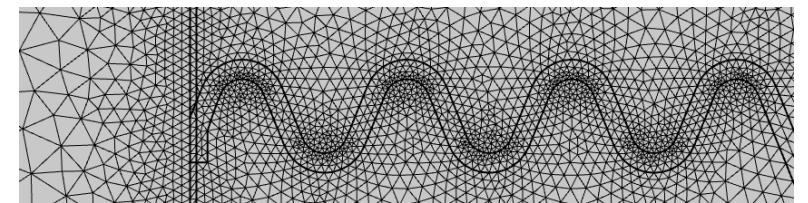
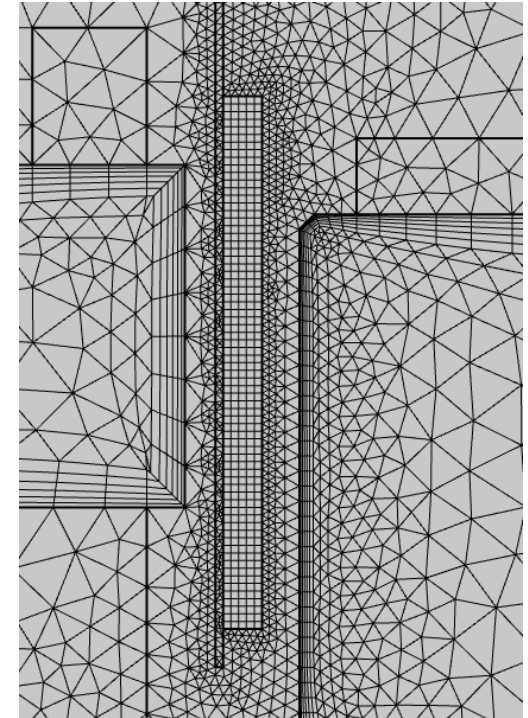
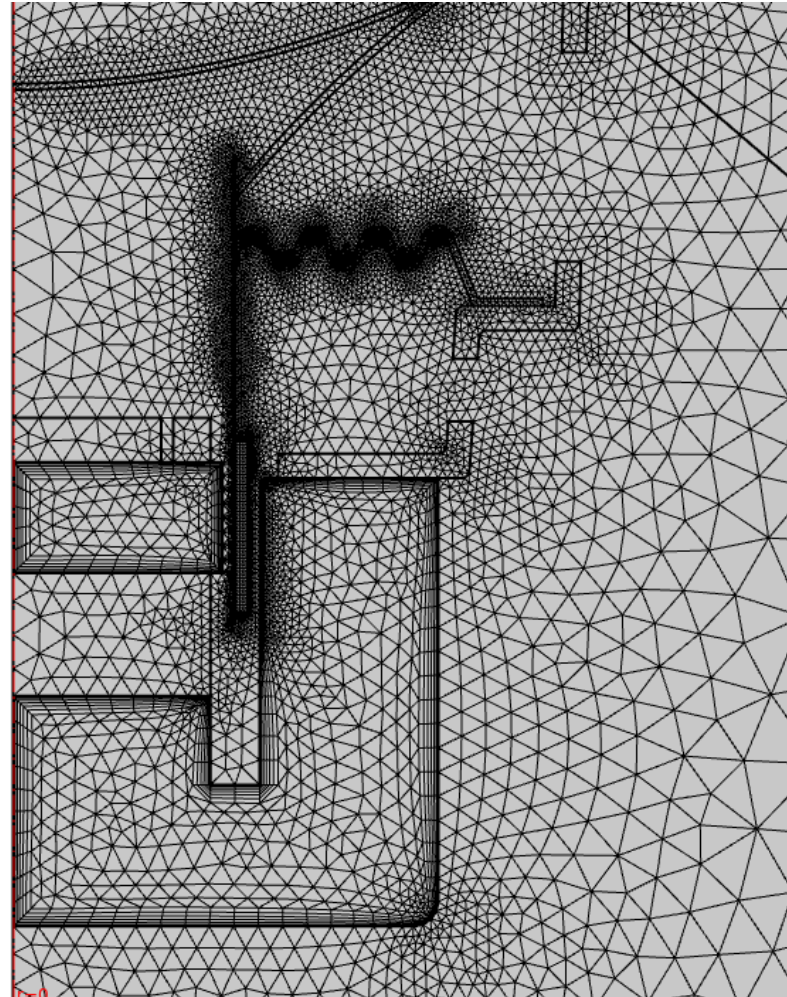


