**ORIGINAL PAPER**

# Acoustic pre-design studies of ducted fans for small aircraft

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## Abstract
This publication presents an analytical method for the aerodynamic and acoustic pre-design of ducted fans for small aircraft. Based on studies of the primary design variables, the paper discusses the physical sound generation phenomena, as well as the interdisciplinary relationships of ducted fan design. First, the fan design and analysis methods are described. On the basis of an aerodynamic mean line method, the radial distribution of the flow velocities is used to determine the steady blade flow. Unsteady aerodynamic excitations are calculated by means of Sears' blade response function. To determine the generation and propagation of sound within the ducted fan, Goldstein's acoustic analogy is solved analytically. The methods are applied to a reference case, for which studies show that ducted fans offer significant potential in reducing sound emission, compared to free propellers. Since the rotor-alone noise of subsonic ducted fans is always cut-off, tonal sound is predominantly excited by rotor–stator interactions. These sources can be significantly reduced by a proper selection of the rotor blade and stator vane numbers, as well as optimal lean and sweep of the stator vanes. Large diameters and axial gaps are acoustically advantageous, but reduce fan stage efficiency and increase nacelle drag due to large wetted areas, especially at cruise. As a result, the importance of considering these complex interdependencies in a comprehensive design approach is shown. The pre-design method presented can be used to determine an optimal ducted fan design, taking into account interdisciplinary trade-offs, with an emphasis on noise. Analysis of the ducted fan concept shows that the ducted fan can be a promising alternative to the free propeller, especially if low noise emission is required.

## 1 Introduction

Technical progress in the field of electric propulsion systems is enabling greater design freedoms, so leading to new aircraft and mobility concepts. Among these are small aircraft intended to serve as urban and regional air taxis. For such applications, noise is a key aspect and needs to be taken into account at an early design stage.

The ducted fan is particularly promising as a means of reducing propulsion noise. Previous aircraft equipped with ducted fans include the *Norman Islander* [4, 36], the *Fanliner* [2], and the *Fanjet* [10]. However, no small aircraft currently in series production is driven by a ducted fan, partly due to efficiency, mass, and drag disadvantages in relation to the free propeller, and partly because of integration challenges. Nevertheless, for enhancing urban and regional air mobility, overcoming these challenges and accepting efficiency losses might be worthwhile to gain a significant noise reduction. Electric drives allow for compensation through new design freedoms and improved propulsion integration. For example, the ducted fan's operating characteristics can be better matched to electric or hybrid electric powertrains, than to conventional internal combustion engines [35]. Hence, ducted fans are currently being designed for some small aircraft [3, 11], such as the *Airbus E-Fan* [17] and the *Silent Air Taxi* [9].

Compared to free propellers, ducted fans have the potential to reduce propulsion noise, since the predominant noise of a free propeller—the rotor alone-noise—is cut-off within the nacelle of a ducted fan. If the nacelle length is sufficient,

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the rotor alone-noise is therefore not radiated into the far-field. For a ducted fan, the predominant noise sources originate in the rotor–stator interactions, which can be minimized through the implementation of a number of fan stage design measures. In addition, the nacelle shields the sound emission, so that the sound propagates and radiates more directionally, thus helping reduce the perceived noise further. Secondary measures for noise reduction, such as acoustic liners, can be installed within the nacelle as well.

A number of acoustic pre-design methods are available to determine the noise emission of a propulsor and, additionally, to identify noise reduction potential. Publications in this field focus mainly on turbofan engines. In addition, methods from industrial fan design are applied to propulsors.

The tool *OPTIBRUI* is being jointly developed by École Centrale de Lyon, Université de Sherbrooke, Airbus, Safran, and Valéo for calculating tonal and broadband interaction noise from fans and ventilators [7, 27]. The aerodynamic excitation is modeled physics-based. Alternatively, it can be specified on the basis of numerical and experimental data. To determine the blade response, analytical models are implemented for both single blades and blade cascades. The sound power in the duct is then calculated analytically using Goldstein's acoustic analogy.

NASA's analytical tool *V072* was developed by Ventres et al. [32, 33] and extended by Meyer and Envia [22]. It is intended for calculating tonal wake interaction noise of turbofans. *V072* was expanded by Nallasamy and Envia [25] to also include broadband wake interaction noise, the resulting tool being called *RSI*. To ascertain the wake interaction noise, the wakes can either be modeled empirically within the tool or specified as input from numerical simulations and measurements. The excited unsteady blade loading is determined on the basis of the approximation of a flat cascade with infinitely thin plates. Using Goldstein's acoustic analogy, the modal expansion of the in-duct Green's function is applied to calculate the sound power.

