Optimized Synchrophasing System of a Turbo-prop Aircraft for Cabin Noise Reduction

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ABSTRACT

Propeller blades represent the main noise source from a turbo-prop (T/P) aircraft, causing both passenger discomfort and community annoyance. In order to significantly reduce cabin noise and vibration, T/P Aircraft is usually equipped with a synchro-phaser that compares and adjusts the azimuthal position of the two propellers.

In this paper, the numerical optimization of a synchro-phasing system of a turbo-prop aircraft equipped with two eight-bladed synchro rotating propellers has been carried out with the twofold aim of reducing both cabin and community noise. A multidisciplinary workflow including aeroacoustic and structural dynamic tools has been developed for coupled aero-vibro-acoustic analyses, with the phase shift among the two propellers assumed as design variable. This workflow has been finally embedded into Optimus, a commercial software environment for process integration and optimization. Two objective functions have been identified for the external and the internal noise reduction. Finally, a Pareto front of the optimal design points has been investigated showing that a reduction of up to 2dBA is feasible for cabin noise in cruise conditions by simultaneously preserving the community noise.

Keywords: aircraft cabin, modeling, cabin noise, community noise, aeroacoustics

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1. INTRODUCTION

Propeller blades represent the main noise source from a turbo-prop (T/P) aircraft, causing both passenger discomfort and community annoyance. The noise levels in the cabin of a turboprop aircraft typically are by 10 to 30 decibels higher than those observed for commercial jet noise and they are dominated by a few low frequency tones. In order to significantly reduce cabin noise and vibration, T/P Aircraft is usually equipped with a Synchro-Phaser that compares and adjusts the azimuthal position of the two propellers. The influence of the relative phase-shift among the propellers on the external and cabin noise has been investigated in the past both numerically and experimentally [1, 2]. Although propeller optimization for community noise reduction was completely investigated in the past [3,4,5,6,7] similar optimization problems for cabin noise reduction have not been completely investigated with a fidelity numerical manner.

In this work, the optimization of a synchrophasing system of a turbo-prop aircraft equipped with two eight-blades synchro rotating propellers has been carried out with the twofold aim of reducing both cabin and community noise.

Normally, synchrophasing is achieved by the pilot adjusting a rotary knob located on the centre pedestal to reduce the noise/vibration levels that are being experienced inside the cabin. Nevertheless, the low frequency acoustic field in the cabin is strongly dependent by the observer position, thus, different passengers experience a completely different well-being. For this reason, this work aims at finding an optimal propellers phase-shift that provides an averaged well-being for all passengers in their seated position. It is achieved through a coupled aero-acoustic and vibro-acoustic approach that represents the relative novel contribution of this work.

2. COMPUTATIONAL APPROACH

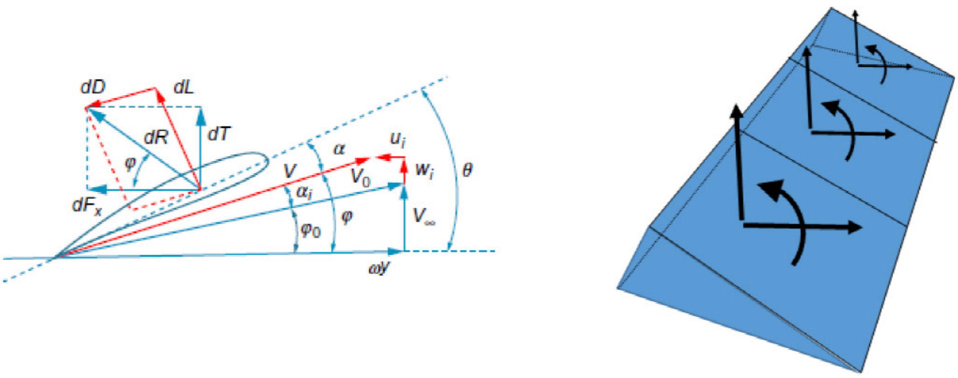
2.1 Propeller aerodynamic trimming and performance

