INSTITUT D'ELECTRONIQUE ET DE TELECOMMUNICATIONS DE RENNES

Reliability and Sensitivity Analysis of Extreme Electromagnetic Events by considering Uncertain Parameters

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3rd DAM Forum, methods for quantifying uncertainties

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Outline

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I. Introduction
II. Reliability analysis of a system
III. Crosstalk problem
IV. Estimation of probability of failure by reliability methods
V. Conclusions about reliability methods
VI. Outlook
VII. References

- Some structures studied in electromagnetism are described by factors which are sometimes poorly defined

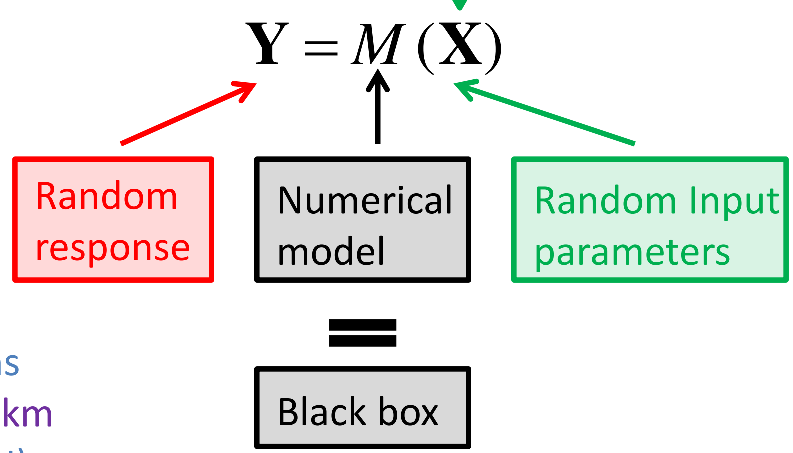
- Case of a cable bundle in an airplane

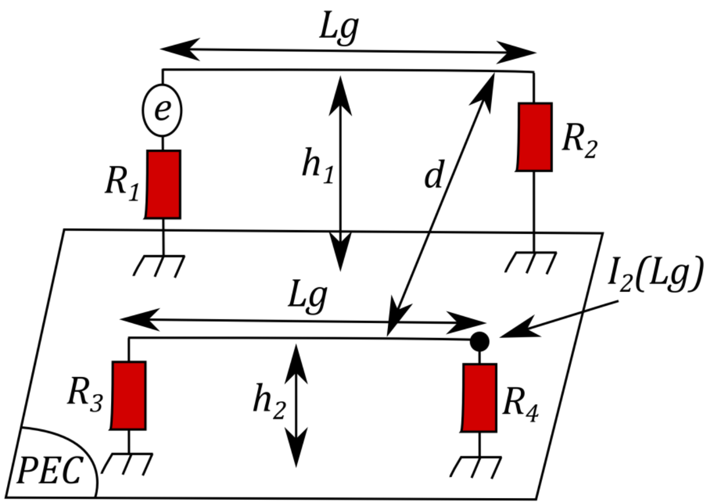
  - variability of this structure between two identical airplanes
  imperfectly defined path, relative position of cables, impedances…

- **Problem: How to predict the levels of interference and risks of default ?**

Source: www.safran-group.com

The A380 contains for example 500 km of cables (SAFRAN).





Input variables uniformly distributed

$R_1(\Omega) \in [1-10]$
$R_2\ , R_3\ (\mathrm{k}\Omega) \in [10-100]$
$h_1\ , h_2\ (cm) \in [1.5-2.5]$
$Lg\ (m) \in [9.5-10.5]$

Input parameters

$e = 1\,V$
$R_4 = 10\,\Omega$
$d = 1\,cm$
$diamwire\,1 = 1\,mm$
$diamwire\,2 = 1\,mm$

Problem: Computing of the probability of failure: $P_f = P(\max_{\Delta f} I_2(Lg) \geq I_t)$

where I_t is an arbitrarily threshold, and $\Delta f = [5-10\ \mathrm{MHz}]$ is a predefined frequency band.

Outline

- Let g(X) the *limit state function*:

$$g(\mathbf{X}) = S - M(\mathbf{X})$$

Threshold value (S)

Computer code providing the interest response (*e.g.* induced current) ($M(\mathbf{X})$)

$$D_f = \{\mathbf{X}\,;\, g(\mathbf{X}) \le 0\}$$ defines the failure domain;

$$D_s = \{\mathbf{X}\,;\, g(\mathbf{X}) > 0\}$$ defines the safe domain;

$$dD = \{\mathbf{X}\,;\, g(\mathbf{X}) = 0\}$$ defines the limit state surface.