At the DLR (German Aerospace Center), Moreau [23] developed the tool *PropNoise* as an unified approach to computing propulsion noise. This tool uses semi-empirical models to calculate both tonal and broadband aerodynamic excitations. This calculation is first performed on a mean line radius, the results of which are then extrapolated radially. Jaron [16] expanded the tool with a RANS-informed determination of the aerodynamic excitation. Blade response is modeled analytically with the incompressible Sears function for a single, infinitely thin, flat plate. Sound power is determined analytically using Goldstein's acoustic analogy for an infinite hard-walled duct.

Since low noise emission is of particular importance in urban and regional air mobility, the aforementioned methods and studies are extended in this publication to include ducted fans of small aircraft. Moreau's [23] approach is developed

further to take into account arbitrary radial flow velocity distributions. Furthermore, the modal approach is implemented for broadband noise. Those aerodynamic and acoustic methods for calculating the sound emitted from ducted fans are presented first. Later, these methods are applied in comprehensive evaluation studies of ducted fans. Based on parametric studies, the influences of the primary design variables on sound emission are investigated. Interdisciplinary design trade-offs of ducted fans are discussed through consideration of the fan stage and nacelle aerodynamics.

## 2 Method

Modeling of the ducted fan comprises the physical fields of steady and unsteady aerodynamics, as well as acoustics. Acoustics are the focus in this publication, while the propulsion system design and performance calculation are described in more detail by Weintraub et al. [35]. The configuration of the propulsor investigated is shown in Fig. 1.

A simplified model of the ducted fan is built with the following assumptions: The fan stage is modeled as an axial compressor with a single repeating stage. In addition, the hub, mean line and casing radii of the fan stage are deemed to be constant. All rotor blades and stator vanes are identical, respectively, and periodically arranged. Furthermore, a homogeneous flow and a constant axial flow velocity are assumed at all cross-sections for the mean line design. To calculate aerodynamic excitation and blade response, the radial strip theory is applied, so each radius is treated independently and is calculated as a two-dimensional problem.

Balancing of thrust and drag are in line with those of a conventional turbofan, as described by Kerrebrock [18], for instance. Nacelle drag is evaluated with the empirical models of Stanhope [29].

This sound calculation methodology is visualized in Fig. 2. Ducted fans are first aerodynamically designed from a given set of free design variables. Subsequently, acoustic analyses are conducted for the critical operating points. Off-design steady and unsteady aerodynamics are used to
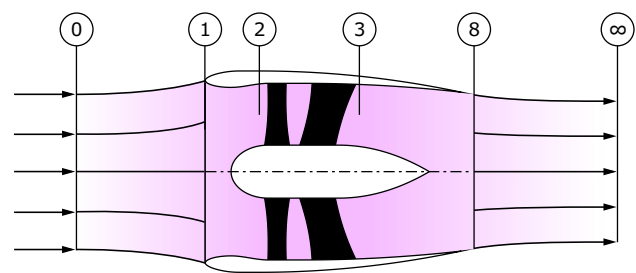


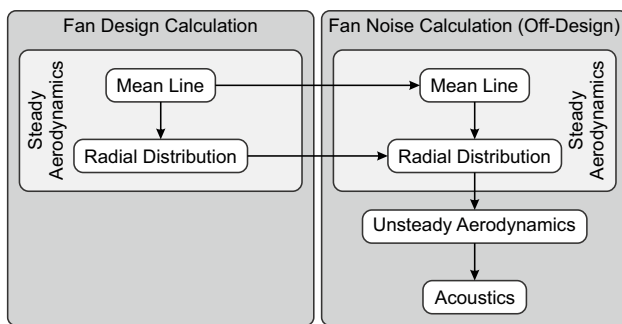**Fig. 1** Propulsor configuration with station nomenclature [35]

**Fig. 2** Sound calculation methodology

calculate the acoustics of ducted fans. To perform the calculations, all methods are implemented in Matlab [30].

## 2.1 Steady aerodynamics

Steady-state aerodynamics of the fan stage are calculated and performance of the ducted fan is analyzed using an aerodynamic mean line method. The flow velocities, as well as the aerodynamic parameters pressure ratio, mass flow and efficiency, are determined on a representative mean radius. Losses are calculated for each operating point by means of analytical loss correlations [5, 34].

Based on the mean line design, a mixed vortex design, as described by Dixon and Hall [6], is used to determine the flow angles over the blade height. To achieve this flow turning, blade profiles of the NACA65-series are designed using the Lieblein method [20], and subsequently stacked to form the three-dimensional blade geometry. For this geometry, the flow velocity distribution around the profiles is calculated using the models of Moreau [23]. Subsequently, the flow diffusion and boundary layers are calculated using the models of Lieblein [19] in the formulation of Moreau [23].