The propeller performance code used in the present study [7] is based on the BEMT (Boundary Element Momentum Theory) approach that combines the propeller momentum balance and the spanwise distribution of aerodynamic forces generated by individual blade airfoils (Figure 1-a). Swirl velocities are duly taken into account. The code uses simplified aerodynamics which, for steady conditions, basically makes use of the 2D aerodynamic coefficients look-up tables and, for unsteady conditions, a BeddoesLieshman type state-space formulation. The code solves a transcendental equation to determine the sectional inflow angles in such a way to deal with large angles of attack. Several approximations are used for the stall treatment and the flow three-dimensionality.

2.2 External noise

The external tonal noise generated by the propeller is computed by means of the CIRA FW-H solver based on the forward time solution of formulation 1A by Farassat and Succi [10], as described in [11]. Only linear terms, respectively thickness and loading noise contributions, are computed through integrals on the blade surface. To exploit the spanwise distribution of the aerodynamic coefficients provided by the aerodynamic performance tool, a simplified rotor noise model is used (FRN). The FRN model [9] is based on the classical idea of replacing the rotor blade by an equivalent distribution of chordwise compact sources. In the hypothesis of far-field and geometric compactness conditions, the chordwise pressure distribution can be approximated with an equivalent

compact dipole through a linear distribution that guarantee the same span aerodynamic forces. Moreover, in order to model the effect of flow displacement due to the blade motion (thickness noise), an equivalent monopole is introduced by considering a blade section of equivalent area. The blade is therefore modeled as a spanwise sequence of wedges that undergo the same rotational and pitching motion of the original blade (Figure 1-b).
This approach also allows the FW-H computational time to be reduced by a significant factor, making more feasible the computation of large problems and the set of the optimization, while preserving, at the same time, an high accuracy level.



a) *b)*

Figure 1 – Schematic representation of the BEMT+FRN approach. Aerodynamic forces computed with the BEMT approach (a); Spanwise distribution of forces and wedges used as compact sources by FRN approach (b).

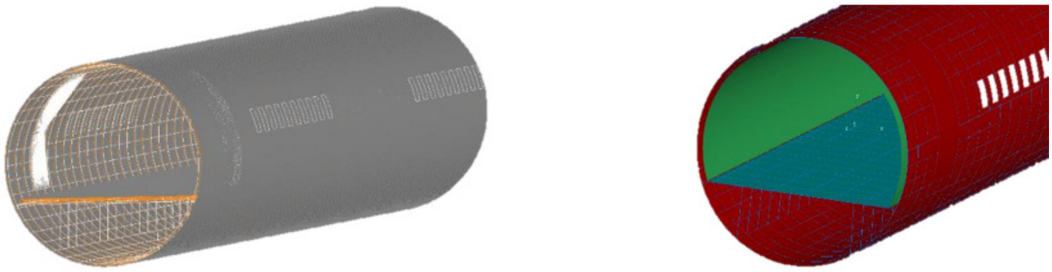
2.3 Cabin noise

Prediction of cabin noise at low frequency requires a full coupled vibro-acoustic analysis to take due account of all mutual interaction mechanisms occurring between structural and acoustic natural modes, especially at the first Blade Passage Frequency (BPF). A Direct Frequency Response analysis fully accomplishes the task when performed on the model representing both the fuselage airframe and the acoustic passenger cabin, by applying the pressure field generated by the propellers on the airframe external surface. The required analysis is executed through NASTRAN commercial code [12] by converting the pressure field to Nodal Forces applied to the 2D shell elements representing the airframe skin. To this purpose, DAREA and DPHASE cards have been used to properly allocate the forces by preserving both amplitude and phase information. The full coupling analysis is automatically set-up by inclusion of ACMODL card within NASTRAN Bulk Data input file. Not coincident conditions where imposed at the structure-fluid coupling interfaces.