### Body Load – Lorentz force



# Malla

- Mesh 1
  - Size
  - Free Quad 1
    - Size 1
  - Free Triangular 1
    - Size 1
    - Size 2
  - Boundary Layers 1
    - Boundary Layer Properties



# Estudios

- ▶ Study 1 - Magnetic test 1 - Discarted
- ▶ Study 2 - Magnetic test 2 - Discarted
- ▶ Study 3 - Mangetic test 3 - Discarted
- ▶ Study 4 - Magnetic test 4 - Discarted
- ▶ Study 5 - Magnetic Field Stationary - No Alu ring - Blocked\_Coil
- ▶ Study 6 - Static BL - Magnetic Field - Si Alu ring - Blocked coil
- ▶ Study 7 - Static Kms - OK - External force
- ▶ Study 8 - Acoustics - No Alu ring
- ▶ Study 12 - Acoustics - Si Alu ring

- ▶ Study 8 - Acoustics - No Alu ring
  - ▶ Step 1: Stationary
  - ▶ Step 2: Frequency Domain Perturbation

Label: Stationary

Study Settings

Include geometric nonlinearity

Results While Solving

Physics and Variables Selection

Modify model configuration for study step

Physics interface	Solve for	Discretization
Magnetic Fields (mf)	<input checked="" type="checkbox"/>	Physics settings
Pressure Acoustics, Freque...	<input type="checkbox"/>	Physics settings

Frequency Domain Perturbation

Compute Update Solution

Label: Frequency Domain Perturbation

Study Settings

Frequency unit: Hz

Frequencies:  $10^2 \wedge \text{range}(0,1/21,11)$  Hz

Load parameter values:

Reuse solution from previous step: Auto

- ▶ Study 7 - Static Kms - OK - External force
  - ▶ Step 1: Stationary

Study Settings

Include geometric nonlinearity

Results While Solving

Physics and Variables Selection

Modify model configuration for study step

- ▶ Solid Mechanics - Kms Spider (solid), Controls spatial fr
  - ▶ Linear Elastic Material 1
    - Damping
    - Axial Symmetry 1
    - Free 1
    - Initial Values 1
    - Fixed Constraint 1
    - Boundary Load - Acoustic coupling
    - Prescribed Displacement - Kms evaluation
    - Boundary Load - Kms evaluation
    - Body Load - External force
    - Body Load - Lorentz force

Values of Dependent Variables

Mesh Selection

Adaptation and Error Estimates

Study Extensions

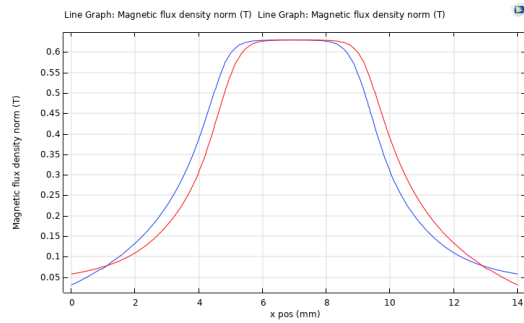
Auxiliary sweep

Sweep type: Specified combinations

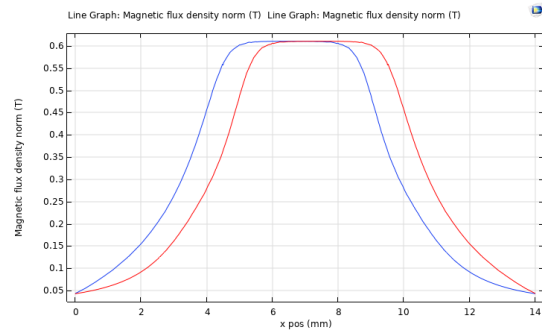
Parameter nam	Parameter value list	Parameter unit
applied_for	range(-6,0.1,-0.1) range(0.1...	N

