A High-Fidelity Interferogram Calculator for Coaxial Cable Fabry-Perot Interferometry

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Coaxial cable Fabry-Perot interferometry (CCFPI) can be used for robust distributed condition monitoring. This abstract presents the development and validation of a high-fidelity analytical tool, I-See, used to predict the interferogram of CCFPI, through finite element analysis and experimentation. This tool enables rapid analysis of CCFPI designs, accounting for cable properties, and isolates the analysis from experimental artefacts. The novel I-See analytical tool will be utilized in ongoing research conducted in this field.

Keywords: distributed sensing, coaxial cable Fabry-Perot interferometry, condition monitoring

Introduction

Coaxial cable Fabry-Perot interferometry (CCFPI) is an emerging field of condition monitoring sensing, analogous to fiber optics, operating in the microwave region of the electromagnetic spectrum. CCFPI provides a distributed sensing solution, avoiding the limitations of multiple point sensors (such as excessive cabling and localized spot monitoring) [1]. The robust structure of the coaxial cable carrier for the technique means CCFPI sensors can withstand more extreme handling and remote, challenging environments than their fiber optic counterparts. There are growing requirements for hardy condition monitoring sensors as clean energy industries develop. With potential applications in the offshore wind, carbon storage and fusion industries this is an important area of research as these industries become primary energy sources and bring new condition monitoring challenges.

The wider scope of current research is to examine the challenges of practical implementation of CCFPI for long-distance strain sensing applications, with the objective of new product development. To underpin this work an analytical tool (I-See (Interferogram Calculator (IC))) has been developed to aid the design of the CCFPI unit cell. Work presented in this abstract describes the creation of this novel tool and discusses the benefits it brings to the field.

A Fabry-Perot interferometer is an optical instrument constructed from two parallel, partially reflective surfaces [2]. Reflections from each surface interfere creating a fringed pattern of maxima (at constructive interference) and minima (at destructive interference). The frequency location of these maxima and minima are determined by the electromagnetic path length difference between the reflection from the first partial reflector and the reflection from the second partial reflector. The technique is not constrained to optical frequencies but can work across the electromagnetic spectrum. A Fabry-Perot interferometer is created on a coaxial cable by making a pair of partial reflectors through a localised change in impedance from either a variation in geometry, as illustrated in Figure 1a, or material property such as permittivity or permeability. The theory of using a coaxial cable Fabry-Perot interferometer (CCFPI) as a strain sensor is well documented [3-5]. As the cable strain increases, the separation distance of the two partial reflectors of the CCFPI increases and the location of the interferogram frequency maxima and minima shift. Strain measurements are deduced from observing frequency shifts in the interferogram pattern.

Research to date has used a single valued speed in the calculation of the interferogram [4], [5]. Novel work presented in this abstract has introduced a high-fidelity term for the phase speed, based on the Telegrapher's equations, which accounts for all losses present in a coaxial cable [6]. The basic CCFPI equations have been

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refined into high-fidelity terms with the phase speed more accurately represented with its dependence on frequency. This forms the basis of the I-See tool, enabling the impact of different coaxial cable properties on an interferogram pattern to be accounted for in rapid analysis.

Experimental/Simulation

I-See is an excel based tool and was written to follow the architecture outlined in Figure 1b. The interferograms generated by I-See were verified by finite element modelling (FEM) High Frequency Simulation Software (HFSS) and experimental samples.

The experimental samples were created by making two crimps, 20cm apart, in KSR400 coaxial cable using a crimping tool. The resulting interferogram was captured using a Vector Network Analyzer (VNA) Copper Mountain S5180B model measuring the S11 signal swept from 100kHz to 4GHz, 10dBm power, 100000 data points. Five experimental samples were measured to analyze the deviation between the experimental interferograms and those generated by I-See.

The experimental arrangement was modelled in HFSS for validation through FEM. A quarter symmetry model of a 0.8m length of KSR400 cable was constructed, with two crimps 20cm apart to mimic the experimental arrangement. The model was solved from 100kHz-4GHz over 800 data points.

Results and discussion

The interferograms of a 20cm CCFPI on KSR400 coaxial cable generated by HFSS, experiment and the newly developed I-See analytical tool are compared in Figure 1c. The frequency location of the interferogram minima is the key metric used to compare the three data sets.

There is good agreement between the I-See and experimental interferograms with an average discrepancy in minima frequencies (Hz) of 0.625%. The average difference in location of frequency minima (Hz) between the I-See data and HFSS is 0.063%. Discrepancies arise from the accuracy of the 20cm distance of the experimental CCFPIs and the inconsistency between the crimped forms of the two partial reflectors. The test data also carries artefacts such as spectral leakage from the gating functions used to isolate the CCFPI interferogram. For this reason, the first and last frequency minima have been discounted from the analysis, as this is where the largest distortion is observed. HFSS results are limited in resolution due to processing power restricting the number of data points practical for analysis. HFSS models a CCFPI on a coaxial cable system and is therefore also subject to non-infinite effects absent from the one dimensional mathematical I-See tool.