3. REFERENCE TEST-CASE

A turbo-prop aircraft configuration equipped with two eight-blade synchrorotating propellers has been considered.
A structural FEM model of the whole aircraft fuselage has been developed with an automatic process that generates the airframe skin with two-dimensional shell elements and the reinforcement components (axial stringers, circumferential frames) with onedimensional equally spaced elements. The interior sandwich lining has been modeled

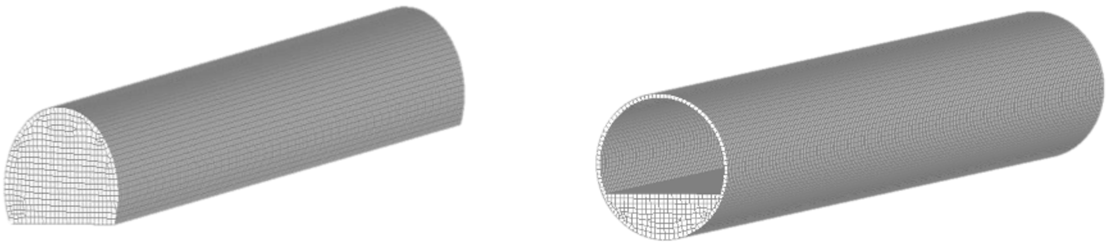
as a two-dimensional laminate constituted by fiberglass skins and a honeycomb core (Figure 2).



a) b)

Figure 2 – Structural FEM model of the fuselage. Without Lining (a); with Lining (b).

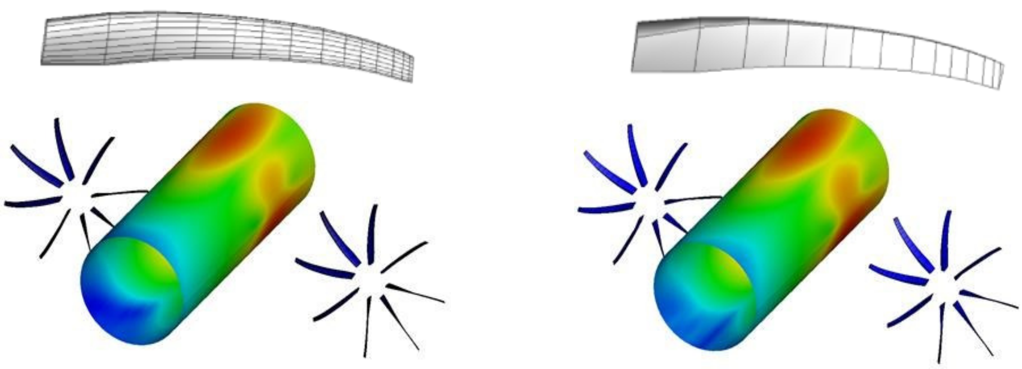
An acoustic FEM model is finally generated to fill the three main fuselage interior cavities, cabin area, cargo area and air-gap separating the airframe from the lining (Figure 3).



a) b)

Figure 3 – Acoustic FEM model of the cavities. Upper Cabin (a); Cargo area cabin & Airgap (b).