## 2.2 Unsteady aerodynamics

Sound in a ducted fan is excited by unsteady aerodynamics, consisting of flow perturbations and resultant unsteady blade forces. To calculate this aerodynamic excitation, analytical and semi-empirical methods based on the work of Moreau [23] are used. For the sake of simplification, several assumptions are made: According to the radial strip theory, the unsteady aerodynamics do not interact between different radii, and hence the calculation can be carried out for each radius individually. The fluctuations are small and can therefore be superposed to the mean flow. Consequently, the predominant flow perturbations of a ducted fan, the potential fields and wakes of the blades, can be treated separately.

The initial velocity fluctuation caused by the potential field is determined using the steady flow velocities around the profiles. Propagation of the potential field is modeled

analogously to an acoustic cut-off mode to calculate its exponential decay and propagation angle [16]. Thus, the resulting velocity fluctuations at the adjacent blade rows are determined for both upstream and downstream propagation.

For the wakes, the initial condition is given by the boundary layer states at the trailing edge of the blades. From the trailing edge, the wakes propagate downstream to the adjacent blade row with a propagation angle corresponding to the mean flow angle. The wake decay is calculated by solving the integral boundary layer equations for a wall shear stress of zero and using Green's entrainment relation [14]. To solve the equations, it is assumed that the wakes are symmetric and Gaussian in shape. In addition to the periodic perturbation, the wakes also influence the turbulence of the flow. The turbulence power spectral density and the turbulence correlation length are determined on the basis of the wake state, using the results of Amiet [1] for the von Kármán spectrum.

A Fourier analysis is carried out to decompose the fluctuations into sinusoidal components with associated azimuthal perturbation mode orders. These are each multiples of the blade number of the row, which generates the flow perturbation. Using this Fourier decomposition, the flow perturbations are transformed into the relative coordinate system of the adjacent blade row. For this row, the resulting unsteady blade lift is calculated from the deterministic velocity fluctuations and the turbulence spectra. On the basis of the Fourier decomposed and transformed flow perturbations, the unsteady pressure distribution and the unsteady lift of the blades are modeled, using the blade response function of Sears [28]. Sears' blade response function applies to an infinitely thin single plate for a mean incidence-free inflow superposed with a sinusoidal gust, so that the blading and flow are simplified according to these assumptions.

## 2.3 Acoustics

To analyze the ducted fan's acoustics, the sound propagation in the flow channel and the sound excitation by the fan stage are determined by means of the analytical models derived from Moreau [23].

For calculating the sound propagation, the flow channel of the ducted fan is modeled as an infinitely long, hard-walled annular duct with constant radii. A uniform axial flow is assumed for all cross-sections and the effects of swirl, vorticity and entropy gradients are neglected. To calculate the in-duct sound propagation, the Green's function derived by Goldstein [13] is used and the resulting eigenvalue problem is solved. The solution is given by duct modes, each defined by an azimuthal and radial mode order. Only a certain number of modes are able to propagate in the duct, referred to as cut-on modes. The remaining modes are unable to propagate, which is why they are classified as cut-off modes. If

the inlet and outlet of the ducted fan are sufficiently long, the sound pressure of the cut-off modes decays within the nacelle. The cut-off modes do not transport any acoustic energy. As a result, the excitation of cut-off modes does not contribute to the sound radiation from the ducted fan [24]. As such, the sound radiation of cut-off modes is not considered within this investigation.

When analyzing the ducted fan sound excited by the blading, a number of sources can be identified. The sound excited by the blade thickness and steady blade forces of the rotor due to its rotation is referred to as the rotor-alone noise. Within the flow channel, the rotor-alone noise of a ducted fan is cut-off as a result of the subsonic flow in the relative system of the rotor [13, 23]. Furthermore, because of the weak shear layers for subsonic propulsors, the strength of quadrupole sound sources is small when compared to the other sources [16]. These sources are neglected in the further considerations. In this case, the sound excited by the ducted fan is calculated only on the basis of the unsteady blade forces and the resulting dipole sound sources.

To calculate the sound excitation in the presence of solid surfaces, Goldstein [12] solved the Lighthill equation [21] using Green's function. The sound sources are integrated over all blades and radii to calculate the sound power. For modeling the sources before integration, the sources are calculated separately for each radius according to the radial strip theory. In analogy to the unsteady lift, the blades are approximated as infinitely thin flat plates. The sources are positioned at the edge of the blade where the aerodynamic excitation occurs. In addition, a distinction is made between tonal and broadband sound. The deterministic, periodic aerodynamic excitations lead to the radiation of tonal sound. The stochastic, turbulent aerodynamic excitations result in broadband sound.

The amplitudes of both the tonal and broadband sound sources follow from the unsteady lift forces calculated, as described in Sect. 2.2. To model the phase of the sources, the tonal and broadband sources are treated separately. The phase of the tonal sources is determined by the phase position of the flow perturbation relative to the source. Since tonal sound sources from different blades are completely correlated, only specific azimuthal mode orders are excited, depending on the azimuthal perturbation mode order and the blade number of the excited row, as described by Tyler and Sofrin [31]. Hence, these modes are referred to as Tyler–Sofrin modes.

