IMPLICATION OF ULTRA HIGH BYPASS ENGINES ON AIRCRAFT DESIGN FEATURES AND MISSION

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ABSTRACT

With respect to the needs of future air traffic high bypass ratio jet engines still have an extremely high potential for further reduction of fuel consumption. The main driving parameter in this context is an increase of engine bypass ratio (BPR) i.e. the ratio between mass flow in the bypass duct and the mass flow passing through the hot part of the engine. However, beside of installation constraints (for example free space under the wings), this beneficial influence of the bypass ratio in general is strongly limited by the increase of installation losses due to larger fan and nacelle diameters. This increase is highly depending on the mission of the airplane which determines a certain combination of flight level and flight speed. In the present contribution this dependency is analysed in more detail. For a given future engine technology and given bypass ratios as a free parameter resulting optimum airframe designs and design cruise Mach numbers are derived. This unconventional approach at the end leads to suggestions for new combinations of engine bypass ratios, airplane design features and flight Mach numbers and flight levels. These combinations are investigated with respect to fuel consumption, main exhaust emissions and overall mission costs. The presented material will contribute also to the upcoming discussion of reducing fuel consumption and the ecological impact of airplanes by a careful choice of flight missions differing from today's standards.

1. INTRODUCTION AND GOALS OF INVESTIGATION

Standard flight missions in today's civil aviation are mainly based on airframe and engine design constraints referring to the 1960s when the first civil transport aircraft were equipped with turbofan engines. Since then, mission design including flight levels and cruise Mach numbers basically hasn't been altered. By contrast, the design of turbofan engines has significantly changed since improvements in aero-thermodynamic efficiency of turbo components and materials today allow much higher bypass ratios. This leads to considerably better propulsive efficiencies. However, taking advantage of these improvements is limited by unadapted flight mission designs.

With respect to this background, Bauhaus Luftfahrt has initialised a general investigation on airframe design and historically grown mission architecture in order to meet the requirements of advanced turbofan engines for minimum mission fuel burn. The goal of the investigations presented in this paper was the determination of optimum engine bypass ratios against mission design. Subsequently, mission fuel burn reduction potentials due to optimised mission profiles.

The approach presented in the following allows the analysis of the complex interaction between engine and airframe. For this purpose, parametric models of airframe and flight mission were set up. For the simulation of the considered ultra high bypass turbofan engine configurations, the gas turbine performance program GasTurb10 was applied. Part of the performed investigations are considerations of the impact of alternative mission designs on economic and ecological factors. Accordant estimation methods have been implemented to compute direct operating costs (DOC) and main exhaust emissions like carbon dioxide (CO_2), water vapour (H_2O) and nitrogen oxides (NO_x).

2. SYSTEM MODELLING

For the realisation of the desired parametric model of the entire system including engine, airframe and mission an appropriate platform had to be found. In order to achieve maximum flexibility in engine, airframe and mission design, a statistics and physics-based parametric aircraft model was implemented in Matlab [1]. As well a parametric flight mission, including numerical algorithms for the computation of mission fuel burn and mission exhaust emissions, was implemented.

All engine-related investigations presented in this contribution are based on a generic GasTurb10 [2] engine model supplied by MTU Aero Engines. The regarded engine concept represents an advanced short duct nacelle separate flow turbofan with ultra high bypass ratio (UHBPR) capabilities. Efficiencies and pressure losses of the engine model used corresponded to technology standard 2010.

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For the intended parametric investigations the following degrees of freedom were identified:

Design variables:
- Design bypass ratio
- Design Mach number
- Design altitude
- Design net thrust

Off-design variables:
- Flight Mach number
- Flight altitude
- Power lever setting

The listing above shows the relevant variable parameters for the engine design as well as for off-design operations. The engine modelling was concentrated on a generic performance investigation, covering a wide range of design bypass ratios without going into mechanical design details of the potentially involved bypass ratio regimes. However, all design parameter variations were verified to be physically consistent. For off-design investigations GasTurb10 standard component maps were employed. The fuel type used for the combustion simulation was a generic hydrocarbon composed of 13.92 percent by weight hydrogen and 86.08 percent by weight carbon.