- We define the probability of failure by

$$P_f = P(g(\mathbf{X}) \le 0) = \int_{D_f} f_{\mathbf{X}}(\mathbf{x})\, d\mathbf{x}$$

Joint probability density function of ***X***

- Disadvantages related to the computation
- direct computation of this integral is difficult (since g(**X**) is rarely analytical)
- Monte Carlo simulation but this method requires a large number of calls to the limit state function g, and therefore to the numerical model

An approximation method FORM (*first order reliability method*) has been developed (Ditlevsen et Madsen, 1996) to compute P_f while reducing the computation cost model M.

The main steps of FORM:

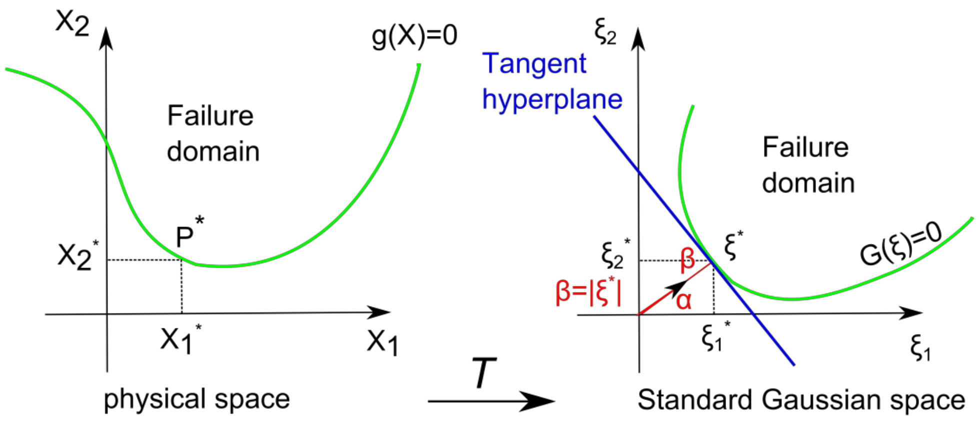
1. Using a transformation T from physical input random variables X_i to standard Gaussian random variables ξ_i by Rosenblatt or Nataf transformation.
   Standard Gaussian random variables → uncorrelated standard Gaussian random variables

2. Find the so-called design point ξ^* (or Most Probable Point (MPP) of failure), which is the point of the failure domain nearest to the origin in the standard Gaussian space (*i.e.* having the maximum probability density function)

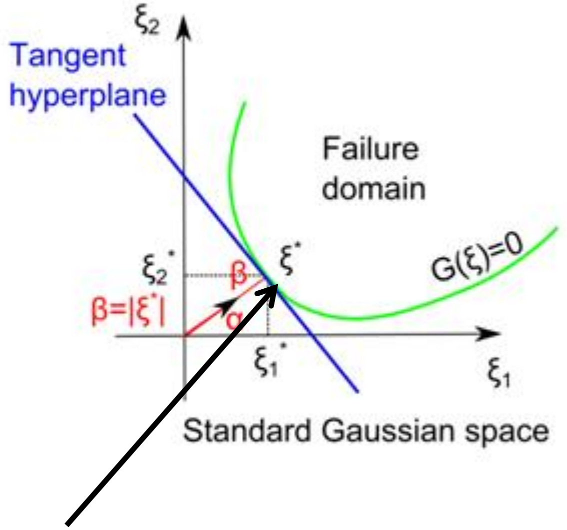
3. Carry out a linear approximation of the limit state function g at the design point ξ^*.
   The failure probability is given by:

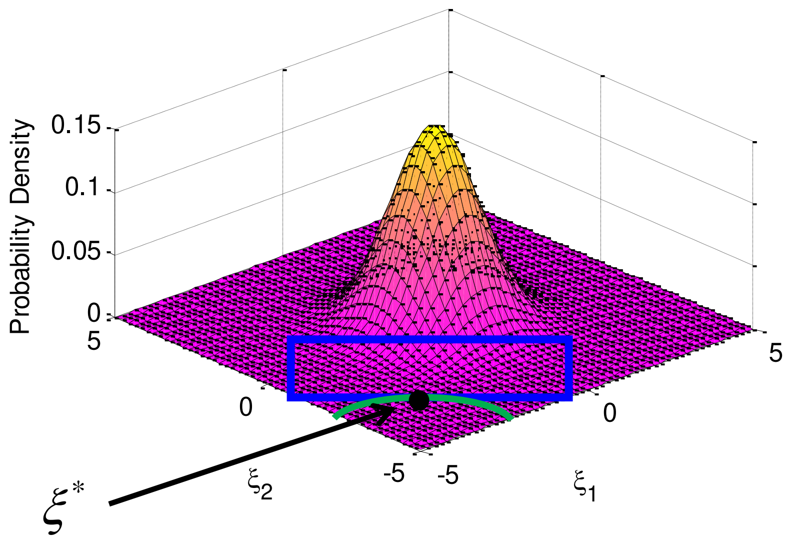
$$P_f \approx P_{f,\text{FORM}} = \Phi(-\beta)$$

Φ is the cdf of an unidimensional Standard Gaussian random variable.



FORM (First Order Reliability Method)