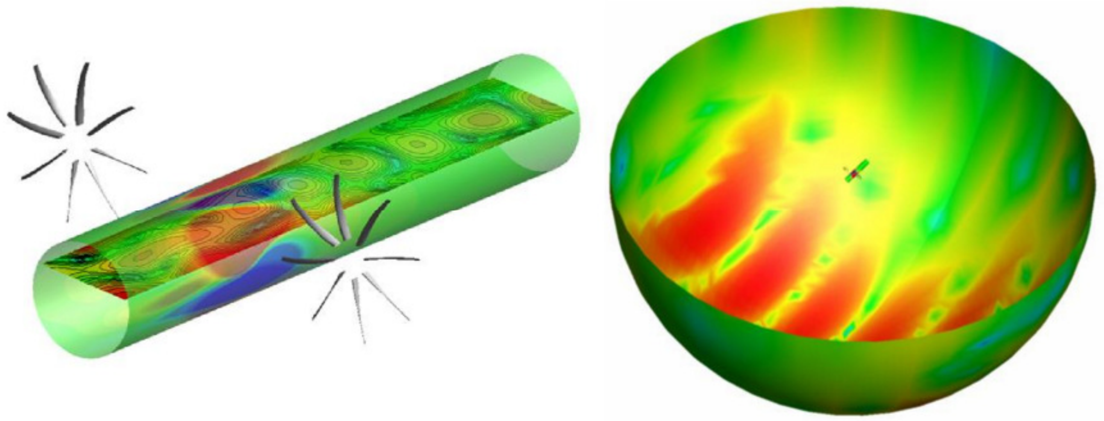
An 8-bladed propeller configuration has been automatically designed through the aerodynamic BEMT approach to meet top level performance requirements of the reference T/P aircraft at cruise condition. The BEMT+FRN approach has been firstly validated against RANS-CFD + FW-H results achieved on the isolated propeller (Figure 4).



a) b)

Figure 4 – Comparison between detailed (a) and compact approach (b) in terms of geometry discretization and Overall Sound Pressure Level contour. Detailed and compact computational approach are, respectively, based on CFD+FW-H and BEMT+FRN codes.

BEMT+FRN approach has been then used to compute acoustic time signals on both the whole fuselage surface and on a far-field hemi-sphere with a radius of 150m and transformed in the Fourier space. The first three Blade Passage Frequencies (BPF), being the dominant contribution, have been converted in acoustic loads acting and applied to the fuselage skin for structural dynamics analyses. Direct frequency vibro-acoustic analyses at the three BPFs has been computed with the NASTRAN software and cabin noise results extracted on a microphones plane located at the passengers’ ear level. Figure 5-a shows the real part of acoustic pressure distribution acting on the fuselage skin at the first BPF and the cabin Sound Pressure Level (SPL) distribution at the seated passenger positions. Figure 5-b shows the SPL contour of the far-field noise radiated by the propellers at the first BPF.



a) b)

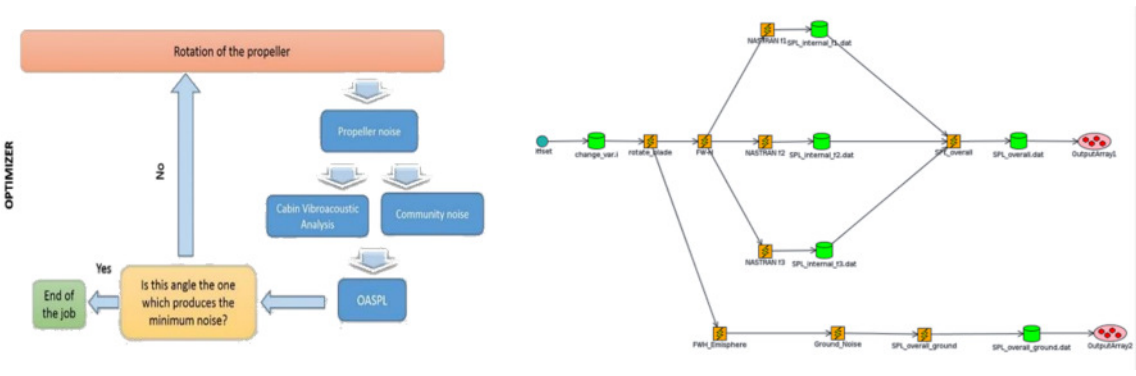
Figure 5 – Cabin noise and community noise computed with the aero-vibro-acoustic approach at the 1st BPF. Real part of the acoustic pressure acting on the fuselage skin and cabin acoustic field in terms of SPL at passengers’ ear level (a). Far-field acoustic field in terms of SPL on the hemi-sphere with a radius of 150 meters (b).