During all design variations involving design bypass ratio, design Mach number and design altitude central core engine characteristics of the GasTurb model were retained constant such as overall pressure ratio, thermal and mechanical efficiencies and turbine entry temperatures. As a first approximation efficiencies and pressure losses are treated independent from engine design thrust. This is applicable since variations in design thrust within the group of engine designs being subject to comparative studies later on is small. Hence, all design parameter variations can be regarded as variations of the engines propulsive device, while the core engine only scales linearly with core mass flow. Adequate iteration schemes were implemented in GasTurb in order to ensure comparability across the whole range of multidimensional parameter variation.

For the integration of the GasTurb engine model into the superordinate aircraft system maximum computation performance was required, since design optimisation concerning mission fuel burn minimisation is a highly iterative process, involving large numbers of design and operating points to be calculated. Therefor, the favourable way of system integration is the application of a surrogate model. Here, a common approach based on the response surface methodology (RSM) using a second-order system of equations was chosen.

$$R = b_0 + \sum_{i=1}^{n_v} b_i x_i + \sum_{i=1}^{n_v} b_{ii} x_i^2 + \sum_{i=1}^{n_v - 1} \sum_{j=i+1}^{n_v} b_{ij} x_i x_j \qquad (1)$$

R surrogate model response
b_0 constant offset coefficient
b_i coefficients of linear terms
b_{ii} coefficients of quadratic terms
b_{ij} coefficients of cross-product terms
n_v number of variables

The RSM technique allows the mapping of the behaviour of complex systems through multivariate regression. Therefor required information is supplied by experimental data recorded from the original system. An intelligent way of sourcing relevant information on the behaviour of the original system is the design of experiments methodology (DoE). DoE allows to maximise information density of gathered system data by actively manipulating relevant system input parameters. By systematically varying system input parameters, experimental effort can be reduced to a minimum.

For the purpose of this paper, full-factorial designs of experiments involving five and more levels per variable were used to analyse system behaviour of the employed GasTurb engine model in design mode. Customised fractional-factorial designs of experiments provided the information basis for the meta-modelling of the GasTurb model's off-design performance. The execution of designs of experiments in GasTurb10 was realised by running GasTurb in batch mode.

After determining the resulting regression coefficients, the behaviour of the surrogate model was visualised against input parameter variation. Subsequently, surrogate model responses and original system responses were compared and the surrogate model was optimised with respect to strong nonlinearities in system behaviour.

The utilisation of a surrogate model for the engine subsystem enables a highly integrated optimisation procedure for aircraft design and mission performance. FIG 1 displays the basic program architecture that was implemented in Matlab.

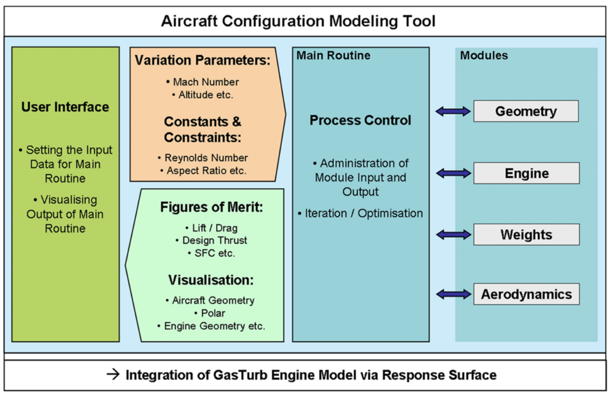

FIG 1. Basic software architecture of implemented Aircraft Configuration Modelling Tool

The shown scheme includes four essential modules being responsible for geometry, engine, weights and aerodynamics. Within these modules, iterative tasks are processed and merged in a superordinate iterative routine, which optimises aircraft design due to requirements set by the user. In order to allow comfortable handling of the developed software tool, a sophisticated graphical user interface (GUI) was designed.

