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FBG_SiMul V1.0: Fibre Bragg Grating Signal Simulation Tool for Finite Element Method Models

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Abstract

FBG_SiMul V1.0 is a tool to study and design the implementation of fibre Bragg grating (FBG) sensors into any kind of structure or application. The software removes the need of an fibre optic expert user, becoming more obvious the sensor response of a structural health monitoring solution using FBG sensors. The software uses a modified T-Matrix method to simulate the FBG reflected spectrum based on the stress and strain from a finite element method model. The article describes the theory and algorithm implementation, followed by an empirical validation.

Keywords: Fibre Bragg Grating, Sensor Simulation in FEM, Structural Health Monitoring, Sensor Implementation and Optimization

1. Introduction

1 **1. Introduction**
2 More demanding structural applications and new design philosophies are
3 increasingly motivating engineers and researchers to implement sensors into
4 structures and to develop new structural health monitoring (SHM) solutions
5 [1, 2]. This opportunity is driven by new low-cost sensors and transducers,
6 new electronics and new manufacturing techniques. In particular, the cost
7 of fibre Bragg grating (FBG) sensors has dropped over the last few years
8 and robust fibre-optic monitoring systems suitable for SHM have become
9 commercial off the shelf hardware.

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10 However, the sustainment of structures using these permanent on-board
11 health monitoring systems is a complex and multi-disciplinary technological
12 field that requires a holistic approach that cannot be addressed solely by ad-
13 vances in the various technology platforms on which the SHM is constructed.
14 What is required is twofold; that the next generation of research scientists
15 and engineers are specifically trained with the skills, research experience,
16 and multi-disciplinary background to adopt the new structural sustainment
17 concepts. And that tools are available that enable the demanding task of
18 integrating, supporting, and maintaining an innovative holistic health man-
19 agement system and to propel its application in the aerospace, wind energy,
20 and other industries.

21
22 The FBG_SiMul software described here is an example of the type of
23 tool that will allow sensor simulation to become part of the design process,
24 where output is simulated and optimised to a structure. This will have
25 an immediate impact on the planning, development and implementation of
26 SHM as well as provoking further research and development to include active
27 control elements in the software and real-time data-driven feedback control
28 for smart structures in the future. Equally important is that the software is
29 robust and runs from a user friendly interface. This ensures its uptake both
30 within and outside the modelling and sensor communities as it provides an
31 opportunity for non-experts to simulate the signals and support their sensor
32 implementation plans; whether for a one-off full-scale structural test, or a
33 series of mechanical test specimens [3].

34 **2. Problems and Background**

35 The shape and response of the FBG reflected spectrum (measured signal)
36 depends on the way that the grating is deformed, i.e., the stress and strain
37 field acting along the grating will define the signal response. The FBG re-
38 sponse simulation based on the stress and strain state from a finite element
39 method (FEM) model was only recently addressed. *Hu* et al.[4] developed a
40 Matlab code to simulate the FBG response under non-uniform strain fields
41 caused by the transverse cracking in cross-ply laminates; and in a similar
42 work, *Hasson* et al.[5] developed a Matlab code to simulate the FBG re-
43 sponse for mode-I delamination detection. However, the code developed by
44 both authors is limited either by the type of FEM model or by the type
45 of sensor response analysed; and, in both cases the code/algorithm for the

46 signal simulation code is not provided.

47

48 Thus, FBG_SiMul was developed to tackle this gap in the FBG simulation
 49 field, where the FBG response is simulated independently of the structure,
 50 loading, or application type. As the software removes the need of a fibre
 51 optic expert user, the FBG sensor response of a structural health monitoring
 52 solution becomes more intuitive.

53 *2.1. Fibre Bragg Grating Signal Response*

54 A FBG sensor is formed by a permanent periodic modulation of the re-
 55 fractive index along its core. When the optical fibre is illuminated by a
 56 broadband light source a narrow wavelength band is reflected back, as shown
 57 in figure 1.

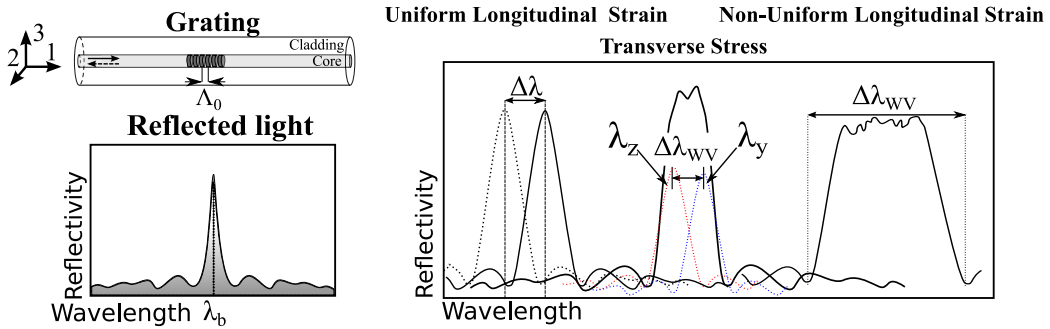


Figure 1: Fibre Bragg grating response for uniform strain, transverse stress and non-uniform strain.