4. OPTIMIZATION PROCESS

4.1 Multidisciplinary workflow

Synchro-phasing system optimization for cabin tonal noise reduction requires suitable models, with adequate level of fidelity, for both the aero-acoustic behavior of the propellers and the coupled acoustic-structural dynamic of the fuselage.

The approach described in the Paragraph 3 and reported in Figure 6-a has been developed in the OPTIMUS [8] environment as depicted in Figure 6-b. SPL data computed at the first three BPFs are finally integrated to achieve the A-weighted Overall Sound Pressure Level (OASPL-A) for each microphone. The averaged and peak value of the OASPL-A are finally computed and used as output metrics of the multi-disciplinary workflow.



a) b)

Figure 6 – Multidisciplinary workflow. Workflow description (a) and implemented workflow in OPTIMUS (b).

4.2 Optimization tool

The commercial optimization tool OPTIMUS [8], developed by Noesis Solutions, has been used for the present study. This software allows to integrate arbitrary analysis codes, automate the Process Integration and Design Optimization (PIDO), control the data exchange between multidisciplinary codes and postprocess the analysis and optimization results. The key functionalities of several optimization methods are fully exploited to address the search of global and local optimal solutions. Design of experiment (DOE) and response surface model (RSM) techniques are available for the definition and exploration of the design space. The design optimization can be carried through genetic, gradient, and coupled genetic/gradient algorithms.

4.3 Parameterization

The phase shift among the two propellers has been assumed to be the only variable of the design space. A dedicated tool is developed to rotate one of the two propellers of an established phase angle between 0 and 45 degrees (Figure 7).

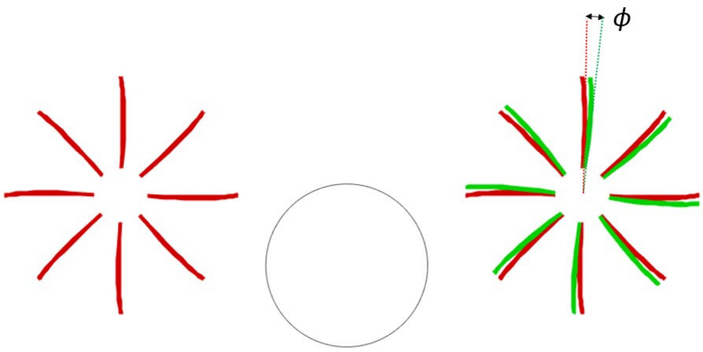


Figure 7 – Phase-shift angle parameterization.

4.4 Multi-Objective Optimization

The optimization strategy pursued in this work is based on a Design Of Experiment and the set of an appropriate Response Surface Model. An Adjustable Full Factorial approach consisting of 60 experiments has been chosen to explore the design space by varying the phase angle. Thus, a RSM is built with a Radial Basis Function (RBF) interpolation model with a cubic spline. The average and maximum value of the A-weighted Overall Sound Pressure Level (OASPL-A) computed on the surface plane at the passenger's ear level have been selected as output metrics for the cabin noise evaluation. The same metrics have been used for the external noise computation on the far-field hemisphere.

Based on the RSM, a multi-objective optimization has been performed. The averaged OASPL-A has been selected as objective function for both community and cabin noise. The Non-dominated Sorting Evolutionary Algorithm (NSEA+) has been chosen with the aim of handling input variable and converge toward a Pareto front. Figure 8 shows the scatter plot of DOE designs into the objectives' plane and the Pareto front resulting from the multi-objective optimization. The scatter plot gives evidence that two possible phase-shift angles exist that provide the same cabin noise performance but the correspondent external noise levels differ of around 1dBA. The nominal shift angle allows to achieve almost the minimum external noise but it is one of the worse angle for the internal noise. From the optimal designs on the Pareto front, three optimal points have been extracted and their relative acoustic performances against the nominal case are reported in Table 1. The Opt-3 is considered the best option since it allows an averaged noise reduction of around 3dBA and a peak reduction of 2dBA in the cabin with a slight penalty of 0.5 dBA for the external noise. However, the impact of external noise on the community is reduced when the aircraft is in cruise condition.