For the mathematical description of geometry, weights and aerodynamics of the airframe, the methods of literature according to D. P. Raymer [3], E. Torenbeek [4], B. W. McCormick [5] et al. were employed. All aircraft configurations considered within the studies presented in the following are based on a conventional civil transport aircraft layout. Therefor, the main aircraft components fuselage, wing, engines and empennage were explicitly modelled. All other components and subsystems were regarded as independent from parameter variations within the presented investigations, and thus, were summarised in a residual of weights and parasite drag.

3. PARAMETRIC STUDIES

The investigation results presented in this paper concentrate on the performance of conventional 150-seat medium range (M/R) aircraft configurations on a 2000nm mission distance. The implemented engine and airframe model covers a design space of Mach numbers from 0.66 to 0.84, altitudes from 10.5km to 11.7km and bypass ratios from 8 to 24. All configurations within the presented material are similar concerning Reynolds number and Mach number. Furthermore, the same engine and airfoil technologies standard apply to all investigated configurations. The studies presented in the following are all based on standard atmospheric conditions.

3.1. Design Point Investigations

Besides mission studies comprehensive design point performance analyses were realised for this contribution. Central aspects concerning engine nacelle drag were modelled and analysed as well as main aerodynamic properties of the complete aircraft configuration.

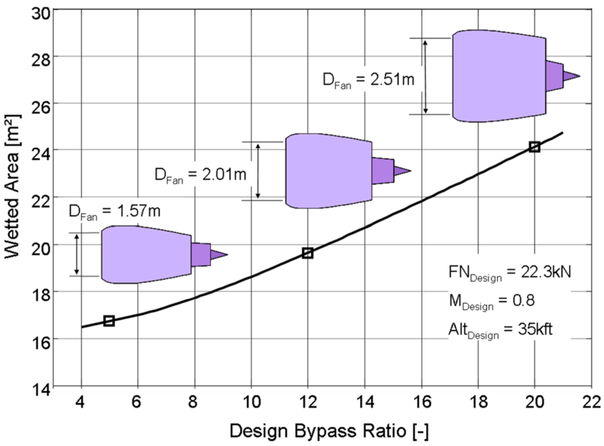

FIG 2. Wetted area of turbofan engine nacelles plotted against engine design bypass ratio

FIG 2 visualises the impact of engine design bypass ratio on wetted nacelle area, which is essential for the calculation of engine drag. The accordant deduced engine drag characteristics were incorporated into the computation and investigation of a high number of aircraft configurations featuring different engine design bypass ratios, design Mach numbers and design altitudes. The following figure shows a group of similar M/R configurations being equipped with different engine bypass ratios and being optimised for different design Mach numbers, pointing up the geometrical differences between different individuals.

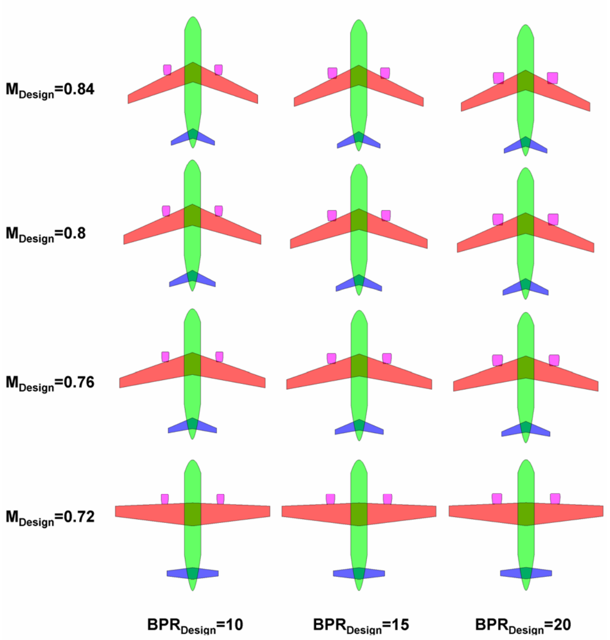

FIG 3. Synopsis of representative aircraft configurations being subject to presented performance analyses.