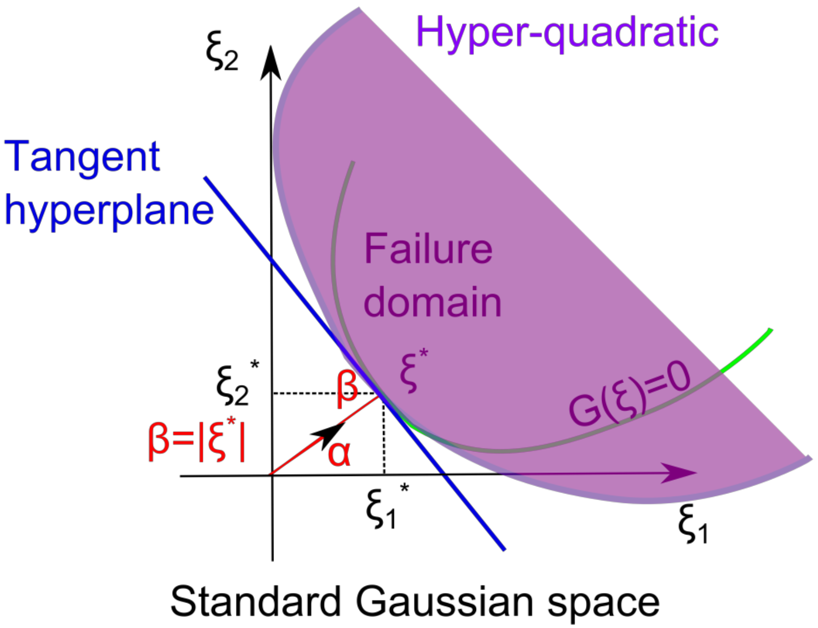




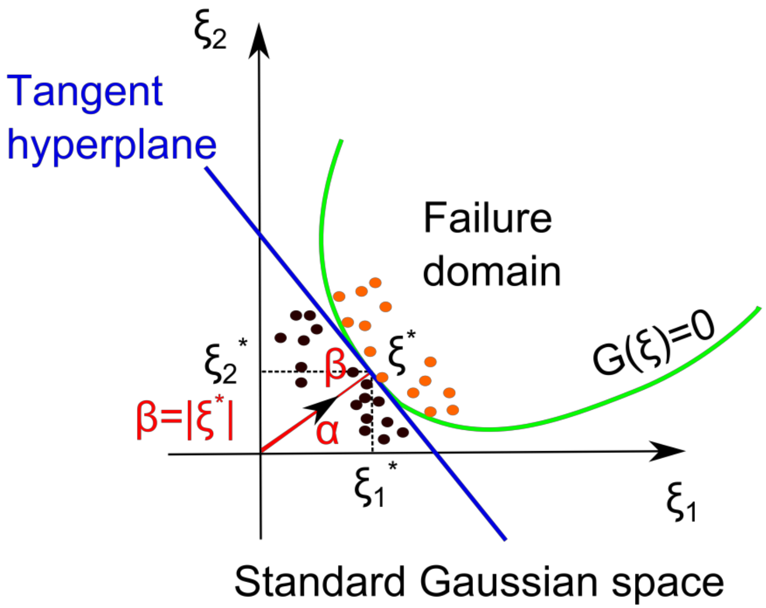
ξ^* is the design point

β is the so-called *reliability index*

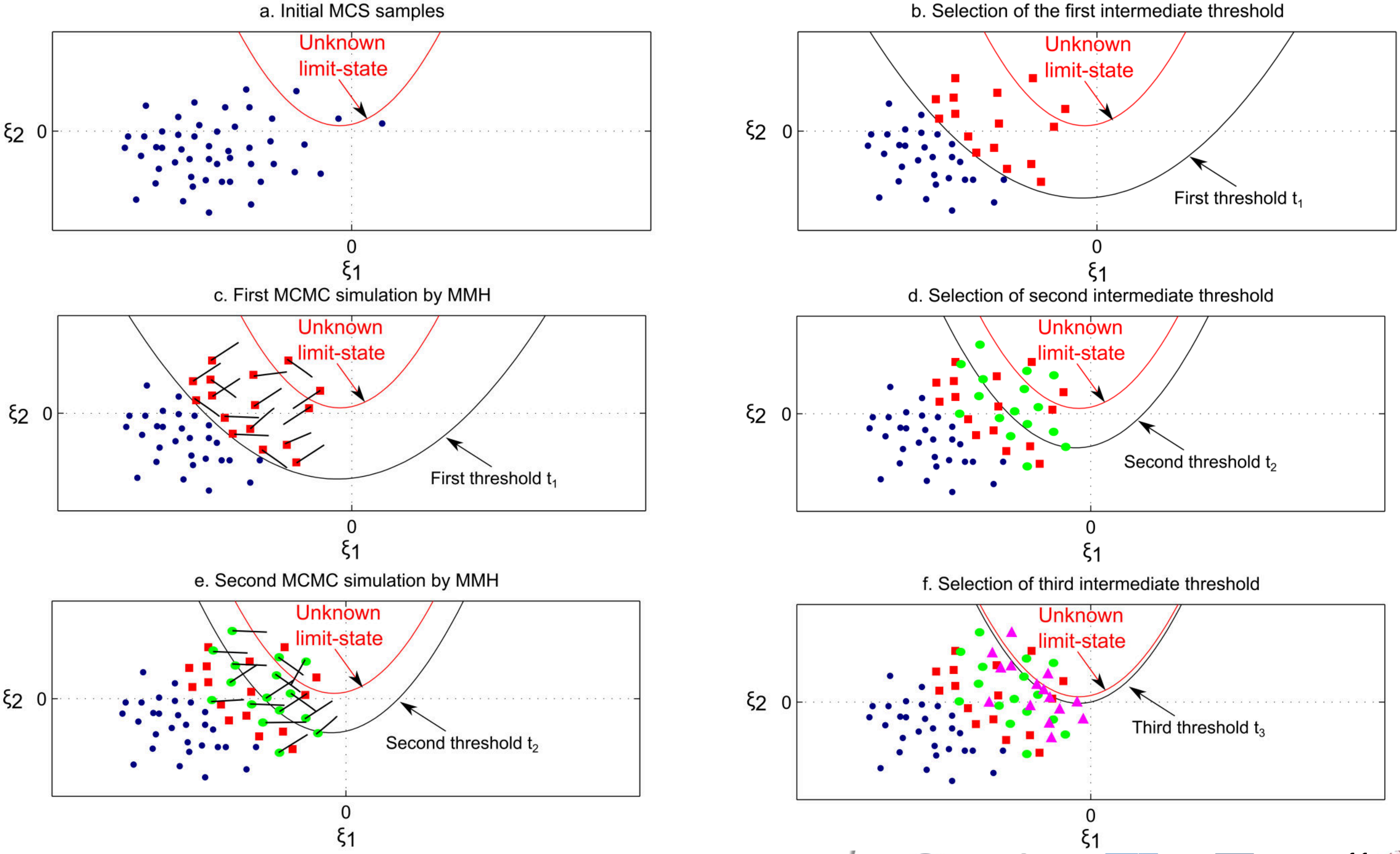
SORM (Second Order Reliability Method)



Importance Sampling (IS)



Subset Simulation (SS)