# Resultados obtenidos

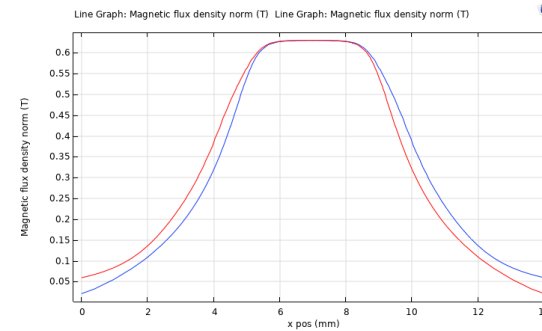
Resultados comparativos circuito magnético - curva  $B(x)$  (curva roja) y  $B(-x)$  (curva azul) – Estudios 1 - 2- 3 – 4



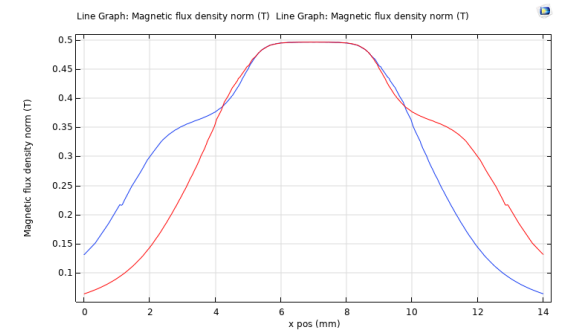
**Geometría 1**



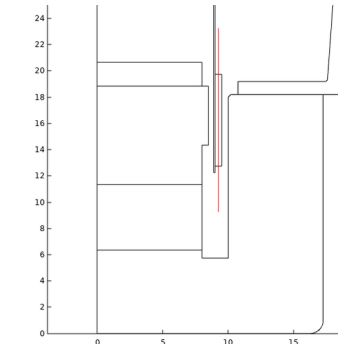
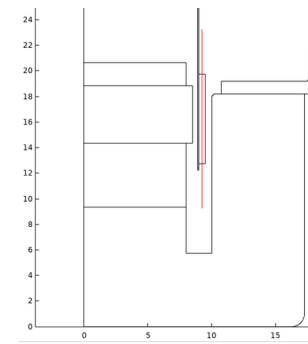
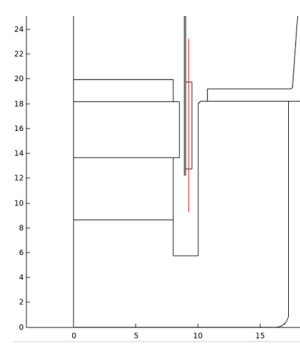
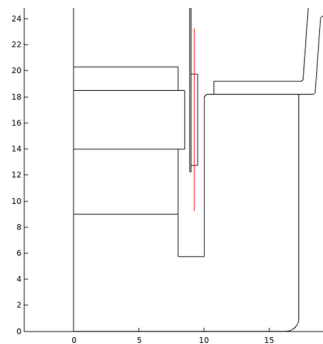
**Geometría 2**