As an appropriate figure of merit for the comparison of the aerodynamic efficiency of various generated aircraft configurations, a commonly used parameter, the specific air range (SAR), was chosen. The SAR is a characteristic for both, the aerodynamic quality of the airframe configuration in terms of its lift/drag ratio (L/D) and the fuel efficiency of the aero engine in terms of specific fuel consumption (SFC). Thus, specific air range reflects overall fuel consumption per travelled distance:

$$SAR = \frac{V_{TAS}}{SFC \cdot FN_{req}} = \frac{V_{TAS}}{SFC} \cdot \frac{L/D}{W \cdot g} \qquad (2)$$

V_{TAS} flight velocity (true air speed)
FN_{req} required net thrust
W aircraft gross weight
g gravitation constant

FIG 4 shows a representative extract of the performed design point analysis for generic M/R civil transport aircraft configurations. Here, engine design bypass ratios between values of 8 and 24 as well as design Mach numbers between values of 0.6 and 0.84 are taken into account. The design altitude of the configurations considered in this diagram is 10.5km, which well corresponds to flight level 350.

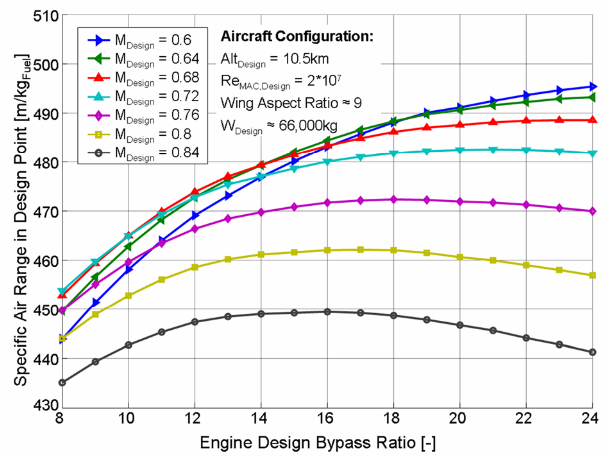

FIG 4. Specific air range of M/R aircraft configurations at design point plotted against engine design bypass ratio

It can be seen that within the displayed range of engine design bypass ratios design Mach numbers of approximately 0.7 lead to maximum specific air ranges for the considered M/R aircraft configurations. Furthermore, the benefit of lower design Mach numbers increases with increasing engine design bypass ratio, even though specific air range scales linearly with true air speed, which is, at constant altitude, directly correlated to Mach number. The maximum SAR variation for a given engine design bypass ratio in the shown case equals 10 percent.

In order to derive optimum combinations of engine design bypass ratio and design Mach number for the complete system, maxima of the SAR plots as a function of engine design bypass ratio, design Mach number and design altitude were numerically determined. Hence, the obtained design recommendations according to the SAR criterion are shown in the following figure.

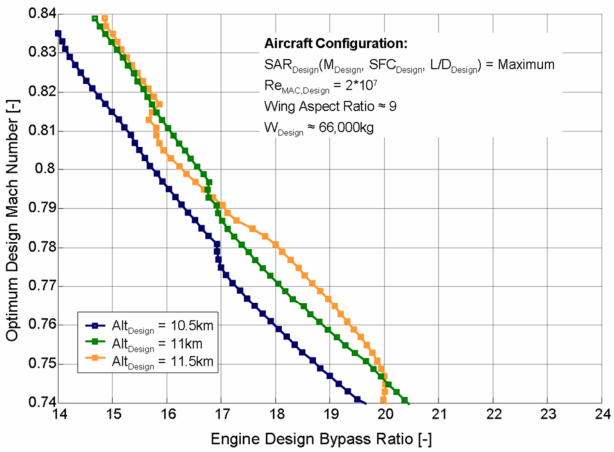

FIG 5. Optimum design Mach number for M/R transport aircraft plotted against engine design bypass ratio

Figure 5 presents optimum Mach numbers for engine and airframe design for given engine design bypass ratios at essential design altitudes derived from design point analysis. It can be seen, that the values of optimum engine design bypass ratio for contemporary design Mach numbers are located clearly beyond today's standard.