58 Any external force/load acting in the grating region will change the effec-
 59 tive index and/or the period of modulation, which will create a shift in the
 60 wavelength and/or modify the shape of the reflected peak. However, differ-
 61 ent stress and strain fields acting in the FBG sensor create different signal
 62 responses [3, 11, 12, 13, 14] (see figure 1); a longitudinal uniform strain field
 63 creates a wavelength shift in the reflected peak ($\Delta\lambda$), but its shape remains
 64 unchanged; a longitudinal uniform and non-uniform strain field, acting along
 65 the grating, causes an increase in the reflected peak width ($\Delta\lambda_{WV}$) and a
 66 wavelength shift ($\Delta\lambda$); a transverse stress field, acting along the grating,
 67 causes a separation of the reflected Bragg peak due to the optical fibre bire-
 68 fringent behaviour, which can be described by an increase in the reflected
 69 peak width ($\Delta\lambda_{WV}$) and a wavelength shift ($\Delta\lambda$).

70 *2.2. Spectrum Simulation: Transfer-Matrix Method*

71 The transfer-matrix method was originally developed to simulate the re-
 72 flected spectrum of FBG sensors under a uniform strain field by *Yamada* and
 73 *Sakuda* [6]; later, this theory was modified to simulate the reflected spectrum
 74 of FBG sensors under other types of strain field or different FBG configu-
 75 rations [7, 8, 9, 10]. The modified T-Matrix method, developed by Peters
 76 et al.[7], consists of dividing the waveguides (grating periodic pattern) into
 77 short segments, and in each segment the grating is assumed to be periodic.
 78 This assumption allows each segment to be handled as a uniform grating and
 79 its signal to be simulated by the original *Yamada* T-Matrix method. Then,
 80 when the grating is deformed, the grating period (Λ) in each increment is
 81 calculated using the average strain acting in that increment; and, the total
 82 reflected signal is reconstructed by combining the signal contribution from
 83 all increments.

84 *2.3. From a Finite Element Method Model to Spectrum Simulation*

85 In a FEM model the structure domain is divided in small sections called
 86 elements, which contain stress and strain information that describes the
 87 structural behaviour. In the T-Matrix method the grating is divided into
 88 short segments, and the simulated signal from each segment is added to the
 89 total reflected signal. Thus, it is possible to simulate the FBG reflected spec-
 90 trum based on a FEM model, by matching the number of short segments used
 91 by the T-Matrix method with the number of elements in the FEM model, as
 shown in figure 2.

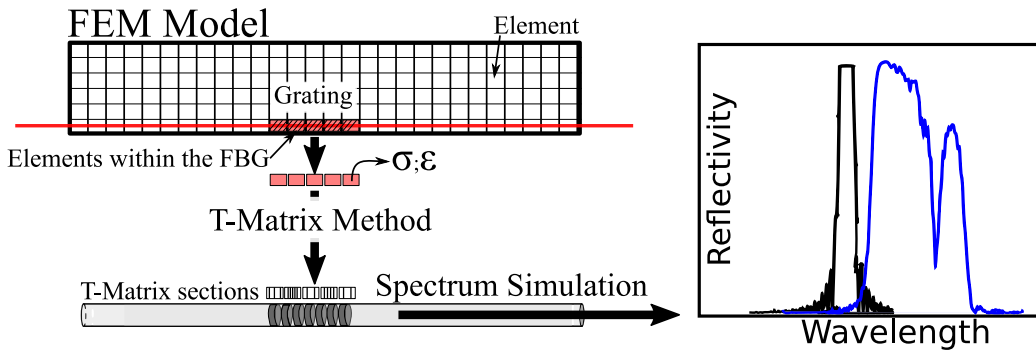


Figure 2: Schematic representation of the algorithm implemented in the FBG_SiMul software: from a FEM model to FBG spectrum simulation;

92

93 Then, the stress and strain from each FEM element is used by FBG_SiMul
94 to simulate the sensor signal, using a modified T-Matrix method. The differnt
95 theory and algorithm structure implemented in the software are presented in
96 appendix A- *Spectrum Simulation Theory and Algorithm*.

97 **3. Software Description**

98 FBG_SiMul was developed with a graphical user-interface, no program-
99 ming knowledge is required to preform FBG simulation; all the input param-
100 eters are pre-checked by the software, meaning that the simulation is robust
101 and the code does not crash. However, the source code (python) is provided
102 and it can be re-used or changed to fit any purpose. The software is provided
103 in two formats: a standalone file, in **.exe** format, which does not require in-
104 stallation or any dedicated software; and, in Python format, which can be
105 modified but requires a python compiler.

106

107 A user-manual is provided together with the software; In this documen-
108 tation the user can find information about the code structure, the type of
109 functions/algorithms implemented, the software input/output and different
110 functionalities, and a software tutorial case.

111 *3.1. Software Conceptual Structure*

112 The FBG_SiMul conceptual structure is shown in figure 3. First, the soft-
113 ware extracts the stress and strain along a predefined path in a FEM model,
114 and save it as a .txt file. This can be made for a specific/single time incre-
115 ment, or for multiple time increments (ex: dynamic models, time dependent
116 behaviour). Next, the software identifies the elements that are inside of each
117 FBG, and creates a local variable per FBG sensor containing all information
118 needed to simulate the FBG response, as the number of elements per grating,
119 and the stress and strain field. Finally, two simulation options are given to
120 the user: reflected spectrum simulation for a specific time increment, to eval-
121 uate the shape of the reflected signal; and, FBG time response, to simulate
122 the sensor response for multiple time increments.