Two kinds of methods

based on the identification of the design point ξ^*

FORM

SORM

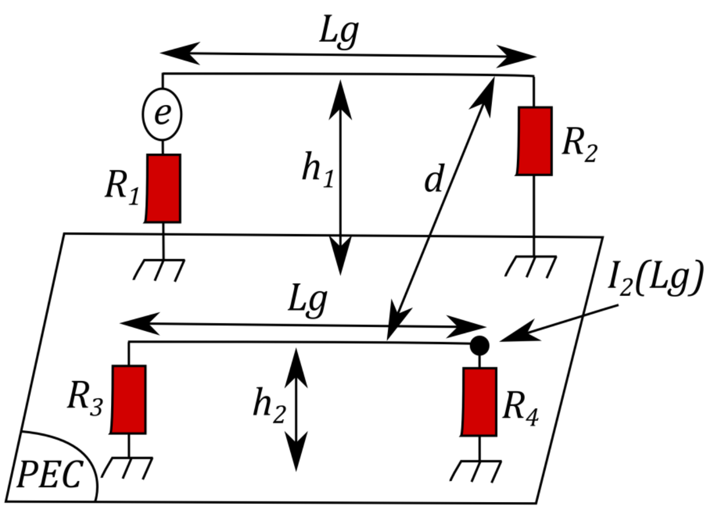
Importance Sampling

based on simulations tending towards the failure domain

→ no identification of the design point ξ^*

Subset Simulation

Outline



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Objectives :

- Compute the probability of failure by reliability methods
- R_4 is the input impedance of a specific device

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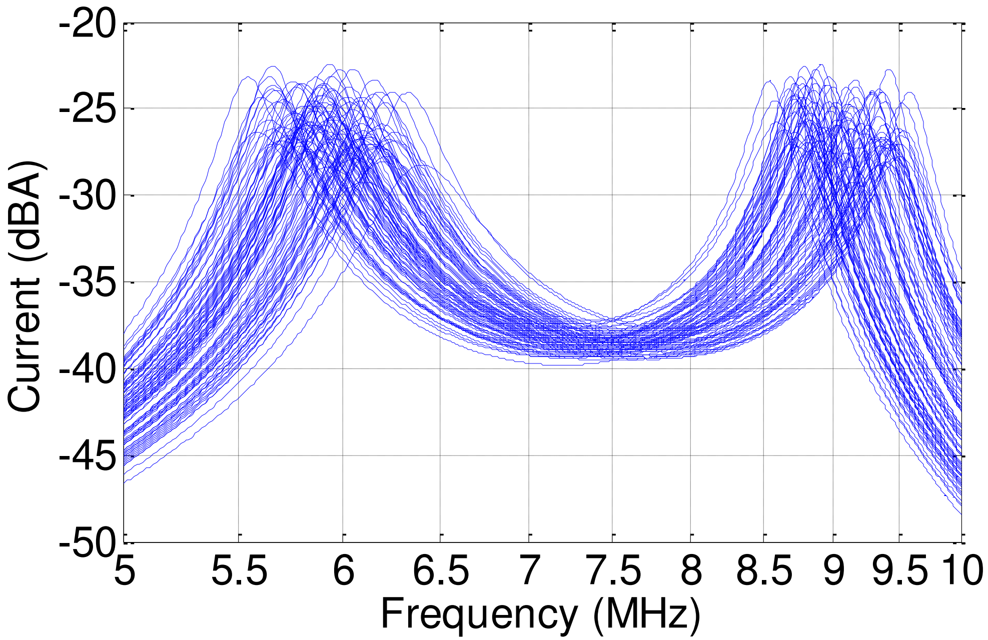
Representation of the induced current $I_2(Lg)$ with respect to the frequency band [5-10 MHz] **(resonance regime)** given by 100 Monte Carlo simulations depending on the uniform random variables: the loads R_1 , R_2 , R_3, the heights h_1 , h_2 and the length Lg of the wires. The impedance R_4 is fixed.