3.2. Mission Investigations

Main part of the studies presented in this paper, are first investigations on fuel consumption, economic efficiency and exhaust emissions of M/R aircraft configurations on a parametric 2000nm flight mission. All processed mission simulations were based on a parametric mission model, including numerical fuel consumption and exhaust emissions computation. Engine fuel flow and emission indices were supplied by the integrated surrogate model of the GasTurb engine model.

For the following mission simulations a group of 165 M/R aircraft configurations varying in engine design bypass ratio, design Mach number and design altitude were considered. These configurations were a representative subset of the configurations being regarded in the design point analysis before. As a first approach, mission profiles with constant cruise Mach numbers and constant cruise altitudes were simulated.

3.2.1. Fuel Consumption

One of the central goals of the studies presented in this paper was the determination of minima in fuel consumption against engine, airframe and mission design. Furthermore, the computational results of the performed fuel burn investigations, formed the basis for subsequent studies on overall mission costs.

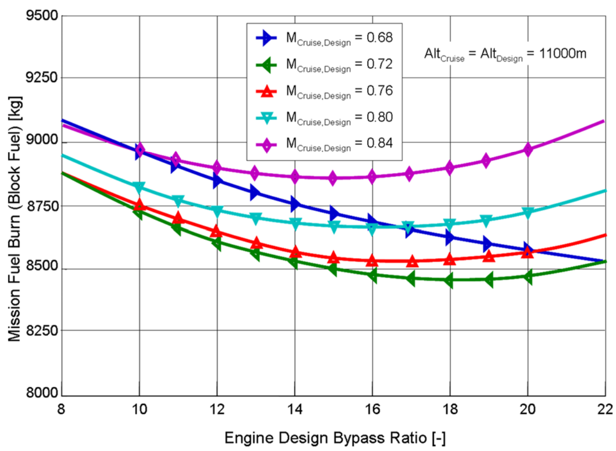

FIG 6. Block fuel burn of M/R aircraft configurations on a 2000nm mission at cruise design conditions plotted against engine design bypass ratio

FIG 6 points out the fuel burn reduction potential of M/R aircraft configurations on a 2000nm mission being designed for and operated at different cruise Mach numbers. Minimum fuel consumption at the representative design cruise altitude of 11,000m appears for a design cruise Mach number of 0.72 and engine design bypass ratios around 18. The figure shows a significant benefit in fuel consumption due to design cruise Mach numbers optimised for the application of ultra high engine design bypass ratios. This benefit in fuel consumption was determined up to 10 percent reduction compared to conventional design cruise Mach numbers for jet engine driven M/R transport aircraft.

Eligible combinations of optimum engine design bypass ratio and design cruise Mach number at different design cruise altitudes are displayed in the following figure. These combinations differ only slightly from the optimum values of the design point analysis (compare FIG 5) and thus substantiate the previously gained results.

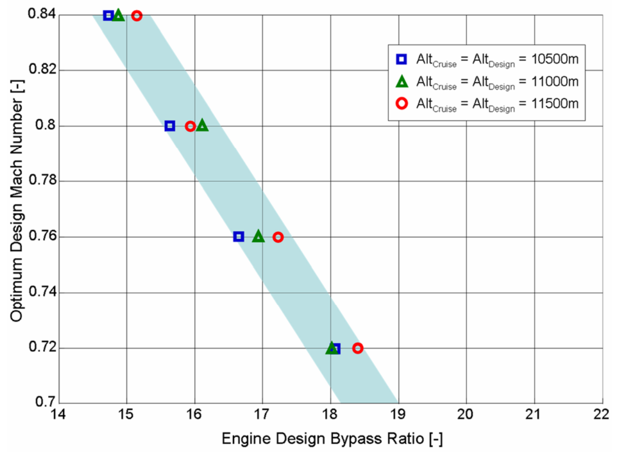

FIG 7. Optimum design Mach number for minimum fuel burn on a 2000nm mission plotted against engine design bypass ratio

3.2.2. Exhaust Emissions

In parallel to the fuel burn investigations the emissions of main exhaust gases were computed during mission simulation. Therefor, carbon dioxide emissions (CO_2), water vapour emissions (H_2O) and nitrogen oxide emissions (NO_x) were recorded. The following figures illustrate the results of the emissions calculation.

