Journal of Sound and Vibration 400 (2017) 457–480

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Energy based correlation criteria in the mid-frequency range

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ARTICLE INFO

Article history:
Received 20 August 2015
Received in revised form
25 January 2017
Accepted 14 April 2017
Handling Editor: A.V. Metrikine

Keywords:
Structural dynamics
Vibroacoustics
Numerical & experimental model correlation
Kinetic energy distribution
Mid-, high-frequency range
High spatial resolution measurements
Model validation
Model updating

ABSTRACT

Aircraft structures are characterized by their lightweight design. As such, they are prone to vibrations. Numerical models based on the Finite Element Method often show significant deviations when the mid-frequency range is considered, where strong interaction between vibrations and acoustics is present. Model validation based on experimental modal data is often not possible due to the high modal density that aircraft fuselage structures exhibit in this frequency range. Classical correlation criteria like the Modal Assurance Criterion require mode shapes and can therefore not be applied. Other correlation criteria using frequency response data, such as the Frequency Domain Assurance Criterion, are highly sensitive to even small structural modifications and fail to indicated the correlation between test and analysis data in the mid-frequency range. Nevertheless, validated numerical models for the mid- to high-frequency ranges are a prerequisite for acoustic comfort predictions of aircraft cabin. This paper presents a new method for the correlation of response data from test and analysis in the mid-frequency range to support model validation in the mid-frequency range and to enable the usage of finite element models in this frequency range. The method is validated on a stiffened cylindrical shell structure, which represents a scale-model of an aircraft fuselage. The correlation criterion presented here is inspired by Statistical Energy Analysis and is based on kinetic energies integrated over frequency bands and spatially integrated over surface areas of the structure. The objective is to indicate frequency bands where the finite element model needs to be adjusted to better match with experimental observations and to locate the areas where these adjustments should be applied.

1. Introduction

In the higher frequency range the vibrations of a lightweight structure couple with the vibrations of the surrounding fluid, which lead to sound radiation. When aircraft cabin comfort is addressed, the structure is a stiffened cylindrical shell, where the enclosed cabin forms a cavity. The accurate prediction of structural vibrations, fluid-structure coupling and pressure fluctuations inside the cavity are essentially important for the optimization of the acoustic comfort inside an aircraft cabin.

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http://dx.doi.org/10.1016/j.jsv.2017.04.024
0022-460X/

For vibroacoustic applications the relevant frequency range of the tonal excitations of the turbo-prop engines is the so-called mid-frequency range. Numerical structural-dynamical models used for vibroacoustic predictions and analyses often show significant deviations from experimental results in the mid-frequency range.

For example, vibroacoustic tests in flight including a propeller excitation have been performed on a SAAB 340 ([1]). A modal correlation of the test data to the results of a FE-model of the SAAB 340 fuselage section failed in the mid-frequency range due to the high modal density and a one-by-one Frequency Response Function (FRF) correlation was not feasible due to the high amount of FRFs ([2]). A Principle Field Shape Analysis of the measured FRF-matrix, which is based on a Singular Value Decomposition, showed more promising results. The field shapes of a chosen frequency band showed a good correlation between measurement and FE-simulation. A Modal and Principle Field Shape Analysis has also been applied to the acoustic field of a Dornier 228 cabin in flight, which is presented in ([3]).

The basic tools for the analysis of vibration problems in the low-frequency range are Finite Element Analysis (FEA) ([4]) on the numerical side and Experimental Modal Analysis (EMA) ([5]) on the testing side. Model validation of Finite Element models for the low-frequency range is mainly based on the correlation of eigenfrequencies and mode shapes from experiment and simulation and the adjustment of model parameters to minimize the deviations indicated by correlation. This is done, for example, for a wing-pylon structure in ([6]).

In the high-frequency range Statistical Energy Analysis (SEA) ([7]) is widely used for the determination of vibration and sound pressure levels in substructures of an overall assembled structure. This method analyses the energy transmission between substructures and requires a high modal density in each substructure. Even though it does not provide high-fidelity local information, SEA can predict the statistical averaged vibration levels of substructures in discrete spectral bands, e.g. third-octave bands. For correlation purposes in the higher frequency range, sound pressure and vibration levels are measured on predefined positions and are compared with simulated levels. The correlation based on eigenfrequencies and mode shapes is no longer possible because it is simply not possible to identify the modal parameters of all modes contributing to measured frequency response functions.

In this paper a correlation technique based on kinetic energy distributions is presented that can be applied on Finite Element models in the mid-frequency range.

2. Technical challenges for model validation from mid to high frequencies

Finite Element model validation is possible in the low-frequency range based on the correlation of experimental and analytical modal parameters, i.e. eigenfrequencies and mode shapes. The modal parameters are unique properties of a structure and can be used for the generation of an equivalent dynamic model of the structure to describe its vibration behaviour. The quality of the correlation between the modal parameters of a numerical model and experimental determined modal parameters is typically given in terms of eigenfrequency deviations and the Modal Assurance Criterion (MAC) ([8]). MAC is a scalar qualifier for the proof of the collinearity of two mode shape vectors, e.g. from simulation and experiment.

It is also possible to correlate measured and simulated operational deflection shapes (ODS) ([9]) in this frequency range. The Frequency Domain Assurance Criterion (FDAC) ([10]) can be applied to these deflection shapes. FDAC, for example, is used in ([11]) to evaluate new methods for dynamic response approximations to FE-results. In ([12]) FDAC is used for model updating based on response measurements of a simple aircraft-structure. In ([13,14]) a FE-model of a satellite is updated and validated by correlating modal parameters, operational deflection shapes and Frequency Response Functions with MAC, FDAC and FRAC ([15]). An other example of model updating and validation with FDAC is performed in ([16]) on a serial modular robot. In addition to FDAC the Partial Modal Assurance Criterion (PMAC) is used, which correlates only a subset of the modal vector.

In the mid- to high-frequency range correlation between simulation and experiment based on modal parameters is no longer possible. The reason for this is the high modal density in the mid- to high-frequency range, which makes a complete Experimental Modal Analysis impossible. Also model updating methods based on a modal approach are difficult for vibroacoustic models, which include frequency depended damping materials ([17]). Therefore, a new criterion is required for the correlation of simulation and experiment beyond the modal analysis domain. The dynamic response in this frequency range is characterized by a mix of global deterministic and local statistical behaviour.

> '[…] the mid-frequency problem (in which a system is neither entirely deterministic nor entirely statistical).' ([18], p. 1).

For the assessment of acoustic excitation, e.g. turboprop engines, and sound radiation it is less important to know exactly the local statistical behaviour. More important is the deterministic global dynamic response of the structure, which dominates the mid-frequency range. Stiffened cylindrical structures, e.g. aircraft fuselage, normally show a global dynamic behaviour in the mid-frequency range. The local vibrations of the skin fields between the stiffeners are superimposed to the global vibration pattern of the fuselage.

In case of acoustic assessment a relationship between the sound pressure level inside an aircraft cabin and the velocity of the fuselage surface can be determined. In a simple case of a flat plate this relationship is given by the Rayleigh-Integral ([19], p. 128). Under the assumption that the cavity density is constant and other effects like air flow are neglected, the Rayleigh-Integral provides an approximation of the sound pressure in a certain distance to the plate by separating the