Computing of the probability of failure by reliability methods

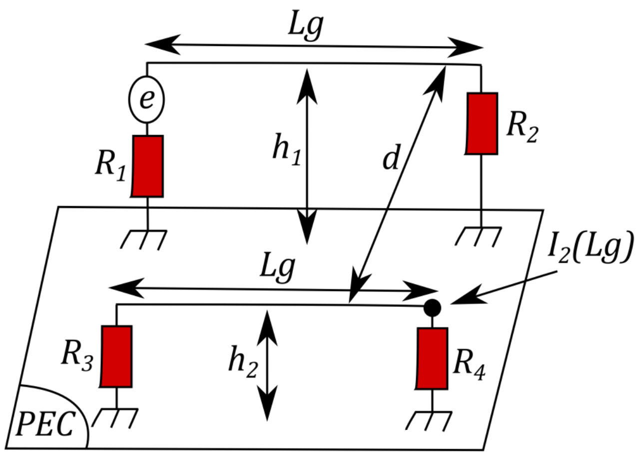
Selected threshold value: $I_t = 70\text{ mA} = -23.09\text{ dBA}$

	FORM	SORM	IS	SS	MCS
$P(\max_{[5-10\text{MHz}]} I_2(Lg) \geq 70\text{ mA})$	0.14	0.08	0.07 ± 13 %	0.09 ± 17 %	0.09 ± 3 %
Number of calls to the numerical model	77	27*	200	200	10,000

* In addtion to FORM

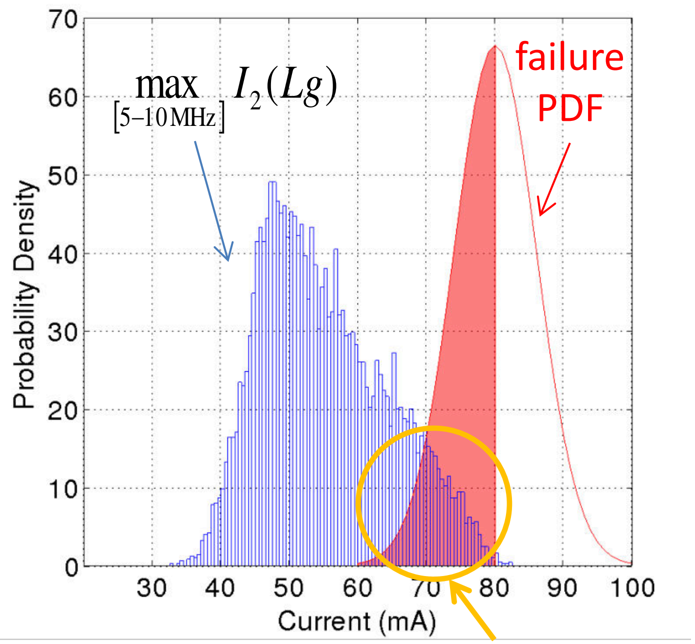
➢ Integration of failure device

- $R_4 = 10\,\Omega$ is the input impedance of a specific device
- Devices may differ from each other due to manufacturing conditions
- Therefore, a set of devices could be represented by a probability density function (PDF) of failure



➡ Thus, a reliability analysis of an electromagnetic system would consist in taking into account the ***probability that the interfering current exceeds a certain threshold*** and the ***probability of having a device failure if the current reaches this threshold value***.

- Integration of failure device



Input variables uniformly distributed

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$$h_1\,,\,h_2\ (cm) \in [1.5-2.5] \qquad Lg\ (m) \in [9.5-10.5]$$

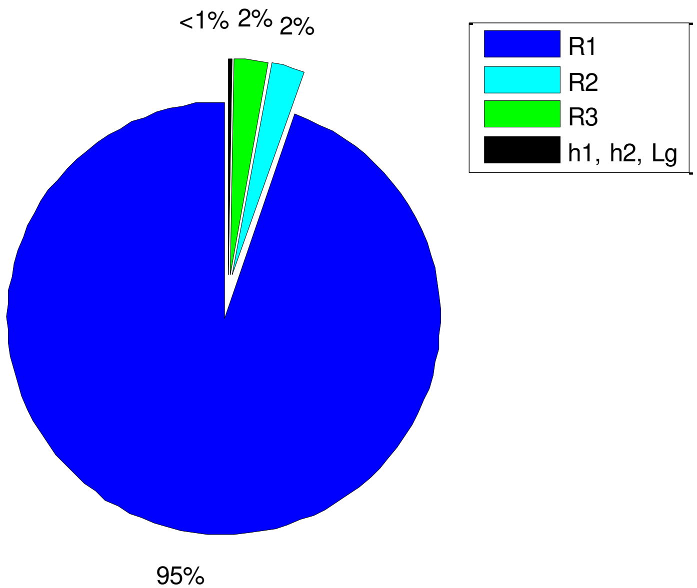
- In blue, 10,000 evaluations of the maximum of $I_2(Lg)$ obtained by Monte Carlo simulation
- In red, failure Gaussian Probability Density Function (PDF) of the device: $N(80, 6)$

