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Computational modelling and experimental verification of the vibro-acoustic behavior of aircraft fuselage sections

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ABSTRACT

The aerodynamics of an aircraft impose significant stresses upon its structure. The turbulent boundary layer (TBL) is a highly turbulent layer that forms along the fuselage skin inducing localized pressure fluctuations resulting its vibration, and in turn, the generation of noise inside the passenger cabin. During flight, the noise generated by the TBL dominates the sound field between 100 Hz and 5 kHz, to be regarded as the frequency range of interest. While the audible range is between 20 Hz and 20 kHz, human hearing and speech intelligibility is most sensitive between 250 Hz and 2 kHz. This investigation considers a BEM-FEM-BEM modelling technique to predict the vibro-acoustic response of the fuselage and an experimental methodology to verify the results (following ASTM and ANSI testing standards) by imitating the frequency profile of the TBL using an acoustic source. The research incited construction of an atypical acoustic testing facility, the development of DAQ software and post-processing techniques of test data. The principal quantity of interest is transmission loss. Four panels (0.04 in., 0.063 in. (milled pockets to 0.043 in.), 0.063 in., and 0.09 in. in thickness) were simulated and tested between 20 Hz and 20 kHz. Analysis of the results sought to determine the limitations of the computational methodology by observing divergence of the predictions from the results. Divergence was defined as a difference exceeding 10% (approximately 4 dB), which was observed beyond 8 kHz. The comparisons show the frequency-averaged errors between the proposed methodologies to be within 5 dB between 20 Hz and 20 kHz, and 3 dB between 100 Hz and 5 kHz. Variability in reproducibility of experimental results (same test specimen and between test specimens) is a significant challenge when determining transmission loss values. The experimental methodology proved successful in differentiating between the panels with confidence using at least six tests over a period of three years. The computational methodology was accurate in estimating the transmission loss and the general (frequency-dependent) response.

1. Background and motivation

In an effort to further develop existing vibro-acoustic analysis techniques, a hybrid computational modelling methodology was developed using Finite Element Method (FEM) and Boundary Element Method (BEM) techniques to predict the vibro-acoustic response of a section of aircraft fuselage. The term BEM-FEM-BEM indicates the use of (1) BEM to excite structural vibrations in a thin structure adjacent to an acoustic excitation source such as the pressure fluctuations caused by a turbulent boundary layer (TBL) on the exterior of an aircraft fuselage during cruising flight, (2) FEM to analyze the vibrations induced into the thin structure caused by an acoustic field, and (3) BEM to calculate the resulting acoustic field on the opposite side of the thin structure resulting from the panel vibrations. BEM-FEM-BEM is abbreviated to FEM-BEM in this paper as a simplified reference.

The hybrid FEM-BEM approach utilizes the benefits of both methodologies. BEM implements Green's theorem to solve the partial differential equations (PDE) through integration. The solution can therefore be considered an exact solution. In contrast, FEM approximates the solution of the PDE using shape functions (e.g. polynomial functions) to best fit the boundary problem. For systems of increasing size and complexity, FEM is less computationally demanding than BEM; the resulting trade-off is precision at the expense of bias. A third common modelling technique known as Statistical Energy Analysis (SEA). It is based on the flow of energy within a system, or between subsystems, to solve the same problem as described above. SEA utilizes energy transfers and losses in its analysis.

The predictions using BEM have been found to be accurate at relatively low frequency ranges, with reported deviations in results at higher frequencies. SEA predicts values across higher frequency ranges more accurately, and has been reported to "fail" to predict results at lower frequencies [1–3]. These results are representative of the

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Nomenclature

α_R	absorption coefficient of the receive room
$\mathfrak{z}_S$	acoustic damping, or chocking, in the source room resulting that occurs as a result of a restricting volume (distortion of sound) of the source room
$\mathfrak{z}$	acoustic distortion, or damping, resulting from the confined space
BEM	Boundary Element Method
dB	decibels
DOF	Degrees Of Freedom
F_F	flanking measure that occurs from the source room into the receive room
F_P	permanent flanking measure that occurs from the source room into the receive room
FEM	Finite Element Method
L_{pbg}	measured sound pressure level with no signal (noise) on
L_{pbgr}	measured background sound pressure level in the receiving room
L_{pf}	sound pressure level of the free field having accounting for background noise
L_{pfm}	measured sound pressure level of the free field with the signal (noise) on
L_{pfr}	measured sound pressure level in the receiving room with the flanking plug installed and with the acoustic source on
L_{pfs}	measured sound pressure level in the source room with the flanking plug installed and with the acoustic source on
L_{pr}	sound pressure level of the room having accounted for the background noise
L_{prm}	sound pressure level of the room with the signal (noise on)
OB	Octave Bands
Q_{SD}	fractional measure of the direct portion of the sound field in the source room
Q_{SR}	fractional measure of the reflective portion of the source field in the source room
SEA	Statistical Energy Analysis
SPL	Sound Pressure Level
$SPL_{CR'}$	uncorrected computational SPL in the receive room
SPL_{CS}	corrected computational SPL (equal to the experimental SPL) in the source room
SWL	Sound Power Level
TBL	Turbulent Boundary Layer
TL	Transmission Loss