FBG_SiMul Conceptual Structure

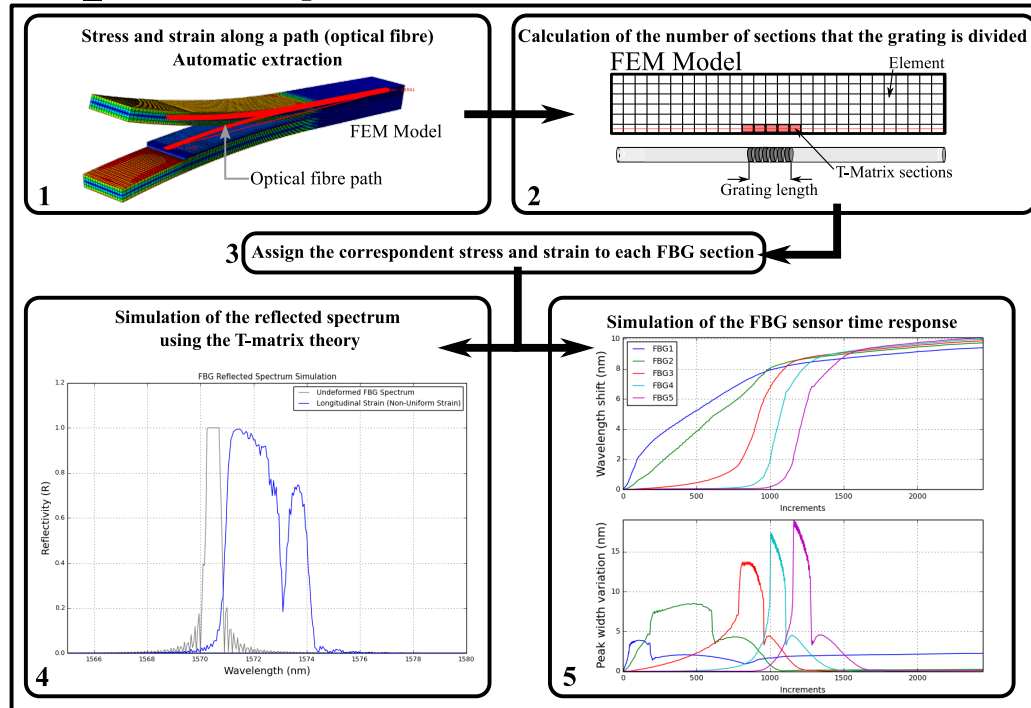


Figure 3: FBG_SiMul conceptual structure. FBG spectrum simulation from a finite element method.

123 3.2. Software Functionalities

124 The software is divided between 4 tabs according to functionality:

- 125
- 126 • **Tab 1- Software:** Software front page, where the user can find information about all the different tabs and their functionalities, open the user manual, or learn more about the software copyright and author;
 - 127
 - 128 • **Tab 2- Extract Stress/Strain along Optical Fibre (Abaqus):**
 - 129 Tool to automatically extract the stress and strain along a pre-defined path in a FEM model. The output is a .txt file containing the stress and strain distribution along a FBG path for a specific time increment.
 - 130 Tool options: multiple FBG paths; coordinate system rotation; single
 - 131 or multiple time increment;
 - 132
 - 133

134 **Note:** this tool was developed for *Abaqus* FEM models. Nevertheless,
135 the user can simulate the FBG response using a different FEM software
136 by extracting the files manually, and ensuring that the files have the
137 required format, as described in the user-manual.

138 • **Tab 3- FBG Spectrum Simulation (Specific Step Increment):**
139 FBG reflected spectrum simulation for a specific time increment. Here,
140 the user can study the FBG spectrum response, plan the sensor loca-
141 tion, optimise the sensor wavelength, check available bandwidth, eval-
142 uate signal distortion or measurement errors, and so forth. The tab
143 output is the FBG reflected spectrum, and it can be saved as an im-
144 age or as a .txt file. Tool options: different SI units, mm or m; type
145 of simulation, as longitudinal uniform strain, longitudinal non-uniform
146 strain or transverse stress; user-defined optical fibre parameters; num-
147 ber of FBG sensors per fibre; FBG length; user-defined FBG array
148 configuration; plot configuration;

149 • **Tab 4- FBG Signal variation (Time Response):** FBG signal re-
150 sponse for multiple time increments. Here, the user can study the
151 wavelength shift variation($\Delta\lambda_{WV}$) and the peak width variation ($\Delta\lambda$)
152 along the selected time increments, compare the sensor response for
153 multiple FBG paths, plan the sensor location, and so forth. The tab
154 output is the $\Delta\lambda_{WV}$ and $\Delta\lambda$ along the selected time increments, and
155 it can be saved as an image or as a .txt file. Tool options: different SI
156 units, mm or m; user-defined optical fibre parameters; number of FBG
157 sensors per fibre; FBG length; user-defined FBG array configuration;
158 plot configuration;

159 4. Software Empirical Validation

160 To validate the software algorithm, 3 input files representing known cases
161 of uniform strain, non-uniform strain and transverse stress were created. The
162 wavelength shift, $\Delta\lambda_{WV}$, and the peak width variation, $\Delta\lambda$, for the 3 cases
163 were calculated using the analytical equations (Eq. (3), (7), and (11)) de-
164 veloped by Pereira et al. [3]. Each input file contains the stress and strain
165 along a 10 mm grating, discretized in 20 segments.