To consider the broadband sources' phases, a statistical averaging is carried out. This takes into account the correlation of the sources, which is calculated using the turbulence correlation length described in Sect. 2.2. Since broadband sound sources from different blades are assumed to be uncorrelated, the excitation not only of Tyler–Sofrin modes, but of arbitrary azimuthal modes is possible.

While modeling the sound generation, which results from the aerodynamic excitation, consideration is also given to the radiation efficiency and the non-compactness of the sources. The radiation efficiency accounts for the excitation of a duct mode by a dipole source and is determined using the wave number of a mode normal to the blade chord. The non-compactness of the sources along the blade chord is calculated on the basis of the chordwise Fourier transform of the dimensionless unsteady lift distribution.

## 2.4 Reference case

An example of an application of ducted fans propelling a hybrid electric small aircraft is described in this section to serve as a reference for the studies that follow: This is a two-seater aircraft, which is designed for a maximum take-off mass of 1000 kg and a cruise speed of 140 kt true airspeed (TAS) at an altitude of 10 kft. This aircraft is driven by a hybrid electric powertrain with a system power of 150 kW, which is shown in Fig. 3. An internal combustion engine runs throughout the mission and contributes the major share of propulsion power. The electric motor is used for boosting during take-off and initial climb to support the internal combustion engine.

The aircraft's thrust is generated by two ducted fans. Owing to the high number of blades, these are designed as fixed pitch fans. For the flight mission, the thrust requirements on the propulsion system are worked out on the basis of performance calculations for the reference aircraft. These are listed in the Table 1.

There are additional figures of merit for the mission. For instance, efficiency during cruise needs to be maximized.
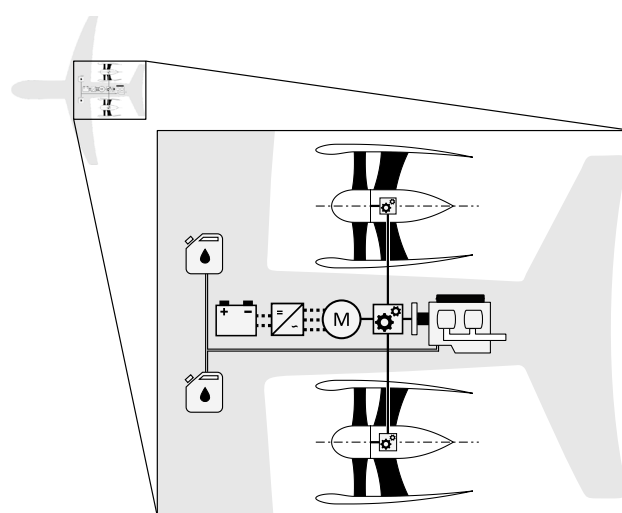


**Fig. 3** Parallel hybrid electric propulsion system architecture under consideration: battery, inverter, electric motor, fuel tanks, combustion engine and power transmission to two ducted fans [35]

**Table 1** Propulsion system thrust requirements

| Op.-point | Ambient cond. | Airspeed | Thrust-req. |
|---|---|---|---|
| Take-off | SL ISA+0 K | 39 kt (TAS) | 1620 N |
| Init. climb | SL ISA+0 K | 62 kt (TAS) | 1100 N |
| TOC | 10 kft ISA+0 K | 140 kt (TAS) | 841 N |
| Cruise | 10 kft ISA+0 K | 140 kt (TAS) | 429 N |

Additionally, the positive incidence at take-off has to be within acceptable limits so that the aerodynamic stability of the ducted fan is retained. To reduce the incidence during take-off, the design point is defined at a lower true airspeed than the cruise speed. This results in a negative incidence during cruise and, in turn, a slightly reduced efficiency as a compromise.

The primary free design variables of the ducted fan are the diameters of hub, tip and nozzle, the axial gap between rotor and stator, the number of rotor blades and stator vanes, as well as the pitch-to-chord ratio of rotor and stator, the rotational speed and the power. Other variables, such as the rotor tip clearance and the radial flow velocity distribution are influenced by additional requirements relating to construction, structural mechanics and aerodynamics. With the free design variables, the aerodynamics and acoustics of the ducted fan are calculated using predefined blade and nacelle geometries.

For the following investigations, one of the aircraft's two ducted fans is designed and analyzed using the methods presented. A baseline design that fulfills the aforementioned requirements is presented in Table 2 and serves as a reference for the investigations. To reduce the deviation and thus the swirl downstream of the stator for maximizing thrust, a lower pitch-to-chord ratio for the stator than for the rotor is chosen. This results in seven rotor blades and eleven stator vanes. The reference case and baseline design are presented in more detail by Weintraub et al. [35].