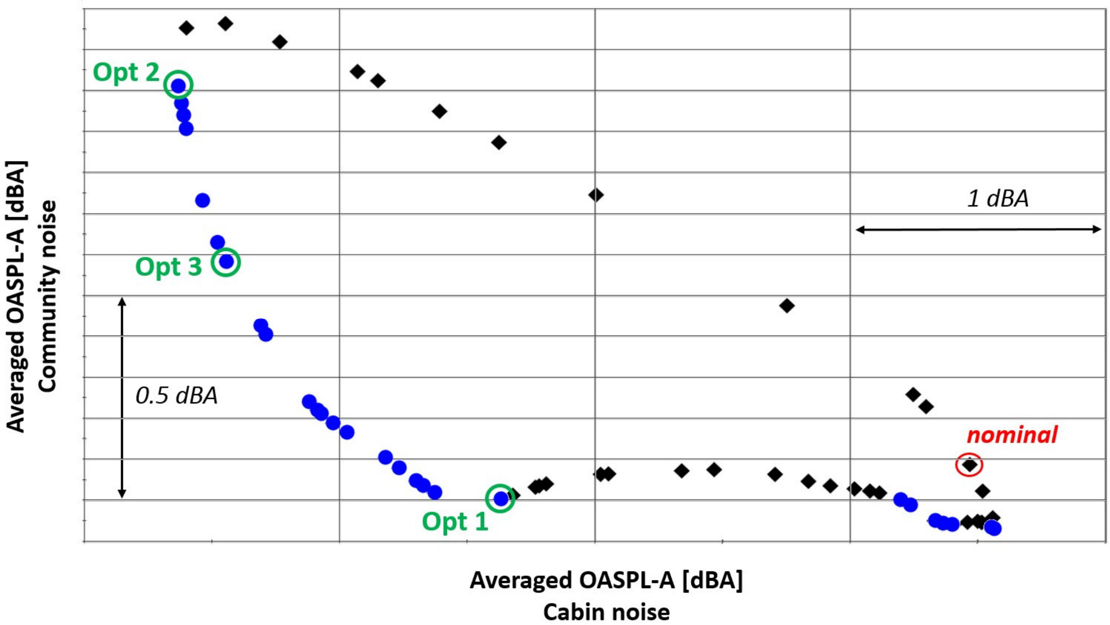


Figure 8 – Scatter plot (diamonds) and Pareto front (circles) of the multi-objective optimization.

Optimum point	Offset	OASPL-A max cabin	OASPL-A avg cabin	OASPL-A avg external
Opt 2	-17,8	-2,1	-3,1	0,9
Opt 3	23,4	-2,1	-2,9	0,5
Opt 1	16,6	-1,5	-1,8	-0,1

Table 1 – OASPL levels gains of optimal angles of the Synchrophasing system. Delta values are computed with respect to the Nominal case.

5. CONCLUSIONS

The optimization of the phase shift angle between two eight-bladed synchro rotating propellers of a turbo-prop aircraft has been carried out.

A multidisciplinary optimization process involving tools for aerodynamics, aeroacoustics and vibro-acoustic analyses has been built to evaluate the effect of the synchrophasing on the cabin noise.

An averaged cabin noise reduction up to 3dBA can be achieved by simultaneously maintaining the same community noise levels. This outcome allows emphasizing the role played by the synchrophasing system on the improvement of cabin noise passengers comfort. It is expected that the involvement of the blade shift angle among the design variables since the early aircraft design stages may lead towards more pronounced noise reductions.

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