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Nonlinear dynamic behavior of an impact damaged composite skin–stiffener structure

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ABSTRACT

One of the key issues in composite structures for aircraft applications is the early identification of damage. Often, service induced damage does not involve visible plastic deformation, but internal matrix related damage. A wide range of technologies, comprising global vibration and local wave propagation methods, can be employed for health monitoring purposes. Traditional modal analysis based methods are linear methods. The effectiveness of these methods is sometimes limited since they rely on a stationary and linear description of the system. The nonlinear interaction between a low frequency wave field and a local impact induced damage in a composite skin–stiffener structure is experimentally demonstrated in this work. The different mechanisms linked to the distorted waveforms are separated with the help of phase portraits. The harmonic waveform distortions are concentrated at the damaged region and increased for higher excitation amplitudes. It is shown that linear damage identification methods are feasible for low excitation amplitudes, but that the presence of nonlinear dynamic effects cannot remain silent for higher amplitudes. Analyzing the damage induced nonlinear effects can provide useful information about the current state of the structure.

1. Introduction

Composite skin–stiffener structures are a typical aerospace structural component used to increase the bending stiffness of a component without a severe weight penalty [1]. These skin–stiffener structures are considered to be safety-critical components. Small defects at the skin–stiffener connection, caused by for example impact, can significantly affect the performance of such a component. Often, the damage does not involve visible plastic deformations, but is barely visible and internal matrix related. This makes skin–stiffener connections a suitable candidate for health monitoring.

A wide range of technologies, comprising global vibration and local wave propagation methods, can be employed to monitor the integrity of structural components [2–6]. The selection of the best technology is often a matter of compromise.

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Traditional low frequency modal analysis based damage identification methods are linear methods [7,3]. Damage sensitive features are extracted by fitting a mathematical model to the responses measured. Despite various successful applications [8,9], the effectiveness of these linear methods is sometimes limited. Firstly, they tend to show a rather low sensitivity [10]. Secondly, these methods rely on a stationary and linear description of the system, which can be inappropriate in case clear nonlinear effects are present in the responses. A more realistic description requires a physical understanding of the effect of the damage on the dynamic behavior of the structure. The interaction between damage and an acoustic wave field can yield dynamic phenomena that exhibit complicated material (e.g. nonlinear elasticity) and geometrical (e.g. contact and friction) nonlinear behavior [11,12]. The symptoms related to these nonlinear phenomena can be utilized for nonlinear system characterization and damage identification purposes.

The most commonly used nonlinear feature is probably the generation of higher harmonics in the structural response. Selective imaging of these higher harmonics was used by Krohn et al. [13] and Solodov et al. [14] to localize and characterize small defects. Alternative nonlinear features are the generated sub-harmonics, DC offsets, wave form distortions, frequency shifts, coherence functions, signal modulations, etc. [3,15]. Various researchers [10,16,17] state the potentially higher sensitivity involved with these characteristics over the classical linear methods. However, difficulties concern the experimental evidence and understanding of the physical mechanisms related to the nonlinearities combined with the diversity of the nonlinear mechanisms originating at different scales of the composite component (micro-, meso- and macroscopic) [11]. Similar nonlinear effects can be a result of different mechanisms, hence hampering the separation of the mechanisms. Nonlinear elasticity and contact nonlinearities can, for example, both yield higher harmonics in a dynamic response [15].

Researchers try to obtain a better understanding of the mechanisms involved with the help of modeling. Della and Shu [18] reviewed models for the vibration of delaminated structures, while Friswell and Penny [19] did the same for crack-like damage. The complexity of the nonlinear effects introduced when non-bonded surfaces come into contact is one of the difficulties encountered in obtaining a realistic model representation. Solodov et al. [12] describe two of the nonlinear mechanisms involved with contact, the clapping and the friction mechanism. The clapping nonlinearity is assumed to be concerned with the lack of stiffness symmetry across the damage interface. One of the studies focusing on this delamination induced mechanism is presented by Müller et al. [20,21]. They experimentally analyzed the vibro-impacting motion, including energy dissipation effects, along the contact interface of the delamination to establish a finite element description. As in many other investigations, their study is limited to an artificial delamination, in this case in a simple aluminum beam.

This paper focuses on a composite skin–stiffener-like structure featuring impact induced damage. An experimental time domain analysis of the nonlinear dynamic behavior introduced by the damage is presented. The impact induced damage is located at the connection between skin and stiffener and mainly consists of delamination damage. The objective is to gain an understanding of the interaction between a dynamic wave field and the local skin–stiffener failure in order to support the development of damage identification approaches that are able to characterize skin–stiffener damage. A low frequency steady-state harmonic shaker excitation was used. Responses were measured by a laser vibrometer at multiple points underneath the skin–stiffener connection. The dynamic mechanisms related to the nonlinear dynamic effects in the harmonic waveforms are identified with the help of phase portraits. Special attention is paid to the spatial effects and the influence of the excitation parameters. The study presented in this paper can lead to guidelines for the applicability of the linear damage identification methods, but can also trigger the development of enhanced damage identification methodologies.

2. Composite skin–stiffener structure

Thermoplastic composites provide specific opportunities due to their relatively high toughness and unique processing capabilities [1]. The ambition for automated manufacturing of large quantities of large composite structures has fueled the development of new cost-reducing joining concepts. Recently, a new butt-joint skin–stiffener concept was developed by Fokker Aerostructures [1]. This simplified manufacturing concept uses preforms, which are connected by an injection molded filler in a co-consolidation process.

The structure investigated in this study is a thermoplastic skin–stiffener section made by Fokker Aerostructures according to their new joining concept. The structure is schematically illustrated in Fig. 1. Both the skin and the stiffener are built from 16 individual plies of unidirectional carbon AS4D fiber reinforced thermoplastic (PEKK) material with a $[90/0]_{4,s}$ lay-up. The filler is made from PEKK and contains 20 wt% short carbon fibers.

The damage scenario analyzed in this study comprises an impact damage located at the connection between skin and stiffener. This connection is considered as a safety-critical area, because damage at this connection can have major implications for the integrity of the entire component. Damage was introduced by utilizing a falling weight impact device and applying a repeated impact up to 15 J. The ultrasonic C-scan in Fig. 2 reveals a relatively complex, but typical fiber reinforced material related damage scenario. The damage consists of delamination at the interface between the skin and the stiffener accompanied by a limited amount of damage between the first and the second ply of the skin. Local delaminations were also introduced underneath one of the supports that was used during the impact testing.