**Geometría 3**



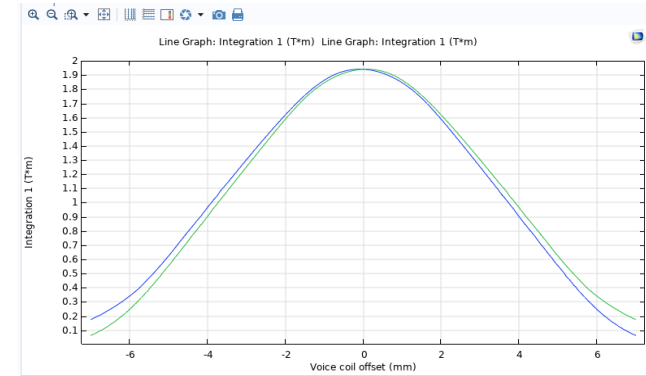
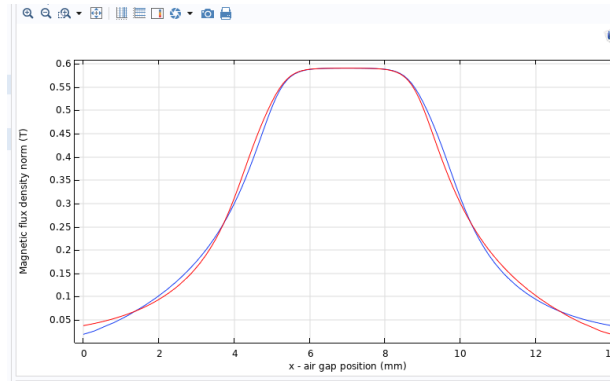
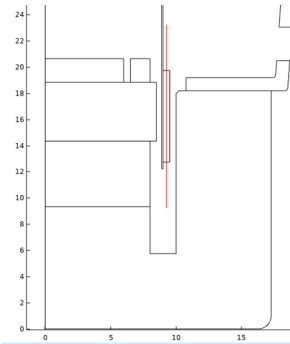
**Geometría 4**



Las geometrías se diferencian por la altura del entre-hierro y la posición en el eje z de la placa de hierro interior. La geometría 4 quiere solo confirmar que el posicionamiento del imán en el circuito magnético influye notablemente sobre la simetría de flujo magnético ( $B$ ) en el entre-hierro y habría que evitar este tipo de configuración.

# Resultados obtenidos

Resultados comparativos circuito magnético - con/sin anillo de cortocircuito – Estudios 5 – 6 – 12 [6][10]



Geometría óptima: Curva B(x) (roja); B(-x)(azul) obtenida usando con una cut-line centrada en la posición de la bobina.

Factor de fuerza: Curva BI(x) (azul); BI(-x)(verde)

Line Graph

Plot Define Cut Line

Label: BI curve(x)

Data

Dataset: Cut Line 2D 5

y-Axis Data

Expression:  $\text{int\_BL}(\text{BL\_integrand} * \text{coil\_location\_r} * \text{coil\_location\_z})$

Unit: T\*m

Integration

Label: Integration 1

Operator name: int\_BL

Source Selection

Geometric entity level: Domain

Selection: Manual

Advanced

Method: Integration

Integration order: 12

Frame: Spatial (r, phi, z)

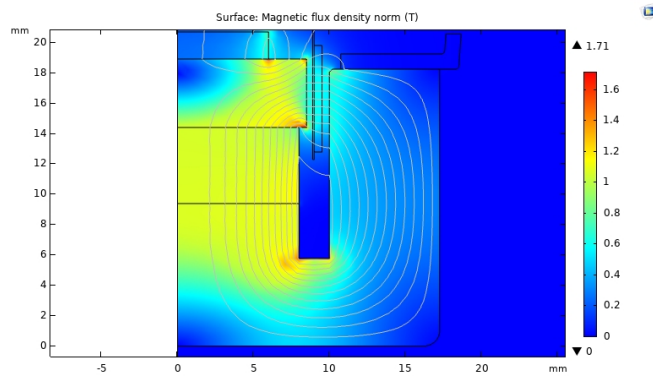
Compute integral in revolved geometry

Name	Expression
coil_location_r	$(r > 9[\text{mm}]) * (r < 9[\text{mm}] + 0.5[\text{mm}])$
coil_location_z	$(z > (\text{dest}(z) - 7[\text{mm}]/2)) * (z < (\text{dest}(z) + 7[\text{mm}]/2))$
BL_integrand	$\text{mf.Br} * \text{N0}^2 * \text{pi} * \text{r} / (3.57 [\text{mm}^2])$
avedisp	$\text{ave\_coil}(w)$