## 2.5 Design study procedure

To identify design trade-offs for ducted fans, parametric studies of the main design variables are conducted for the baseline design described above. The first objective of the studies is to determine the primary sound sources and the potential for noise reduction. For this purpose, design variables that mainly influence sound emission and only have a minor influence on the aerodynamics of the fan stage and nacelle will be investigated. The second goal of the studies is to investigate the interdisciplinary design space and to comprehensively evaluate the designs based on both the acoustics and the aerodynamic characteristics. To this end, the aerodynamic design variables of the fan stage and the nacelle will be examined.

To enable a comparison of the different designs, the net thrust is kept constant in all studies, which leads to different power, pressure ratios, speeds and mass flows.

Initial climb without electrical boost is selected as the operating point for noise evaluation. In view of the high thrust requirements and the low flight altitude of this operating point, the highest noise level is expected on the ground. The initial climb is representative for the overflight of an urban area shortly after take-off and the noise level to which residents living close to an airport are exposed. The overflight measurement after take-off required for noise certification according to ICAO Annex 16, Chapter 10 [15] is also conducted during the initial climb. For the baseline design, the resulting operating point at sea level initial climb required thrust of the ducted fan is shown in Table 3.

The ducted fan acoustics are evaluated on the basis of the overall sound power level. For a comprehensive analysis, an examination of the effects on fan overall efficiency and nacelle drag is carried out. For this purpose, the cruise operating point is investigated. Design boundaries arising from practical considerations, construction or structural mechanics are also considered and discussed.

**Table 2** Baseline design variable selection

| Design variable | Value |
|---|---|
| Fan diameter | 0.600 m |
| Blade tip speed | 135 m/s |
| Design pt. shaft power | 27 kW |
| Blade aspect ratio | 2 |
| Blade pitch-to-chord ratio | 2 |
| Vane aspect ratio | 1.665 |
| Vane pitch-to-chord ratio | 1 |
| Fan hub diameter | 0.180 m |
| Axial gap to rotor chord ratio | 0.7 |
| Vane sweep | 15° |
| Vane lean | 0° |

**Table 3** Fan operating point at sea level initial climb required thrust of the baseline design

| Variable | Value |
|---|---|
| Net thrust | 550 N |
| Power | 31 kW |
| Pressure ratio | 1.0205 |
| Corrected speed | 3900 RPM |
| Corrected mass flow | 16.2 kg/s |
| Overall efficiency | 0.567 |

## 3 Results and discussion

This section is divided into four parts, each of which will explore two design variables. First, an investigation is made of the primarily acoustic design variables, rotor blade and stator vane numbers, as well as lean and sweep of the stator vanes, and their influence on the ducted fan acoustics is determined. Next, the aerodynamic design variables of the fan stage—fan diameter and blade tip speed—and the nacelle—fan diameter and axial rotor-stator gap—are examined to analyze the interdisciplinary design space and comprehensively evaluate the designs.

### 3.1 Rotor blade and stator vane numbers

First, a presentation is given of the blade number study conducted for the ducted fan. The results of this are shown in Fig. 4 as a carpet plot of the overall sound power level, depending on the number of rotor blades and stator vanes. For aerodynamic similarity of the designs, the pitch-to-chord ratios of the rotor and stator rows are kept constant, as in the baseline design shown in Table 2. To vary the blade numbers, the aspect ratios of rotor and stator are changed. Due to the narrow blade number range under consideration, this only has a minor influence on the aerodynamics of the propulsor, as is discussed in detail by Weintraub et al. [35]. For this reason, the subsequent investigation only examines the effects of the rotor blade and stator vane numbers on the ducted fan acoustics.
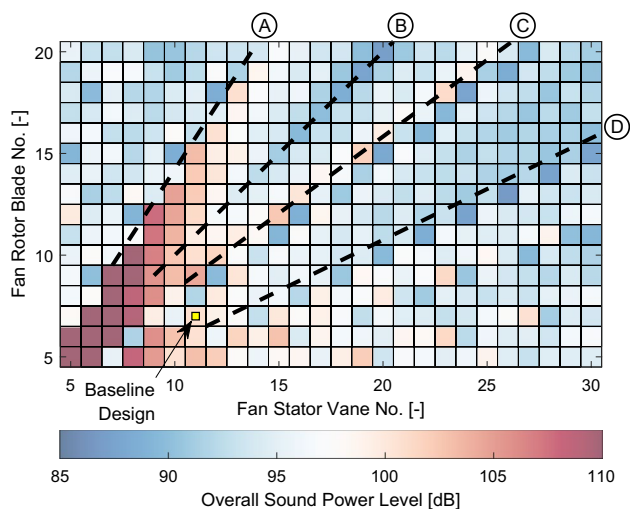


**Fig. 4** Influence of stator vane number and rotor blade number on the overall sound power level at sea level initial climb required thrust. To improve the representation of the effects discussed, the range of values in the diagram is limited to a minimum of 85 dB and a maximum of 110 dB