	FORM	SORM	IS	SS	MCS
$P_{f,\mathrm{system}}$ (%)	3.26	1.97	[1.67 – 2.11]	[1.66 –2.36]	[2.00 - 2.19]
Number of calls to the numerical model	1113	135*	1100	1800	10,000

* In addtion to FORM

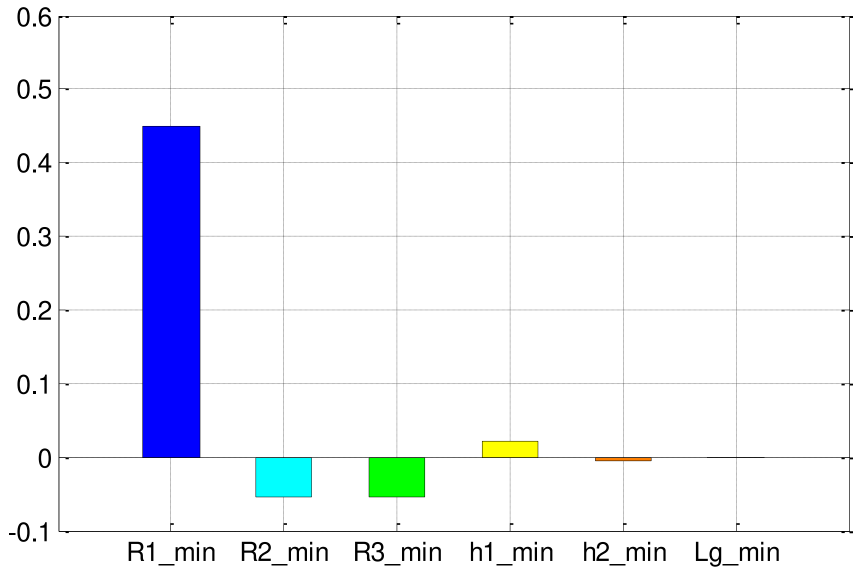
➢ **Local sensitivity analysis** from FORM for the threshold value: $I_t = 60\ \text{mA} = -24.44\ \text{dBA}$

Importance factors



- Importance factors show that R1 is the most important variable on exceeding 60 mA. Other variables are negligible

Elasticity of lower bounds of each random variable



- Elasticity of lower bounds of each random variable show that an increasing of the lower bound of R1 will cause a decreasing of the probability on exceeding 60 mA

- Integration of failure device

Input variables uniformly distributed

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Number of calls to the numerical model	1113	135	1100	1800	10,000

(*e.g.* $I_t = 60\text{ mA} = -24.44\text{ dBA}$: $P(\max_{[5-10\,\text{MHz}]} I_2(Lg) \geq 60\text{ mA}) \approx 30\ \%$)

After exploitation of Sensitivity Analysis from FORM

Input variables uniformly distributed

$R_1(\Omega) \in [2-10]$ $R_2, R_3\ (k\Omega) \in [10-100]$
$h_1, h_2\ (cm) \in [1.5-2.5]$ $Lg\ (m) \in [9.5-10.5]$

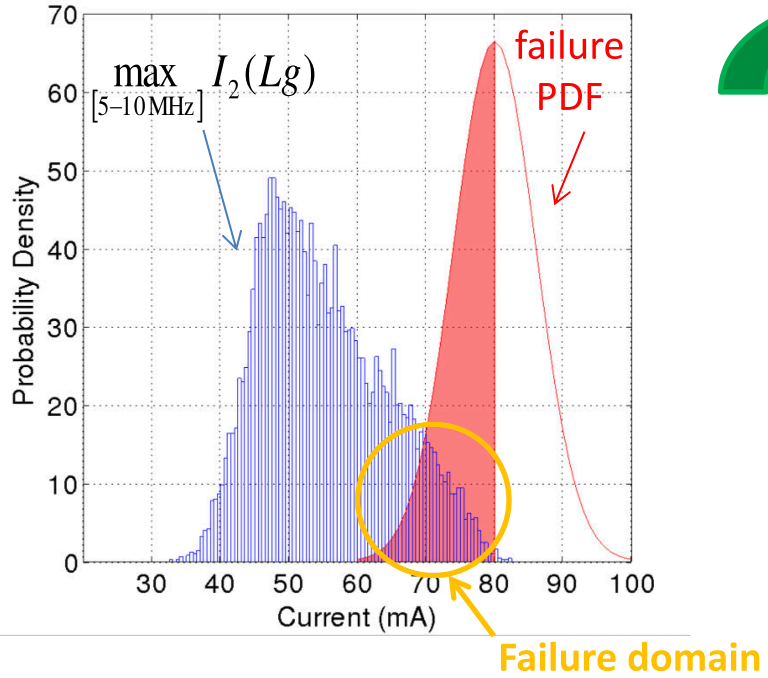
	FORM	SORM	IS	SS	MCS
$P_{f,\text{system}}$ (%)	1.36	0.74	[0.67 – 0.85]	[0.53 – 0.94]	[0.73 – 0.80]
Number of calls to the numerical model	984	108	900	1558	10,000