166

167

Theoretical results:

168

• Uniform strain: grating under 1.0 $\varepsilon(\%)$ longitudinal strain. Theoretical output: $\Delta\lambda = 12.16 \text{ nm}$, $\Delta\lambda_{WV} = 0$; for $p_e = 0.215$ and $\lambda_b = 1550 \text{ nm}$.

169

170

• Non-uniform strain: half grating under 1.0 $\varepsilon(\%)$ and the other half under 0.5 $\varepsilon(\%)$ longitudinal strain. Theoretical output: $\Delta\lambda = 9.15 \text{ nm}$, $\Delta\lambda_{WV} = 6.07 \text{ nm}$; for $p_e = 0.215$, $\lambda_b = 1550 \text{ nm}$, $n_{eff} = 1.46$ and $\Lambda_0 = 530.82$.

171

172

173

174

• Transverse stress: grating under a compressive stress of 100 MPa in the z direction. Theoretical output: $\Delta\lambda = 0 \text{ nm}$, $\Delta\lambda_{WV} = 0.3839 \text{ nm}$; for $p_{11} = 0.121$, $p_{12} = 0.270$, $E = 70 \text{ GPa}$, $\nu = 0.17$, $\lambda_b = 1550 \text{ nm}$, $n_{eff} = 1.46$ and $\Lambda_0 = 530.82$.

175

176

177

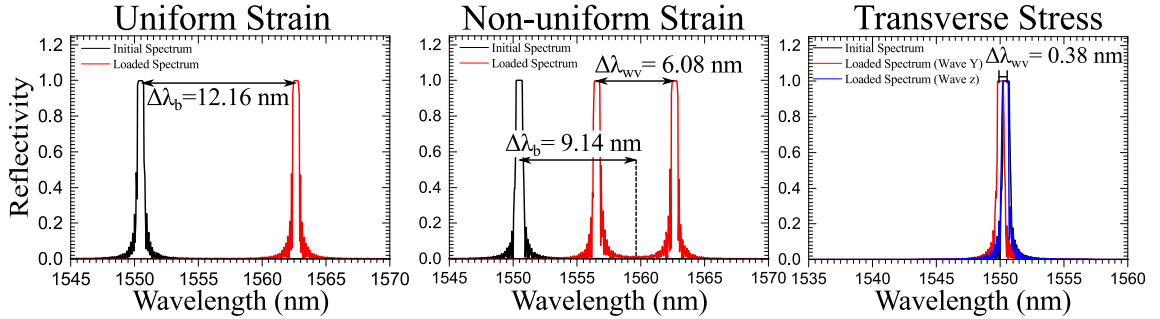


Figure 4: FBG_SiMul simulation results. Simulated test cases: uniform strain, non-uniform strain, and transverse stress.

178

The three empirical test cases were simulated with good accuracy by the FBG_SiMul software, as shown in figure 4. Thus, it can be concluded that the software can represent the FBG response for different type of strain/stress fields.

179

180

181

182 5. Illustrative Example

183

In this section, the FBG_SiMul was used simulate and design a delamination/crack monitoring solution based in FBG sensors. A double cantilever beam (DCB) FEM model, based on the work presented by Pereira et al. in [3], was used to represent the delamination phenomenon. The complete FEM

184

185

186

187 model description and a simulation tutorial can be found in the FBG_SiMul
 188 user-manual.

189 The simulated virtual FBG array was composed of 5 gratings, spaced
 190 by 10 mm (see figure 5), and its path was a 0.03 mm line parallel with
 191 the delamination plane. Then, the FBG array spectrum response in the
 192 presence of a crack was simulated using the FBG_SiMul tab 3; and, the
 193 FBG signal response during the delamination process was simulated using
 194 the FBG_SiMul tab 4.

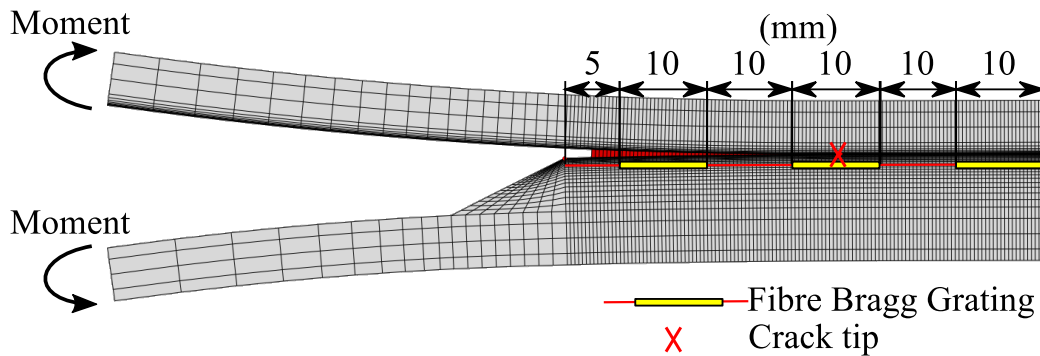


Figure 5: FBG array configuration in the DCB specimen.