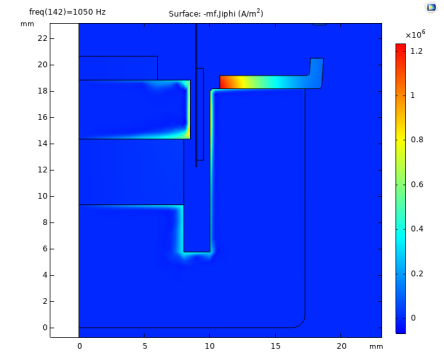
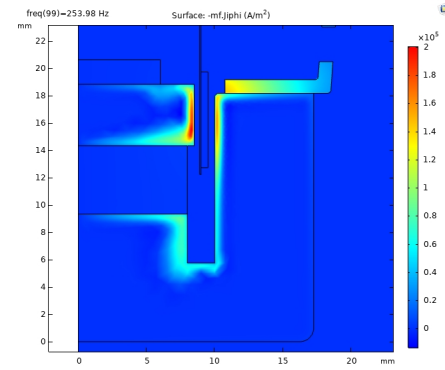
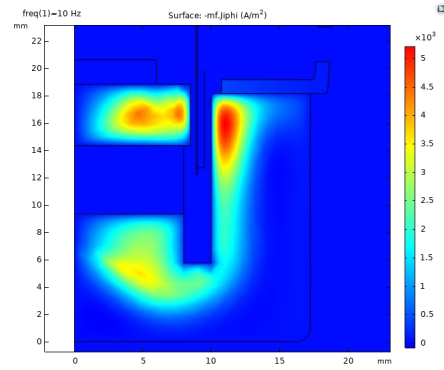
Settings Comsol

# Resultados obtenidos

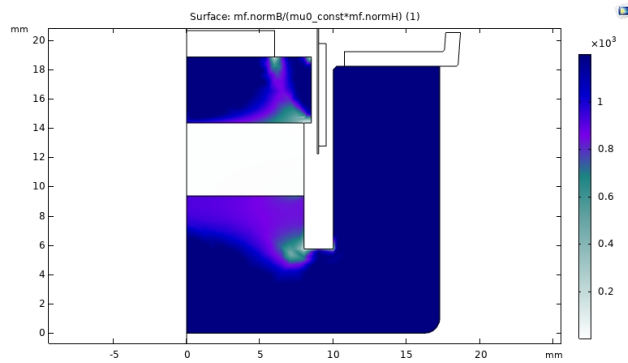
Resultados comparativos circuito magnético - con/sin anillo de cortocircuito – Estudios 5 – 6 – 12 [6][10]



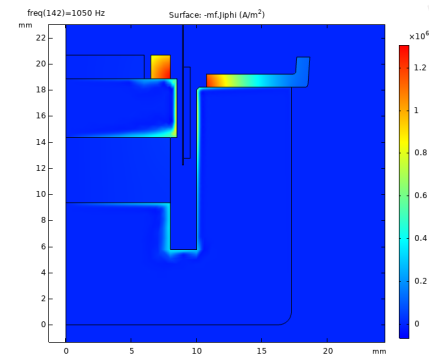
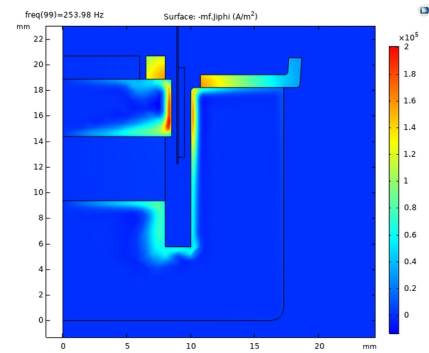
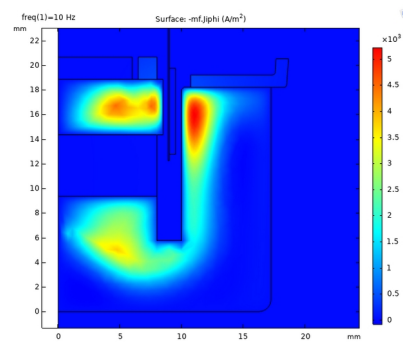
Densidad de flujo magnético B(T) + líneas de flujo



Eddy currents f= 10Hz; 253 Hz; 1000 Hz (No Alu ring)