(*e.g.* $I_t = 60\text{ mA} = -24.44\text{ dBA}$: $P(\max_{[5-10\,\text{MHz}]} I_2(Lg) \geq 60\text{ mA}) \approx 22\ \%$)

- Integration of failure device

When: $R_1(\Omega) \in [1-10]$

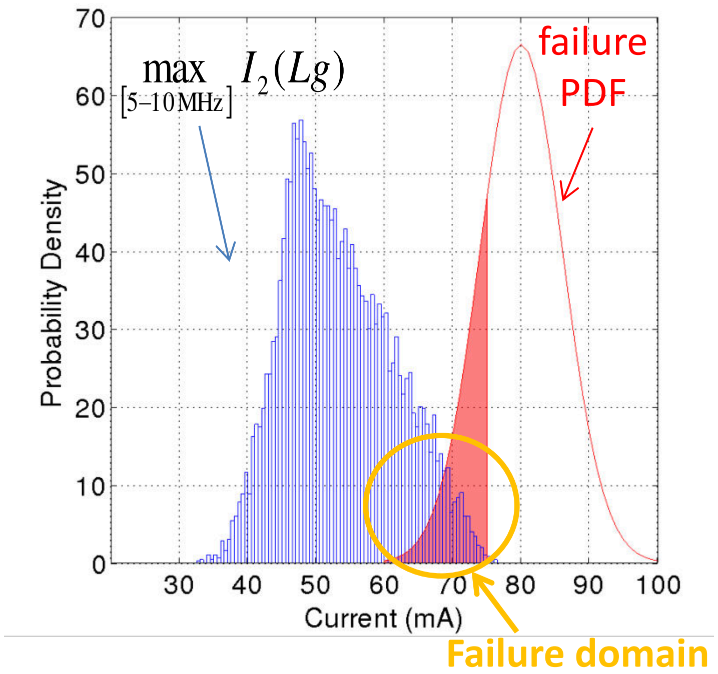
$$P_{f,\text{system}} \approx 2\ \%$$



Sensitivity Analysis from FORM

When: $R_1(\Omega) \in [2-10]$

$$P_{f,\text{system}} \approx 0.8\ \%$$



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➢ Summary Table on reliability methods, +++ indicates a very efficient method contrary to - - -

Method	Efficiency (Accuracy / Computational cost)	Remarks
Monte Carlo simulation (MCS)	- - -	Can deal with any type of problem but the computational cost is too high
FORM- SORM	++	Requires a validation of the results since some non-linear case (**resonance**) can cause problems
Importance Sampling (IS)	+++	Requires a validation of the results since some non-linear case (**resonance**) can cause problems – More robust than FORM-SORM
Subset Simulation (SS)	+++	Simulation Method introduced for estimation of failure probability in **high dimensions** – More robust than IS

Outline

- Reliability analysis (probability of failure)
  - Application to a real case more complex
    (Increasing of the number of random variables for a 3D EMC problem: interaction field/cables)

Outline

- J.-M. Bourinet, C. Mattrand, and V. Dubourg, *A review of recent features and improvements added to FERUM software*, in Proc. of the 10th International Conference on Structural Safety and Reliability (ICOSSAR 2009), Osaka, Japan, 2009.

- M. Lemaire, *Structural reliability*, John Wiley & Sons, 2010.

- B. Sudret, *Uncertainty propagation and sensitivity analysis in mechanical models – Contributions to structural reliability and stochastic spectral methods*, Habilitation à diriger des recherches, Université Blaise Pascal, Clermont-Ferrand, 2007.

Thank you for your attention

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