195 5.1. FBG Spectrum Simulation

196 The reflected spectrum was simulated for a specific time increment using
 197 the FBG_SiMul tab 3-FBG Spectrum Simulation, where the crack tip was
 198 situated 36 mm from the beginning of the optical fibre, which corresponds
 199 to the middle of the second grating.

200 A screen-shoot of the FBG_SiMul plot/output window is shown in figure
 201 6, where the deformed reflected spectrum (red curves) can be compared with
 202 the original reflected spectrum (grey curves). It can be observed that the
 203 two first FBGs measure a high amount of wavelength shift ($\Delta\lambda$) and peak
 204 width variation ($\Delta\lambda_{WV}$), as result of the presence of the crack.

205 5.2. FBG Time Response Simulation

206 The FBG response was simulated using the FBG_SiMul tab 4-FBG Signal
 207 Variation. It was used multiple time increments, representing the delamina-
 208 tion of the DCB specimen, from an undamaged to a fully damage state. A

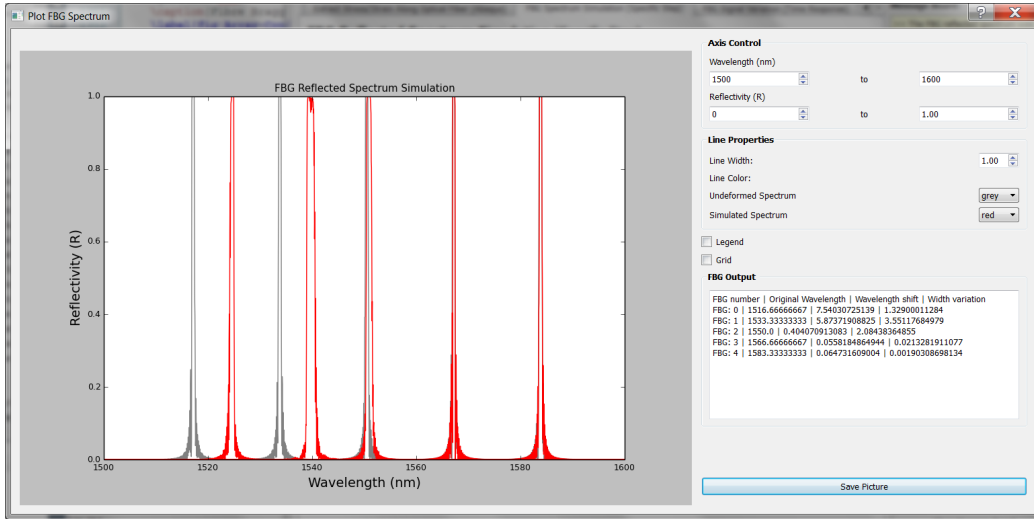


Figure 6: FBG_SiMul plot window: FBG reflected spectrum simulation for the non-uniform strain contribution.

209 screen-shoot of the FBG_SiMul plot/output window is shown in figure 7,
 210 where the top plot represents the wavelength shift ($\Delta\lambda_{WV}$), and the bottom
 211 plot represents the peak width variation ($\Delta\lambda$). This simulation shows an
 212 increase of the $\Delta\lambda$ as the crack passes the position of the grating, caused by
 213 change in the material compliance and load distribution; and, an increase
 214 of the $\Delta\lambda_{WV}$ when the crack is near the grating, caused by a non-uniform
 215 strain field generated at the crack tip.

