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Operational Modal Analysis of a wing excited by transonic flow

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ABSTRACT

Operational Modal Analysis (OMA) is a promising candidate for flutter testing and Structural Health Monitoring (SHM) of aircraft wings that are passively excited by wind loads. However, no studies have been published where OMA is tested in transonic flows, which is the dominant condition for large civil aircraft and is characterized by complex and unique aerodynamic phenomena. We use data from the HIRENASD large-scale wind tunnel experiment to automatically extract modal parameters from an ambiently excited wing operated in the transonic regime using two OMA methods: Stochastic Subspace Identification (SSI) and Frequency Domain Decomposition (FDD). The system response is evaluated based on accelerometer measurements. The excitation is investigated from surface pressure measurements. The forcing function is shown to be non-white, non-stationary and contaminated by narrow-banded transonic disturbances. All these properties violate fundamental OMA assumptions about the forcing function. Despite this, all physical modes in the investigated frequency range were successfully identified, and in addition transonic pressure waves were identified as physical modes as well. The SSI method showed superior identification capabilities for the investigated case. The investigation shows that complex transonic flows can interfere with OMA. This can make existing approaches for modal tracking unsuitable for their application to aircraft wings operated in the transonic flight regime. Approaches to separate the true physical modes from the transonic disturbances are discussed.

1. Introduction

In recent years significant progress has been made in developing and refining modal parameter identification methods that use environmental loads as the primary source of structural excitation. Those methods are today known under the name Operational Modal Analysis (OMA) [1]. Modal parameters identified with OMA have been shown to be suitable for Structural Health Monitoring (SHM) of large civil engineering structures [2]. However, only limited publications have investigated the application of similar techniques to aircraft wings, and there is a lack of knowledge across a range of critical areas.

Abdelghani et al. [3] investigated an output-only subspace-based damage detection algorithm using a Paris MS760 airplane in a Ground Vibration Test (GVT). They showed that it is possible to detect small mass (2%) and stiffness changes (blocked and released ailerons). The structure was artificially excited at two points with random white signals. Mevel et al. [4], Debille and Peeters [5] and Peeters et al. [6] extracted natural frequencies and damping ratios from in-flight data, thereby showing that it is essentially possible to track some modal parameters during aircraft operation. However, they only published limited quantitative results and no information about the flight conditions.

The application of OMA to transonic flow has not been previously demonstrated. This is significant as transonic flow not only involves complex aerodynamic phenomena, but is the dominant flight regime for large passenger transport aircraft. As such, the performance of the various OMA techniques and their associated autonomous mode detection algorithms has not been characterized. For example, Stochastic Subspace Identification (SSI) is considered to be one of the most powerful parametric time-domain system identification methods [7], which was investigated in a variety of output-only damage detection or SHM studies [2,8]. The vast majority of hitherto proposed SSI-based automatic modal parameter extraction methods for SSI try to automatize the interpretation of the consistency or stabilization diagram [9]. In contrast, Frequency Domain Decomposition (FDD) is a non-parametric frequency-domain method, which is an extension of the classic Peak Picking (PP) approach and was studied for damage detection and SHM as well [8,10]. Modal parameters are automatically de-

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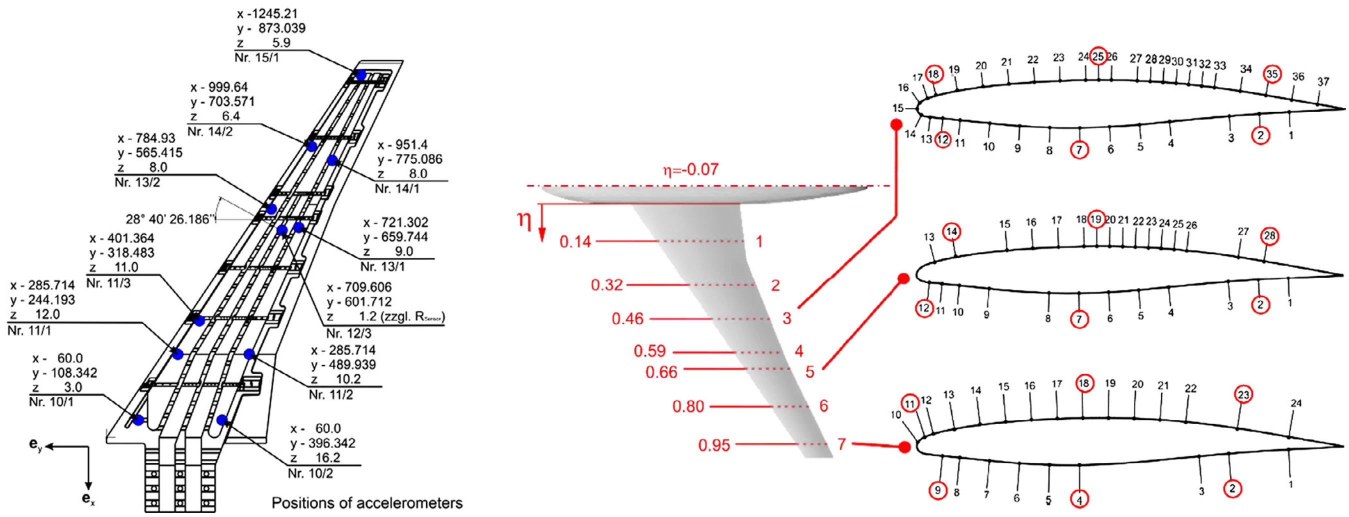

(a) Acceleration sensor positions.