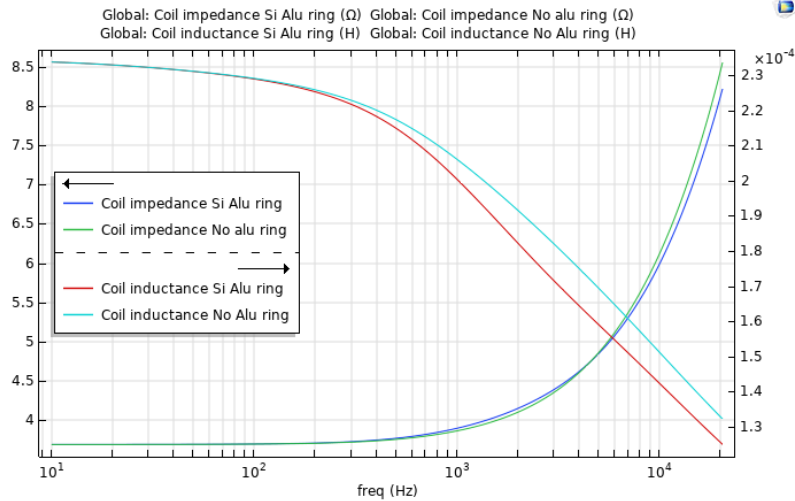
Permeabilidad magnética



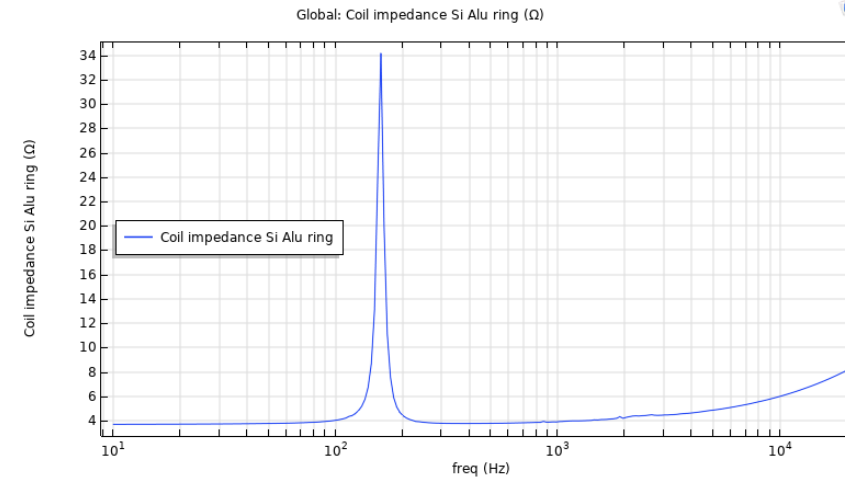
Eddy currents f = 10Hz; 253 Hz; 1000 Hz (No Alu ring)

# Resultados obtenidos

Resultados comparativos circuito magnético - con/sin anillo de cortocircuito – Estudios 5 – 6 – 12 [6][10]



Comparación curva impedancia/inductancia con y sin anillo de cortocircuito y con bobina bloqueada en el entre hierro (modelo simplificado de la inductancia de la bobina).



Curva de impedancia altavoz. Frecuencia de resonancia:  $f = 160\text{Hz}$  – baffle