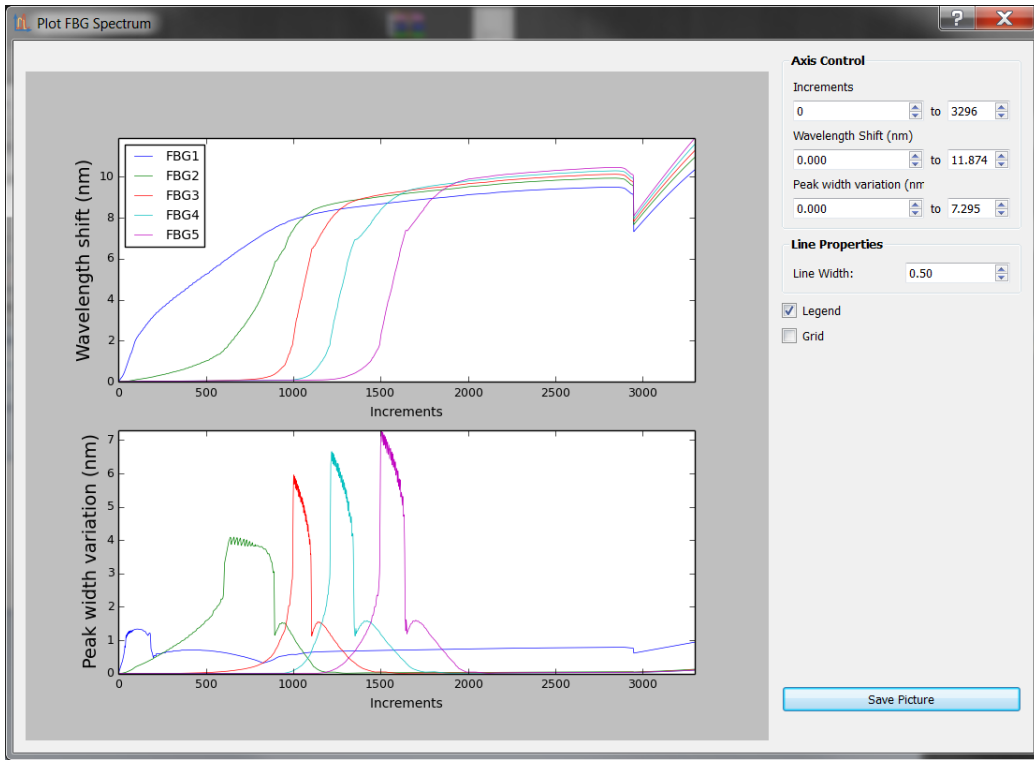


Figure 7: FBG_SiMul plot window: FBG time response simulation.

216 6. Conclusions

217 FBG_SiMul provides the user with a tool to study and design structural
 218 health monitoring solutions based on FBG sensors. The software is divided
 219 in 3 main tools: a tool to extract the stress and strain along an optical fibre
 220 path from a FEM model; a tool to simulate the reflected spectrum for a
 221 specific time increment; and a tool to simulate the FBG time response.

222

223 The software uses a modified version of the T-Matrix method to simulate
 224 the FBG signal from a FEM model. Thus, it can simulate the FBG response
 225 independently of the type of structure, loading or application. Also, the
 226 software removes the need of a fibre optic expert to plan and design monitor-
 227 ing solutions. The user interacts with the software through a user-interface,
 228 meaning that no programming knowledge is required, making parameter ma-
 229 nipulation more intuitive to the user. Also, the input data is pre-checked by

230 the software, meaning that the simulation is robust and does not crash or
231 give calculation errors.

232 **Acknowledgements**

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235 Initial Training Network.

236 **References**

- 237 [1] D.F.O. Braga, S.M.O. Tavares, L.F.M. da Silva, P.M.G.P. Mor-
238 eira, P.M.S.T. de Castro, Advanced design for lightweight struc-
239 tures: Review and prospects, *Prog. Aerosp. Sci.* 69 (2014) 2939.
240 doi:10.1016/j.paerosci.2014.03.003.
- 241 [2] P. Takoutsing, R. Wamkeue, M. Ouhrouche, F. Slaoui-Hasnaoui, T.
242 Tameghe, G. Ekemb, Wind Turbine Condition Monitoring: State-of-
243 the-Art Review, New Trends, and Future Challenges, *Energies.* 7 (2014)
244 25952630. doi:10.3390/en7042595.
- 245 [3] G.F. Pereira, L.P. Mikkelsen, M. McGugan, Crack Detection in Fibre
246 Reinforced Plastic Structures Using Embedded Fibre Bragg Grating
247 Sensors: Theory, Model Development and Experimental Validation.,
248 *PLoS One.* 10 (2015) e0141495. doi:10.1371/journal.pone.0141495.
- 249 [4] H. Hu, S. Li, J. Wang, Y. Wang, L. Zu, FBG-based real-time evaluation
250 of transverse cracking in cross-ply laminates, *Compos. Struct.* 138 (2016)
251 151160. doi:10.1016/j.compstruct.2015.11.037.
- 252 [5] O. Hassoon, M. Tarfoui, a El Malk, Numerical Simulation of Fiber Bragg
253 Grating Spectrum for Mode- Delamination Detection, *Int. J. Mech.*
254 *Aerospace, Ind. Mechatronics Eng.* 9 (2015) 144149.
- 255 [6] M. Yamada, K. Sakuda, Analysis of almost-periodic distributed feedback
256 slab waveguides via a fundamental matrix approach., *Appl. Opt.* 26
257 (1987) 34743478. doi:10.1364/AO.26.003474.

- 258 [7] K. Peters, M. Studer, J. Botsis, A. Iocco, H. Limberger, R. Salath,
259 Embedded optical fiber Bragg grating sensor in a nonuniform strain
260 field: Measurements and simulations, *Exp. Mech.* 41 (2001) 1928.
261 doi:10.1007/BF02323100.
- 262 [8] H.-Y. Ling, K.-T. Lau, W. Jin, K.-C. Chan, Characterization of dynamic
263 strain measurement using reflection spectrum from a fiber Bragg grating,
264 *Opt. Commun.* 270 (2007) 2530. doi:10.1016/j.optcom.2006.08.032.
- 265 [9] Y. Chen, J. Li, Y. Yang, M. Chen, J. Li, H. Luo, Numerical modeling
266 and design of mid-infrared FBG with high reflectivity, *Opt. - Int. J. Light*
267 *Electron Opt.* 124 (2013) 25652568. doi:10.1016/j.ijleo.2012.07.016.
- 268 [10] A. Ikhlef, R. Hedara, M. Chikh-bled, Uniform Fiber Bragg Grating mod-
269 eling and simulation used matrix transfer method, *IJCSI Int. J. Comput.*
270 *Sci.* 9 (2012) 368374.
- 271 [11] L. Bjerkan, K. Johannessen, X. Guo, Measurements of Bragg grating
272 birefringence due to transverse compressive forces, *Proc. 12th Interna-*
273 *tional Conference on Optical Fiber Sensors*, 16 (1997) 6063.
- 274 [12] F. Jlich, J. Roths, Comparison of transverse load sensitivities of fibre
275 Bragg gratings in different types of optical fibres, in: F. Berghmans,
276 A.G. Mignani, C.A. van Hoof (Eds.), *Opt. Sens. Detect.*, 2010: p.
277 77261N. doi:10.1117/12.854019.
- 278 [13] L. Sorensen, J. Botsis, T. Gmr, J. Cugnoni, Delamination detec-
279 tion and characterisation of bridging tractions using long FBG opti-
280 cal sensors, *Compos. Part A Appl. Sci. Manuf.* 38 (2007) 20872096.
281 doi:10.1016/j.compositesa.2007.07.009.
- 282 [14] S. Stutz, J. Cugnoni, J. Botsis, Crack fiber sensor interaction and char-
283 acterization of the bridging tractions in mode I delamination, *Eng. Fract.*
284 *Mech.* 78 (2011) 890900. doi:10.1016/j.engfracmech.2011.01.014.