The overall sound power emitted by the ducted fan varies between a level of 85 dB for large rotor blade and stator vane numbers and a level of 120 dB in the range of small blade numbers. With an overall sound power level of 100 dB, the baseline design of the ducted fan is already about 20 dB quieter than comparable current free propellers of equal power, which emit sound at a power level of about 120 dB [26]. Starting from the baseline design, a further reduction of 10–15 dB in the overall sound power level can be achieved for ducted fans if appropriate blade numbers are chosen. However, having a large numbers of blades becomes increasingly unrealistic in view of the manufacturing and constructional boundary conditions. The blade number range under investigation is therefore restricted to a maximum of 15 rotor blades or stator vanes. Even when limited to this range, it is possible to reduce the overall sound power level to a minimum of 88 dB. In this way, ducted fans offer some potential as quiet propulsion systems for future urban and regional air mobility.

Subsequently, the distinctive pattern shown in Fig. 4 is discussed. To this end, the primary sound sources are first identified. Sound is predominantly excited by tonal sources resulting from rotor–stator interactions caused by potential fields and wakes. These determine the overall sound power level being analyzed. For most blade numbers, excitation by the rotor blade wakes, which impinge on the stator vane leading edges, predominates. Only at low rotor blade and stator blade numbers, is the excitation by the potential fields of the blades predominant, resulting in higher overall sound power levels of 120 dB.

Furthermore, four ranges with particularly low overall sound power levels occur: These are marked by *A* to *D* in Fig. 4. These result from the predominant sound excitation from tonal sources generated by the interaction of the rotor and stator. From these sources, only Tyler–Sofrin modes for the harmonics of the blade passing frequency are excited, as mentioned in Sect. 2.3. The azimuthal mode order is, therefore, determined by the number of rotor blades and stator vanes and influences the mode propagation characteristics.

In the ranges above line *A* and below line *C*, only cut-off Tyler–Sofrin modes are excited for the first blade passing frequency. Below line *D*, the Tyler–Sofrin modes of the second blade passing frequency are also cut-off. Since cut-off modes do not transport any acoustic energy, the sound power emitted, and so too the overall sound power level of the ducted fans, decreases in these ranges [24]. As the excitation of cut-off Tyler–Sofrin modes depends on the chosen number of rotor blades and stator vanes, these ducted fan designs are referred to as cut-off designs. In range *A*, the number of rotor blades is greater than the number of stator vanes. These ducted fan designs are therefore named inverse cut-off designs.

Another range of low overall sound power levels occurs along line *B*, where the number of rotor blades equals the number of stator vanes. Consequently, the predominant tonal sound sources from the interaction of rotor and stator excite cut-on Tyler–Sofrin modes of azimuthal order 0. Regarding the radial mode order, the excitation decreases the higher the order, so the strongest excited radial mode is also of order 0. As such, the resulting predominant modes are the plane waves and these propagate in the axial direction.

Those modes are generated at the stator vanes due to the aerodynamic excitation by the wakes. The resulting unsteady blade forces act normally to the blade surfaces and hence orthogonally to the chord, as do the sound-exciting dipole sources. The stator vane chord is almost uncurved and axially aligned since the flow in the stator is only slightly turned towards an axial outflow. This means that the dipole axis is almost circumferentially oriented. Since the dominant modes propagate in the axial direction, the axis of the dipoles is orthogonally to it. This orthogonality results in a weak excitation of the modes and consequently a low radiation efficiency of the sources, as described in Sect. 2.3. For this reason, the predominant Tyler–Sofrin modes of azimuthal order 0 for designs with an equal number of rotor blades and stator vanes are only weakly excited. This results in the ducted fan emitting a low overall sound power. However, owing to mechanical boundary conditions, such a configuration—with equal numbers of rotor blades and stator vanes—is not feasible.

In view of the dependencies presented of the overall sound power level on the excited Tyler–Sofrin modes and their propagation capabilities and directions, there are no definite design trends. A cut-off or inverse cut-off design, as well as a design with low radiation efficiency, seem to be acoustically advantageous. Since these influences depend on the application, blade number studies are always mandatory so that the acoustically optimum number of blades for a ducted fan can be determined.

## 3.2 Stator vane lean and sweep

In addition to the number of blades, their three-dimensional design, in terms of lean and sweep, is investigated here. As far as fan stage aerodynamics are concerned, lean and sweep, in particular, affect the secondary flows, which are only considered when the detailed design is carried out. As a result, the goal of the studies presented here is restricted to acoustics. In view of the centrifugal forces acting on the rotor blades, the three-dimensional design features are applied to the stator vanes only. The following section discusses the influence of leaned and swept stator vanes on the overall sound power level.

