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A stochastic global identification framework for aerospace structures operating under varying flight states

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ABSTRACT

In this work, a novel data-based stochastic "global" identification framework is introduced for aerospace structures operating under varying flight states and uncertainty. In this context, the term "global" refers to the identification of a model that is capable of representing the structure under any admissible flight state based on data recorded from a sample of these states. The proposed framework is based on stochastic time-series models for representing the structural dynamics and aeroelastic response under multiple flight states, with each state characterized by several variables, such as the airspeed, angle of attack, altitude and temperature, forming a flight state vector. The method's cornerstone lies in the new class of Vector-dependent Functionally Pooled (VFP) models which allow the explicit analytical inclusion of the flight state vector into the model parameters and, hence, system dynamics. This is achieved via the use of functional data pooling techniques for optimally treating – as a single entity – the data records corresponding to the various flight states. In this proof-of-concept study the flight state vector is defined by two variables, namely the airspeed and angle of attack of the vehicle. The experimental evaluation and assessment is based on a prototype bio-inspired self-sensing composite wing that is subjected to a series of wind tunnel experiments under multiple flight states. Distributed micro-sensors in the form of stretchable sensor networks are embedded in the composite layup of the wing in order to provide the sensing capabilities. Experimental data collected from piezoelectric sensors are employed for the identification of a stochastic global VFP model via appropriate parameter estimation and model structure selection methods. The estimated VFP model parameters constitute two-dimensional functions of the flight state vector defined by the airspeed and angle of attack. The identified model is able to successfully represent the wing's aeroelastic response under the admissible flight states via a minimum number of estimated parameters compared to standard identification approaches. The obtained results demonstrate the high accuracy and effectiveness of the proposed global identification framework, thus constituting a first step towards the next generation of "fly-by-feel" aerospace vehicles with state awareness capabilities.

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Acronyms

AoA	angle of attack
AR	autoregressive
ARMA	autoregressive moving average
ARMAX	autoregressive moving average with exogenous excitation
ARX	autoregressive with exogenous excitation
BIC	Bayesian information criterion
CFD	computational fluid dynamics
CMOS	complementary metal–oxide–semiconductor
FEM	finite element model
FP	functionally pooled
FRF	frequency response function
GA	genetic algorithm
HALE	high altitude long endurance
iid	identically independently distributed
LCO	limit-cycle oscillation
LPV	linear parameter varying
MA	moving average
MEMS	micro-electro-mechanical systems
NLS	nonlinear least squares
OLS	ordinary least squares
PCB	printed circuit board
PE	prediction error
PZT	lead zirconate titanate
RSS	residual sum of squares
RTD	resistive temperature detector
SACL	structures and composites laboratory
SHM	structural health monitoring
SPP	samples per parameter
SQP	sequential quadratic programming
SSS	signal sum of squares
UAV	unmanned aerial vehicle
VFP	vector-dependent functionally pooled
WLS	weighted least squares
X	exogenous

Important conventions and symbols

Definition is indicated by $:=$. Matrix transposition is indicated by the superscript T.

Bold-face upper/lower case symbols designate matrix/column-vector quantities, respectively.

A functional argument in parentheses designates function of a real variable; for instance $P(x)$ is a function of the real variable x.

A functional argument in brackets designates function of an integer variable; for instance $x[t]$ is a function of normalized discrete time $(t = 1, 2, \ldots)$. The conversion from discrete normalized time to analog time is based on $(t-1)T_s$, with T_s designating the sampling period.

A hat designates estimator/estimate; for instance $\widehat{\boldsymbol{\theta}}$ is an estimator/estimate of $\boldsymbol{\theta}$.

1. Introduction

The next generation of intelligent aerospace structures and aerial vehicles will be able to “feel”, “think”, and “react” in real time based on high-resolution state-sensing, awareness, and self-diagnostic capabilities. They will be able to sense and observe phenomena at unprecedented length and time scales allowing for real-time optimal control and decision making, significantly improved performance, adaptability, autonomous operation, increased safety, reduced mission and maintenance costs, and complete life-cycle monitoring and management. One of the main challenges of the current state-of-the-art research is the development of technologies that will lead to autonomous “fly-by-feel” aerial vehicles inspired by the unprecedented sensing and actuation capabilities of biological systems. Such intelligent air vehicles will be able to (i) sense the external environment (temperature, air pressure, humidity, etc.) [1,2], (ii) sense their flight and aeroelastic state (airspeed, angle of attack, flutter, stall, aerodynamic loads, etc.) and internal structural condition (stresses, strains, damage) [3–5], and (iii) effectively interpret the sensing data to achieve real-time state awareness and health monitoring [6–13].