285 **Appendix A: Spectrum Simulation Theory and Algorithm**

286 In a free state, without strain and at a constant temperature, the spectral
 287 response of a homogeneous FBG is a single peak centred at wavelength λ_b ,
 288 which can be described by the Bragg condition.

$$\lambda_b = 2n_{eff}\Lambda_0 \quad (1)$$

289 The parameter n_{eff} is the mean effective refractive index at the location
 290 of the grating, Λ_0 is the constant nominal period of the refractive index
 291 modulation, and the index 0 denotes unstrained conditions (initial state).

292 The change in the grating period due to a uniform strain field is described
 293 in equation (2),

$$\Lambda(x) = \Lambda_0[1 + (1 - p_e)\varepsilon_{FBG}(x)] \quad (2)$$

294 where the parameter p_e is the photo-elastic coefficient, and $\varepsilon_{FBG}(x)$ is the
 295 strain variation along the optical fibre direction [7]. The variation of the
 296 index of refraction δn_{eff} of the optical fibre is described by equation (3),

$$\delta n_{eff}(x) = \overline{\delta n_{eff}} \left\{ 1 + \nu \cos \left[\frac{2\pi}{\Lambda_0} x + \phi(x) \right] \right\} \quad (3)$$

297 where ν is the fringe visibility, $\phi(x)$ is the change in the grating period along
 298 the length, and $\overline{\delta n_{eff}}$ is the mean induced change in the refractive index [7].

299 By the couple-mode theory, the first order differential equations describ-
 300 ing the propagation mode through the grating x direction are given by equa-
 301 tions (5) and (5).

$$\frac{dR(x)}{dx} = i\hat{\sigma}R(x) + i\kappa S(x) \quad (4)$$

$$\frac{dS(x)}{dx} = i\hat{\sigma}S(x) + i\kappa R(x) \quad (5)$$

302 The parameter $R(x)$ and $S(x)$ are the amplitudes of the forward and
 303 backward propagation modes, respectively, $\hat{\sigma}$ is the self-coupling coefficient
 304 as function of the propagation wavelength λ , and κ is the coupling coefficient
 305 between the two propagation modes [7, 8, 9].

306 The self-coupling coefficient $\hat{\sigma}$ for a uniform grating ($\phi(x) = 0$) in function
 307 of the propagation wavelength λ is described in equation (6), where the

308 parameter λ_b is the FBG reflected wavelength in an unstrained state defined
 309 by the equation (1).

$$\hat{\sigma} = 2\pi n_{eff} \left(\frac{1}{\lambda} - \frac{1}{\lambda_b} \right) + \frac{2\pi \overline{\delta n_{eff}}}{\lambda} \quad (6)$$

310 The coupling coefficient between the two propagation modes κ is defined
 311 by equation (7), where the parameter m is the striate visibility that is ≈ 1
 312 for the conventional single mode FBG [8, 9].

$$\kappa = \frac{\pi}{\lambda} m \overline{\delta n_{eff}} \quad (7)$$

313 Spectrum reconstruction

314

315 The optical response matrix of the i th (each segment) uniform grating
 316 can be described by the coupled mode theory [4, 8]. By considering the FBG
 317 length (L) divided in n short segments, then the $\Delta x = L/n$ is the length
 318 of each segment. Note that n is constrained by the grating period [8], as
 319 described by equation (8).

$$n \leq \frac{2n_{eff} L}{\lambda_b} \quad (8)$$

320 For the FBG length limits, $-L/2 \leq x \leq L/2$, and the boundary condi-
 321 tions, $R(-L/2) = 1$ and $S(L/2) = 0$, the solution of the coupling mode of
 322 equations (5) and (5) can be expressed as:

$$\begin{bmatrix} R(x_{i+1}) \\ S(x_{i+1}) \end{bmatrix} = F_{x_i, x_{i+1}} \begin{bmatrix} R(x_i) \\ S(x_i) \end{bmatrix} \quad (9)$$

323 where $R(z_i)$ and $S(z_i)$ are the input light wave travelling in the positive
 324 and negative directions, respectively, and $R(z_{i+1})$ and $S(z_{i+1})$ are the output
 325 waves in the positive and negative directions, respectively. Thus, the TTM
 326 matrix $F_{x_i, x_{i+1}}$ for each segment (Δx) of the grating can be calculated using
 327 the equation (10) and (11).