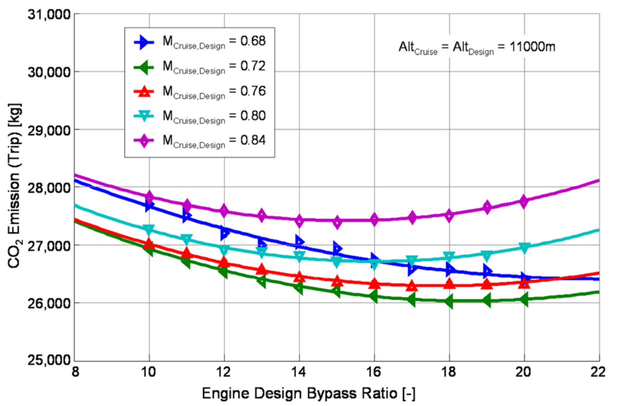

FIG 8. Trip CO_2 emissions of M/R aircraft configurations on a 2000nm mission distance at cruise design conditions plotted against engine design bypass ratio

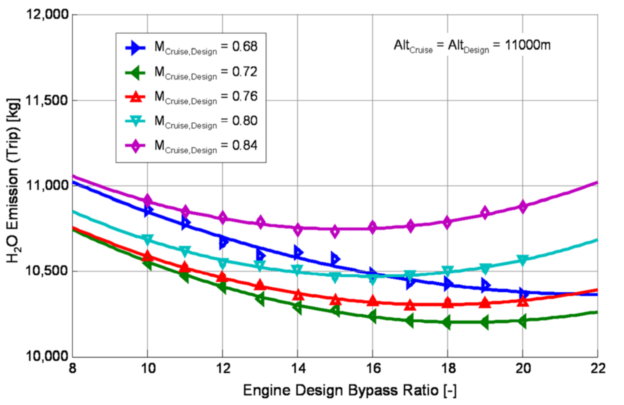

FIG 9. Trip H_2O emissions of M/R aircraft configurations on a 2000nm mission distance at cruise design conditions plotted against engine design bypass ratio

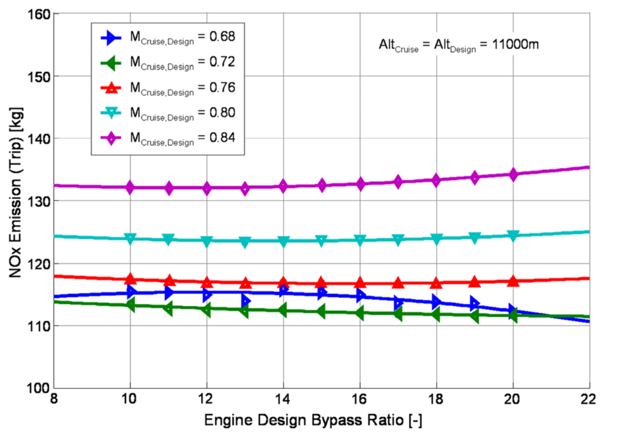

FIG 10. Trip NO_x emissions of M/R aircraft configurations on a 2000nm mission distance at cruise design conditions plotted against engine design bypass ratio

Since, due to very high combustion efficiencies, carbon dioxide and water vapour emissions scale nearly directly proportionally with fuel consumption, reduction potentials, here, can be realised by optimising design of aircraft and mission for minimum fuel consumption. However, nitrogen emissions mainly depend on the ambient conditions within the engine's combustion chamber concerning temperature and pressure. Significant variations of NO_x emissions against engine design bypass ratio could not be determined. However, higher design cruise Mach number appear to lead to stronger NO_x emissions.