I-See provides a novel, rapid method to analyze a CCFPI design, accounting for cable properties through the inclusion of loss terms and a high-fidelity phase speed term. It is significantly faster to run than FEM and so provides a more cost-effective analysis. It can be used to quickly verify experimental arrangements, improving confidence in testing which ultimately saves time and money in avoiding experimental mistakes. I-See isolates the unit-cell of a CCFPI which enables the impact of different unit cell designs to be analyzed away from real-world artefacts such as spectral leakage and non-infinite effects seen in HFSS and experiment. Improvements are to be made in the amplitude prediction through inclusion of reflection coefficient calculations which are currently automatically handled in HFSS.

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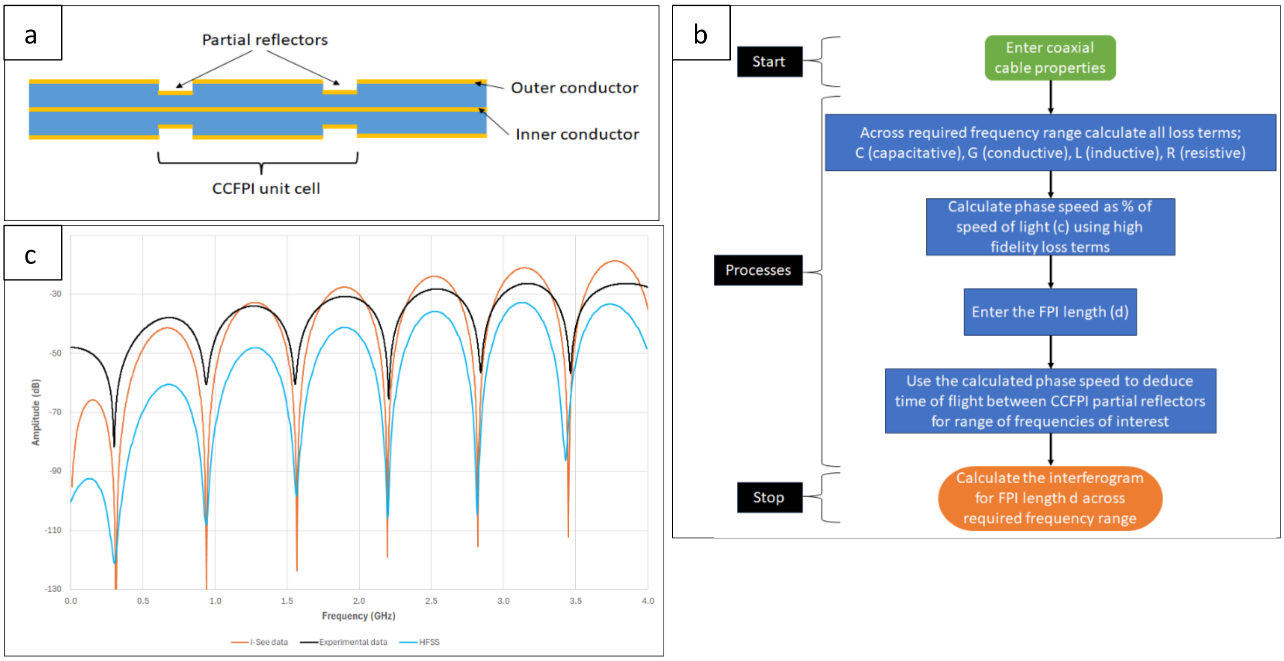

Figure 1. a) Schematic of a CCFPI unit cell b) Architecture of the I-See analytical tool c) Interferograms of a 20cm CCFPI on KSR400 cable deduced through experiment, finite element modelling and analytical modelling

Conclusion

The Telegrapher's equations have been combined with standard CCFPI equations to create a high-fidelity analytical model of a CCFPI unit cell, accounting for the coaxial cable properties. This excel-based analytical tool, I-See, predicts the interferogram of a CCFPI and has been validated through FEM and experimental data. I-See provides a method for rapidly verifying and optimizing experimental CCFPI set-ups, streamlining testing costs. The novel tool includes the impact of cable properties on CCFPI results, not previously accounted for in the CCFPI analytical equations presented in research to date. It also isolates the CCFPI behaviour from real-world effects to enable the analysis of new CCFPI unit cell designs away from measurement artefacts.

I-See underpins research currently being conducted on the challenges of practical implementation of CCFPI for long-distance strain sensing applications. Further work to improve I-See will include calculations for the reflection coefficients of the partial reflectors to improve the interferogram amplitude prediction.

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