First, an investigation of the lean angle of the stator vanes is carried out. A positive lean angle is defined in the opposite
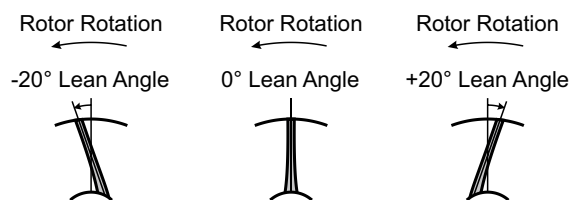


**Fig. 5** Definition of the stator vane lean angle. The view is in streamwise direction. Positive stator vane lean angle is defined in opposite direction to rotor rotation
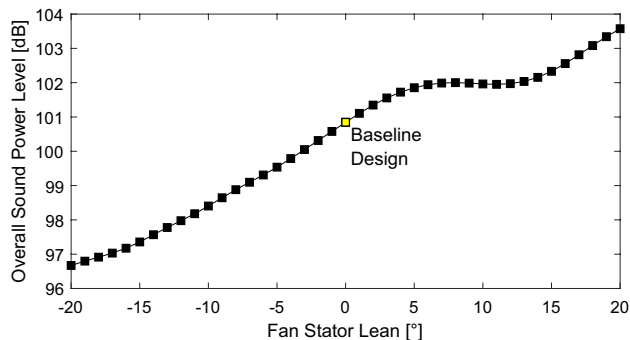


**Fig. 6** Influence of stator lean on the overall sound power level at sea level initial climb required thrust

direction to the rotor rotation, as shown in Fig. 5. The effect of the stator vane lean angle on the overall sound power level is presented in Fig. 6. Due to practical considerations, the stator vane lean angle is limited to ± 20°.

Starting from the unleaned stator vane of the baseline design, a negative lean angle of 20° reduces the overall sound power level by around 4 dB. In contrast, a positive lean angle of 20° increases the overall sound power level by around 3 dB. This trend is due to radial differences in the phase of the aerodynamic excitation.

Since sound is predominantly excited from tonal sources, these sources radiate with the phase defined by the aerodynamic excitation, as described in Sect. 2.3. The influence of the stator vane lean angle on the phase position of the aerodynamic excitation is described by Envia and Nallasamy [8] and is as follows: The phase position of the flow perturbation is defined relative to the blade edge, on which the fluctuation impinges, and depends on the radial position. Differences in the propagation of the flow perturbation and the blade edge position result in a varying relative phase position and a phase difference along the blade height. As a result of this phase difference of the aerodynamic excitation, phase changes occur for the sound sources. As the phase difference of the aerodynamic excitation between hub and tip increases, the number of phase changes along the blade height also increases. Since sources of opposite phase

interfere destructively, the larger number of phase changes increases the destructive radial interferences. Accordingly, the sound excitation of the entire blade and therefore the overall sound power emitted by the ducted fan is reduced.

For the configurations of the ducted fan investigated in Fig. 6, the sound is predominantly generated by tonal sources at the stator vanes, which are excited by the rotor wakes. Given the radial flow velocity distribution, the wakes propagate more in the circumferential direction against the rotor rotation at the tip and more in the axial direction at the hub. The wakes are therefore tilted against the direction of rotor rotation when impinging on the stator leading edges. In turn, the circumferential positions of the stator leading edges are displaced by the lean of the stator vanes. A stator vane lean in the opposite direction to the wakes increases the difference in phase position between the hub and the tip for the impingement of the wakes on the stator leading edges. Consequently, with a negative lean of the stator vanes, the phase difference of the aerodynamic excitation along the blade height increases. The greater the number of phase changes along the blade height, the more destructively the interference of sound sources of different radial positions. For this reason, the overall sound power emitted by the ducted fan decreases as the lean angle of the stator vanes becomes more negative. Conversely, a positive lean angle reduces the phase difference and the number of phase changes along the blade height. This causes the sound sources of different radial positions to interfere more constructively and the overall sound power emitted to increase.

Analogously, the lean of the stator vanes affects the phase position of the stator potential field relative to the trailing edge of the rotor blades. Since the propagation characteristics of the stator potential field differ from the rotor wake, the greatest constructive radial interferences and, in turn, sound power levels occur at a positive stator lean angle of about 6°. In this case, the sound power level excited by the stator potential field is equal to that of the wakes. For this reason, the overall sound power level is constant for a positive lean angle of the stator vanes between 6° and 13°.