(b) Pressure sensor positions. Only the measurements from the circled pressure sensors are used in this investigation.

Fig. 1. Accelerometer and pressure sensor positions and labels (adapted from [14]).

tected by searching for local maxima of the first singular value and subsequently checking the modal coherence in the vicinity of the peaks [11]. It is not known how the different mathematical foundations of automatic SSI and FDD perform for transonic flow excitation and whether there are any limitations of the techniques within this unique context. In addition, no wing-based OMA publications have used input load measurements to gain critical insight into the aerodynamic excitation.

This study focuses on modal parameter extraction from a large-scale wind tunnel wing model excited by transonic flow. Modal parameters (natural frequencies, mode shapes and damping ratios) are extracted from dynamic measurements of the High Reynolds Number Aerostructural Dynamics (HIRENASD) wind tunnel model using two OMA-techniques: FDD and SSI. Previous studies have shown that a periodic pressure wave builds at the surface of the HIRENASD wing, when operated in the transonic flow regime [12]. The properties of this transonic phenomenon and its interaction with the elastic structure are studied in detail in this work within the context of the OMA techniques. The identified natural frequencies are compared to existing Experimental Modal Analysis (EMA) and Finite Element Method (FEM) results. The Angle Of Attack (AOA)-variability of the identified modal properties as well as the AOA-variability of the encountered transonic pressure waves are examined. These findings are assessed in the context of SHM for aircraft structures.

2. Methods

2.1. HIRENASD model and data

A dataset from the HIRENASD wind tunnel experiment is used for the present investigation. The HIRENASD project was a study of an elastic wing model in the transonic regime carried out in 2006. The tests were conducted at the European Transonic Wind tunnel (ETW). The aeroelastic behavior of a fixed-wing model was investigated at Reynolds and Mach numbers that are typically encountered by large aircraft in cruise flight. The wing was equipped with 9 functional accelerometers whose positions are shown in Fig. 1a and 205 functional pressure sensors distributed over 7 span-wise sections, which are shown in Fig. 1b.

The 1.3 m semispan wing model was developed with Mach-number and Reynolds-number similarity in mind. The structure was designed to withstand the high aerodynamic loads and, at the same time, to allow for well measurable deformations. Other design goals were well separated fundamental eigenmodes, the ability to artificially excite the structure in a wide frequency range and operability under cryogenic conditions. According to Korsch et al. [13] the desired static and dynamic system properties were attained in an iterative design process using academic and commercial finite element analysis and fluid–structure interaction tools. Detailed information about the experiment, the design goals and the iterative process of development were published in [12,13].

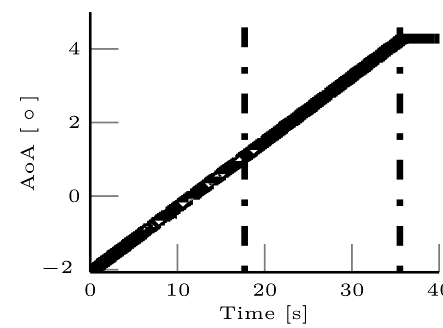

Fig. 2. AOA time-history.

In this study results from a single 41 second measurement at a fixed operation point are investigated. The dataset was recorded at 279 K total temperature and 136 kPa total pressure. The free-stream Mach number was set to 0.8 resulting in a mean chord-based Reynolds number of 7×10^6 ($c_{ref} = 0.3445$ m). The AOA was slowly changed during the recording window from $-2.1°$ to $+4.2°$ at a rate of change of $\approx 0.18°/s$ (Fig. 2). The dataset was separated into two non-overlapping blocks with a duration of 17.95 s each. The split was performed to confine the non-stationary influence of the AOA-sweep and to be able to assess the variation of the identification process. The block size is chosen to include approximately 500 recurrences of the lowest natural frequency to allow for a statistically valid identification. Additional investigations with a further subdivided dataset were conducted to examine the natural frequency evolution with increasing AOA.

Modal parameters were extracted using the commercial software ARTeMIS Modal [15]. Linear trends were removed, the data were processed through a low-pass filter with a cut-off frequency of 480 Hz and subsequently decimated to a sampling rate of 1000 Hz. The resolution for the Curve-fit Frequency Domain De-