# Resultados obtenidos

## Resultado estudio 7: stiffness – kms spider

Global Evaluation

[-] Evaluate

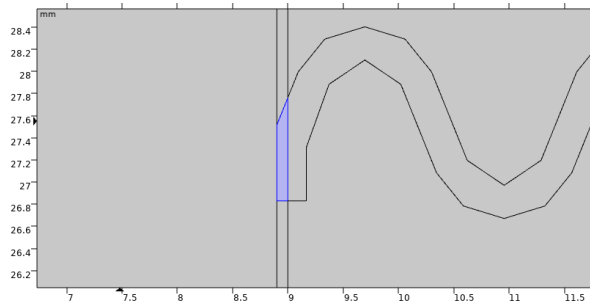
Label: Global Evaluation 1

Data

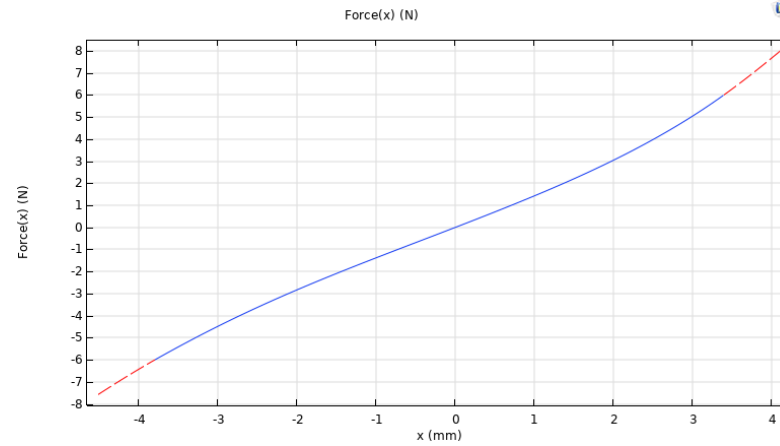
Dataset: From parent

Expressions

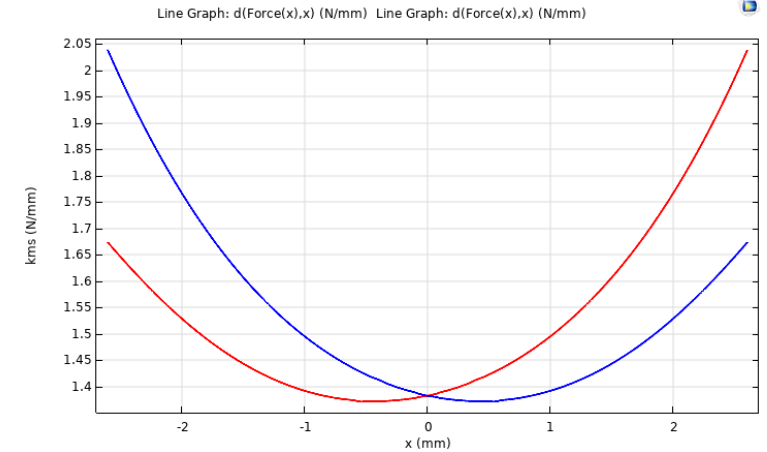
Expression	Unit	Description
ave_coil(w)	mm	Average coil displacement
applied_force	N	Applied force



Settings Consol



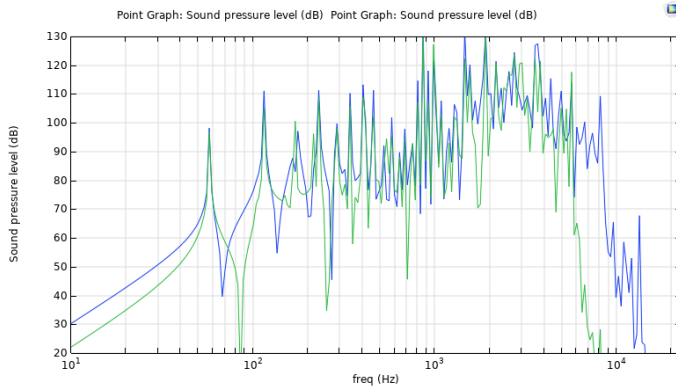
Curva Fuerza (N) vs desplazamiento (mm)



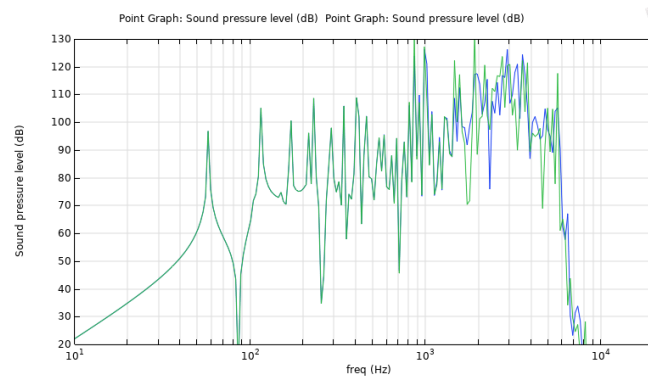
Curva rigidez spider kms(x) (roja) y kms(-x) azul

