A Surrogate-Assisted Analysis Framework for the Design Optimisation of Low-Boom Supersonic Transport

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URL	http://hdl.handle.net/10097/00135868

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学 位 論 文 題 目	A Surrogate-Assisted Analysis Framework for the Design Optimisation of Low-Boom Supersonic Transport (低ブーム超音速旅客機の設計最適化のための サロゲート支援解析フレームワーク)
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論文内容要約

A new automated framework for the analysis and design optimisation of low-boom supersonic transport (SST) is developed called "SST Optimisation, Uncertainty, and Design framework" (SOUnD). In recent years, there has been a renewed interest in SST, however one of the major issues with flying supersonic is the associated sonic boom, and recent international talks to lift bans on supersonic overland flight necessitate quieter SST, potentially with a challenging target of around 65 dB(A). Hence, a fast yet accurate method of designing low-boom wing planforms and exploring the design space is required. A conceptual designer needs a method to optimise the wing planform in 3D and generate useful, generalisable, global results. Furthermore, the manual process of geometry generation, mesh gridding, CFD data extraction/post-processing, and sonic boom propagation is also very labour intensive and is not desirable within an optimisation cycle.

In Chapter I, the challenges of supersonic flight and an introduction to efficient optimisation are discussed. To help a conceptual aircraft designer discover and explore new low-boom wing planforms, multidisciplinary design analysis and optimisation (MDAO) can be used to converge on desirable designs. Surrogate-assisted optimisation and machine learning methods, such as Bayesian optimisation (BO) can be used to accelerate the process by reducing the number of actual evaluations required. Kriging models are used as an inexpensive surrogate of the objectives and constraints. They can be coupled with the expected hypervolume improvement (EHVI) acquisition function to create a single function combining all the objectives and uncertainties. Kriging Believer (KB) is used to generate multiple samples so that CFD can be performed in batches, allowing high performance computing (HPC) environments to be fully utilised. Boom propagation can also be parallelised, making full use of multi-core workstations, allowing boom carpets to be analysed in minutes.

In Chapter II, the SOUnD framework is introduced, and the basic methodology and process workflow is developed. The processing capabilities of modern multi-core workstations and the University's Univa Grid Engine (UGE)-based HPC system to use available computational resources efficiently. A simple single-section wing planform parameterised with six-variables is optimised for low Euler drag and low A-weighted sonic boom loudness using a local optimiser (L-BFGS-B). This approach was found to successful, confirming that an EHVI-based BO within a KB loop was able to minimise the target objectives as desired.

In Chapter III, the addition of parasite drag is developed using a fast empirical method and is tested on the existing and an expanded eleven-variable two-section planform. A global optimiser (genetic algorithm) was also used so that the efficacy of using a local or global optimiser could be compared for EHVI-based BO for this class of problem. Although local optimiser was faster, the global optimiser resulted better convergence and proximity to the estimated Pareto front. An estimated wall-clock time of over 500 hours is saved using the KB-based BO in a parallel computing environment, reducing the time taken to run a 200-sample study from around 4 weeks to two weeks. CFD simulations were performed at a fixed angle of attack and a minimum lift constraint; this resulted in many samples generated to explore the feasible/infeasible boundary created by this constraint, and mad comparisons between designs more difficult. Low-boom designs tended to converge to high aspect ratio wings that were highly swept with dihedral, whereas low-drag designs tended to converge to short-span wings that featured compression lift.

In Chapter IV, a new baseline design representative of a real-world SST is constructed and explored, featuring a three-section wing parameterised with 45 design variables. A fixed lift methodology using two meshes was proposed and demonstrated. Furthermore, the addition of RBM as a third minimisation objective was used to explore the multi-objective multidisciplinary trade-offs. Neural network-based self-organising maps were used to reduce the dimensionality of the data for visualisation and polynomial chaos expansion, Shapley effects, was used to derive design variable sensitivities. The baseline design was found to be located on the low-drag ND front, with other low-drag designs similarly featuring thin wing section and high outboard sweep. Low-RBM wings tended to converge to forward-sweep designs with strong forward placement of the wing, which encouraged the formation of strong shockwaves under the aircraft to generate compression lift, like waveriders. Low-boom designs used strong rearward sweep, anhedral, and a very rearward placement of the wing, which lengthened the volume distribution of the aircraft to minimise noise and propagate shocks away from the undertrack. The extreme locations of the wing planforms resulted in many untrimmable and/or unstable designs.

In Chapter V, a semi-empirical method to calculate the centre of gravity, trim, longitudinal stability was introduced and implemented. Conceptual design methods to rapidly estimate the masses the main aircraft components were coupled to the geometry design and layout functionality of OpenVSP to efficiently generate mass properties for planform designs. The solutions obtained in the previous chapter were filtered using trim and stability criteria to discover designs which could be more realistically flown. The trade-offs for these designs are then explored and a wave drag analysis was performed to analyse the effect of optimisation objectives on each drag component. A compromise solution was found that reduced the root bending moment coefficient by 25% and the sonic boom loudness by 24% at the cost of a 5% increase in drag in comparison to the baseline aircraft design. At 85.6 dB(A), the lowest loudness design that was feasible is still very loud and is not likely to be acceptable, however is considerably quieter than the Concorde's sonic boom, which was 5 times louder at over 100 dB(A).

As a result of the research carried out in this dissertation, conceptual-level analysis and design optimisation of low-boom supersonic wing planforms can now be efficiently performed and will assist researchers and engineers to design the next generation of low-boom supersonic transport. Features and characteristics of low-boom design were explored, and trade-offs were analysed. The competing objectives between low-boom, low-drag, and low-RBM design are clear – there is no ideal design that can satisfy all three objectives. Furthermore, trim and stability were also found to be important constraints in optimisation of low-boom aircraft and should be actively included during low-boom optimisation to avoid the evaluation of many designs which are not trimmable. Based on the results obtained, a Mach 2.2 target flight speed is simply too fast to achieve a low-boom design using wing planform modifications alone. Lower loudnesses may be achievable if the fuselage is included for optimisation, but the low-boom target of 65 dB(A) is unlikely to be reached – future SST will likely also need to reduce their target flight Mach number. In future work, development of SOUnD to handle non-symmetrical aircraft will allow novel designs with promising low-boom capabilities to be analysed. Inclusion of a mixed fidelity approach will also allow wide design spaces to be explored even more efficiently.