3.2.3. Overall Mission Costs

For a first estimation of the economic impact of alternative mission profiles and accordant implications on engine and airframe design, a parametric model for engine life cycle costs (LCC) was set up in cooperation with MTU Aero Engines [6]. Therefore, manufacturing costs and maintenance costs were modelled against variations of the engine's propulsive device, which is directly correlated to the bypass ratio parameter. The engine LCC model was then embedded into a direct operating costs (DOC) model including first-order aircraft price and maintenance cost estimation, which was implemented according to the Association of European Airlines (AEA)-1989a method [7]. The obtained DOC results for the considered 2000nm mission distance for the investigated configurations at a representative design cruise altitude are shown in the following figure. Here, a fuel price of 0.60US$/kg was assumed.

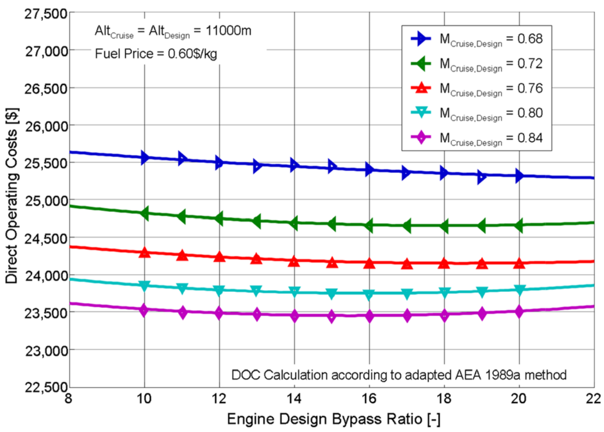

FIG 11: Direct Operating Costs of M/R Aircraft Configurations on a 2000nm-Mission at Cruise Design Conditions plotted over Engine Design Bypass Ratio

It appears, that based on the applied DOC calculation method, the benefit due to reduced fuel consumption at lower design cruise Mach numbers could not be transferred into the presented mission costs consideration. Reasons for that can be found in the influence of flight Mach number on mission block time, which, in turn, has a negative effect on other DOC shares, such as crew cost.

4. SUMMARY AND CONCLUSIONS

The material presented in this contribution investigates the dependency of fuel consumption on engine, airframe and mission design. In order to handle the complex interaction between engine, airframe and mission highly integrated parametric system model was implemented in Matlab. Therefor, a GasTurb engine model supplied by MTU Aero Engines was mapped and embedded into the complete system employing response surface methodology.

Based on the implemented model of the complete system comprehensive design point analyses were performed. A large number of different medium range aircraft configurations varying in engine design bypass ratio, design Mach number and design altitude were evaluated against specific air range, which is a commonly used figure of merit for the aerodynamic efficiency of the aircraft. Here, combinations of optimum engine design bypass ratio and design Mach number could be derived, being suitable for application in aircraft preliminary design. Accordingly, optimum values of engine design bypass ratio were determined between 14 and 21 for design Mach numbers between 0.74 and 0.84.

Subsequently, mission fuel burn, exhaust emissions and overall costs were investigated in detail for a 2000nm mission distance. For this purpose, a representative group of aircraft configurations taken from the set of configurations regarded in the design point analysis were investigated. Here, fuel burn reduction potentials due to design cruise Mach numbers optimised for ultra high bypass ratio engines up to 10 percent compared to conventional design cruise Mach numbers for jet engine driven M/R transport aircraft could be shown. Minimum block fuel burn at the representative design cruise altitude of 11,000m was derived for a design cruise Mach number of 0.72 and engine design bypass ratios around 18. Accordingly, minima for carbon dioxide and water vapour emissions were determined. As well, first results on the emission of nitrogen oxides against mission design could be obtained.

Based on the employed DOC calculation according to AEA 1989a a reduction of overall mission costs due to fuel burn optimised could not be shown for an assumed fuel price of 0.60US$/kg. It appears that for further investigations, more accurate cost models will have to be applied, taking into account actual airline cost models and the future development of fuel price.

However, further mission simulations will be necessary to supplement the studies on fuel consumption and overall mission costs, especially considering nontypical flight levels and variable cruise trajectories. As well, in order to gain more accurate results on the environmental impact of alternative flight mission profiles including additional exhaust emissions such as unburned hydrocarbons (UHC), carbon monoxide (CO) and soot, more sophisticated models will have to be applied.

5. REFERENCES

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