# Resultados obtenidos

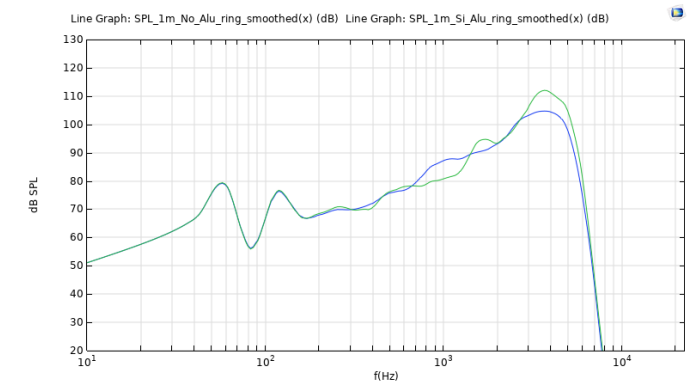
Resultado comparativo análisis en frecuencia estudio 8 -12:



Respuesta en frecuencia altavoz a 50cm (azul) y 1 m (verde) – free air



Respuesta en frecuencia altavoz a 1 m –  
Curva verde - complejo magnético con anillo de cortocircuito  
Curva azul - complejo magnético sin anillo de cortocircuito



Respuesta en frecuencia altavoz a 1 m versión smoothed –  
Curva verde - complejo magnético con anillo de cortocircuito  
Curva azul - complejo magnético sin anillo de cortocircuito

# Conclusiones

- Altavoz electrodinámico 2 pulgadas –  
Simulación COMSOL multiphysics
- Anillo de cortocircuito – solo modelo  
simplificado
- No-linealidades:  $Bl(x)$ ;  $kms(x)$
- Respuesta en frecuencia acústica
- Trabajos futuros:
  - modelo completo inductancia bobina [11]
  - kms conjunto spider – surround
  - estudio térmico
  - simulación altavoz en caja cerrada / bass reflex

# Referencias

- [1] Leo Beranek ,”Acoustics “ – Electro-mechano-acoustical circuits - Chap.3 part VIII pag. 70 – Acoustical Society of america (1993)
- [2] LoudspeakerEquivalentCircuit image By CaptainKwah - Own work, CC BY-SA 4.0, <https://commons.wikimedia.org/w/index.php?curid=36907747>;  
MechanicalSubsystemModelingLoudspeaker image by By CaptainKwah - Own work, CC BY-SA 4.0, <https://commons.wikimedia.org/w/index.php?curid=36369414>
- [3] Wolfgang Klippel, “Loudspeaker Nonlinearities – Causes, Parameters, Symptoms”, Klippel GmbH
- [4] <https://www.engineeringtoolbox.com> / <https://www.elektrisola.com/> / <https://www.engineersedge.com>
- [5] AC/DC Module User’s guide COMSOL version 5.5
- [6] <https://www.comsol.com/video/modeling-loudspeakers-in-comsol-multiphysics>
- [7] Acoustic Module User’s guide COMSOL version 5.5
- [8] Teoría de Mecánica Estructural - parte2.6.1 – Apuntes del Master en COMSOL Multiphysics – MUCOM – Universidad de Malaga [2019/20]
- [9] Mecánica estructural – acoplamiento multifísico - Apuntes del Master en COMSOL Multiphysics – MUCOM – Universidad de Malaga [2019/20]
- [10] Modelo de Comsol “OW Microspeaker: Simulation and Correlation with Measurements”
- [11] J. Vanderkooy, “A Model of Loudspeaker Driver Impedance Incorporating Eddy Currents in the Pole Structure,” J. Audio Eng. Soc., Vol. 37, No. 3, pp. 119-128, March 1989.

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