descriptions of the methodologies in the former paragraph. The evaluation of a structure's modal responses at lower frequencies is a simpler problem than that at higher frequencies due to the intrinsically larger modal density. With more complex systems, the evaluation of the system of equations becomes more difficult (especially at higher frequencies) via deterministic methods (BEM and FEM). Probabilistic methods (SEA) are generally more accurate at predicting the response at higher frequencies (utilizing the higher modal density: a larger population of conditions) than low frequencies (lower modal density: smaller population of conditions). For these reasons (complexity of structure and frequency range of interest), deterministic methodologies (BEM and FEM) are used to evaluate "micro"-scale simulations (i.e. subsystems), whereas probabilistic methodologies (SEA) are used for "macro"-scale simulations. Specialized hybrid techniques have been developed to pursue interest in applications that require a combination of the benefits of two or more, more fundamental methodologies (e.g. BEM-SEA and FEM-SEA in aerospace, rail, infrastructure). A demonstration of the benefits and disadvantages of deterministic and probabilistic approaches, respectively. Failure is defined as the significant divergence between the results generated by using computational predictions and experimental methods to analyze the same problem; specifically at higher frequencies.

Traditionally, hybrid FEM-BEM and FEM-SEA are used where there is an interaction between different dynamic systems (between vibrations, fluid, electromagnetism, acoustics, heat, etc.). A coupled analysis occurs when two, or more, dynamic systems influence each other concurrently. An analysis can include multiple systems and be considered uncoupled, where one system does not influence the other system (or one systems effects on another system are negligible) [4]. In the proposed FEM-BEM model, the structural vibrations of the model are predicted through FEM. The vibro-acoustic coupling and acoustic analysis is solved through BEM.

The principal mechanisms of the problem are vibrations and acoustics, though an understanding of fluid mechanics is also important. An aircraft fuselage develops a layer of turbulent air next to the skin during flight at cruising speed known as the Turbulent Boundary Layer (TBL). The TBL results in the shearing of air (acoustic noise) around the aircraft which in turn generates pressure fluctuations across the exterior surface of the fuselage. The resulting pressure differences (34.5 kN/m^2 to 51.4 kN/m^2 at MACH speeds of 0.60 and 0.78, respectively for a Boeing 737) cause the structure (primarily the skin that is unsupported between formers and stringers) to vibrate resulting in acoustic noise inside the cabin [5]. The resulting acoustic noise dominates inside the cabin between 100 Hz and 5000 Hz, or more selectively between 500 Hz and 2000 Hz [5]. The aforementioned frequency ranges are of principal interest, however measurements and predictions were recorded and analyzed across the entire human audible spectrum (20 Hz to 20 kHz). The aerodynamics of the aircraft structure contribute to the TBL model which considers the "Reynold's number (and flow) dependence of κ, the von Kármán constant, and proper scaling of inner and outer flows" [6]. The problem can therefore be described as an aero-vibro-acoustic problem.

As mentioned previously, the principal interests of this investigation were vibrations and acoustics. Provided the known aforementioned generalizations of the aerodynamic contribution, it was possible to reduce the problem to a vibro-acoustic analysis by incorporating the aerodynamic influence as physical inputs (initial/boundary conditions). Through the principles of vibro-acoustic reciprocity [7], the applied forces and/or pressure fluctuations that excite vibration in the structure were replaced using an acoustic noise source for simpler computational and experimental analysis. The above-mentioned description imitates the principles of modal analysis using an acoustic source [8]. The investigation could therefore be regarded as an acoustic-vibro-acoustic problem (which justifies the use of the given description of BEM-FEM-BEM) for the computational analysis and experimental testing.

The new design strategy amalgamates computational modelling and experimental testing using an atypical facility. Herein, the computational predictions were verified experimentally. The experimental methodology was developed as a practical, low-cost solution that could be utilized during the product design stage. A primary motivation of this work is to review the change in the vibro-acoustic response resulting from milling (reduction of thickness) of the fuselage skin. However, the principal objective of this work was to develop repeatable and reproducible computational and experimental methodologies to predict the dynamic response with confidence of aircraft skin to TBL excitation and the subsequent acoustic noise that is generated inside the aircraft due to the vibrating skin. This necessitated an associative formula to relate the experimental and computational efforts. Though a number of quantities were calculated and measured, it was decided that quantities of interest are sound pressure and transmission loss. The limits of the acoustic facility were measured through investigation of qualification tests that are recommended and defined by international