$$F_{x_i, x_{i+1}} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \quad (10)$$

$$\left\{ \begin{array}{l} S_{11} = \cosh(\gamma_B \Delta x) - i \frac{\hat{\sigma}}{\gamma_B} \sinh(\gamma_B \Delta x) \\ S_{12} = -i \frac{\kappa}{\gamma_B} \sinh(\gamma_B \Delta x) \\ S_{21} = i \frac{\kappa}{\gamma_B} \sinh(\gamma_B \Delta x) \\ S_{22} = \cosh(\gamma_B \Delta x) + i \frac{\hat{\sigma}}{\gamma_B} \sinh(\gamma_B \Delta x) \\ \gamma_B = \sqrt{\kappa^2 - \hat{\sigma}^2} \end{array} \right. \quad (11)$$

Finally, the grating total response matrix F is obtained by multiplication of each segment response matrix, as described in equation (12).

$$F = F_{x1} \cdot F_{x2} \dots F_{xn}. \quad (12)$$

328 And, the reflectance of the grating can be described by the equation (13).

$$R = \left| \frac{S(-L/2)}{R(-L/2)} \right|^2 = \left| \frac{S_{21}}{S_{11}} \right|^2 \quad (13)$$

329

FBG_SiMul spectrum simulation algorithm structure

330

331 The structure of the spectrum simulation algorithm implemented in the
 332 FBG_SiMul is shown in figure 8.

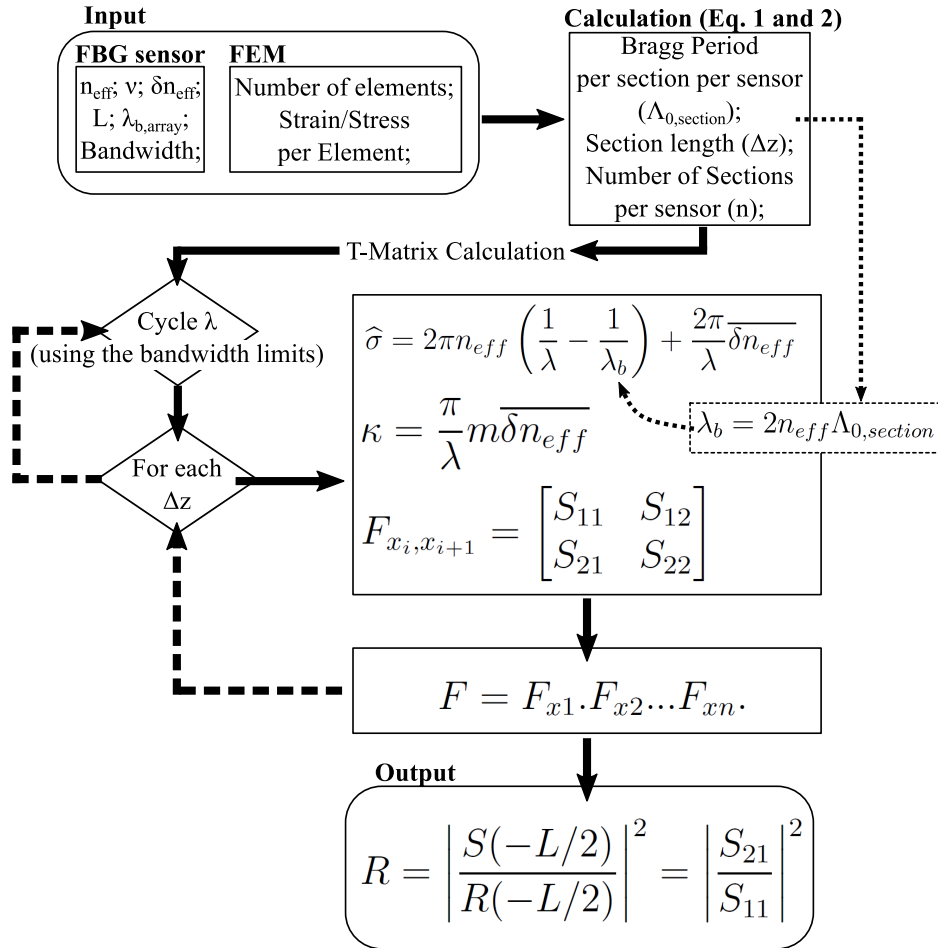


Figure 8: FBG_SiMul spectrum simulation algorithm structure.

333 **Required Metadata**

334 **Current executable software version**

Nr.	(executable) Software metadata description	Please fill in this column
S1	Current software version	V1.0
S2	Permanent link to executables of this version	https://github.com/GilmarPereira/FBG_SiMul.git
S3	Legal Software License	GNU GPL-3
S4	Computing platform/ Operating System	Windows;
S5	Installation requirements & dependencies	None for standalone file; Python 2.7.5 for Python format;
S6	If available, link to user manual - if formally published include a reference to the publication in the reference list	https://github.com/GilmarPereira/FBG_SiMul/blob/master/Standalone_Version/Software_Documentation.pdf
S7	Support email for questions	gfpe@dtu.dk; gilmar_fp@outlook.com;

Table 1: Software metadata (optional)