The sweep angle of the stator vanes is the next to be investigated. A positive sweep angle is defined for the displacement of the stator vane tip in the downstream direction, as shown in Fig. 7. The influence of the stator vane sweep angle on the overall sound power level is presented in Fig. 8.
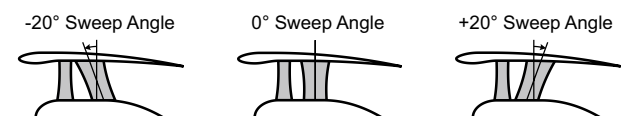


Fig. 7 Definition of the stator vane sweep angle. Positive stator vane sweep angle is defined for displacement of the tip in downstream direction
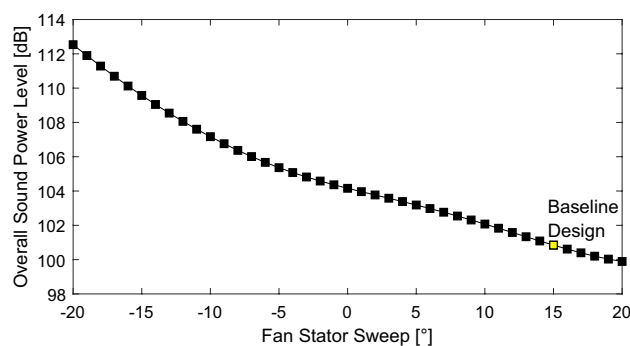


Fig. 8 Influence of stator sweep on the overall sound power level at sea level initial climb required thrust

Because of practical considerations, the stator vane sweep angle is limited to ± 20°.

Compared to the unswept stator vanes, the overall sound power level for stator vanes with a 20° positive sweep angle decreases by about 5 dB. Conversely, with a negative sweep angle of 20°, the overall sound power level increases by about 8 dB. This trend is analogous to the stator vane lean due to radial differences in the phase of the aerodynamic excitation and additionally, due to decay of the aerodynamic excitation amplitude. Both effects arise from the predominant excitation of tonal sound sources.

Since the tonal sound sources are excited primarily at the stator vanes by the rotor wakes, the stator vane sweep angle affects the phase of the excitation, as described by Envia and Nallasamy [8]. A positive sweep increases the axial gap between the rotor and stator and so the propagation distance of the flow perturbations at the tip, compared to the hub. Since the wakes propagate more in the circumferential direction on a larger radius, by enlarging the propagation distance at the tip, the wakes become more tilted when they impinge on the stator vanes. Between hub and tip, the difference in phase position of wake relative to stator leading edge increases with increasing sweep. The phase difference of the aerodynamic excitation along the blade height grows, and the interference of sound sources from different radial positions is more destructive. In the case of a positive sweep of the stator vanes, the result is a reduction in the emission of overall sound power from the ducted fan.

In addition to the phase, the axial gap influences the decay of the flow perturbations. For larger axial gaps, the wakes and the potential fields decay to a greater extent. The unsteady aerodynamic flow perturbations therefore have a smaller excitation amplitude when they impinge on the adjacent blade row. Since the sources radiate sound more efficiently at the tip due to the larger radii, the influence of the excitation amplitude on the sound generation is greater at the tip than at the hub. Therefore, increasing the axial gap at the tip and decreasing it at the hub by a positive sweep of

the stator vanes results in a reduction in the sound excitation through the entire blade and so a reduction too in the overall sound power level.

Inversely, the axial gap at the tip decreases when there is a negative sweep. Given the higher excitation amplitude, the overall sound power increases. In the case of large negative sweep angles, the sound generation by the stator potential field predominates compared to the wakes, because the axial gap at the tip is small then. The overall sound power level thus increases strongly for large negative sweep angles.

Since the sweep, compared to the lean of the stator vanes, influences both the phase and the amplitude of the unsteady aerodynamic excitation, its effect on the sound generation is greater. Increasing the sweep of the stator vanes therefore has a greater influence on the overall sound power level than a corresponding increase in the lean of the stator vanes.

In summary, beyond the blade numbers, the three-dimensional design of the blades has a major influence on the overall sound power emitted. Based on the results presented for the lean and sweep of the stator vanes, the following design trends arise for the low-noise design of ducted fans: To reduce sound emission, it is beneficial to increase the lean angle of the stator vanes in the rotor's direction of rotation. A sweep of the stator vanes when the tip is displaced in the downstream direction decreases sound emission even more effectively. Since different flow perturbations are superposed and the equations are nonlinear, performing lean and sweep studies is beneficial for a new design. These investigations should take into account further boundary conditions, such as mechanical or installation requirements of the specific application.

## 3.3 Fan diameter and blade tip speed

The fan diameter and blade tip speed are the two aerodynamic fan stage design variables that determine the flow turning through the blading, as described in Sect. 2. These design variables are now investigated in terms of aerodynamics and acoustics. First, the influence on the aerodynamics of the fan stage is shown in Fig. 9 based on the ducted fan's overall efficiency during cruise. The fan overall efficiency is defined as the ratio of the propulsive power to the shaft power.

As the diameter increases, the profile losses rise, due to the larger wetted blade surfaces. By contrast, the losses caused by secondary flows, such as the rotor tip gap flow, decrease. This means that there is an optimum diameter for maximum fan isentropic efficiency. Because of the high cruise speed, the propulsive efficiency is almost independent of the fan diameter, so the optimum diameter for maximum overall efficiency corresponds to that for isentropic efficiency.
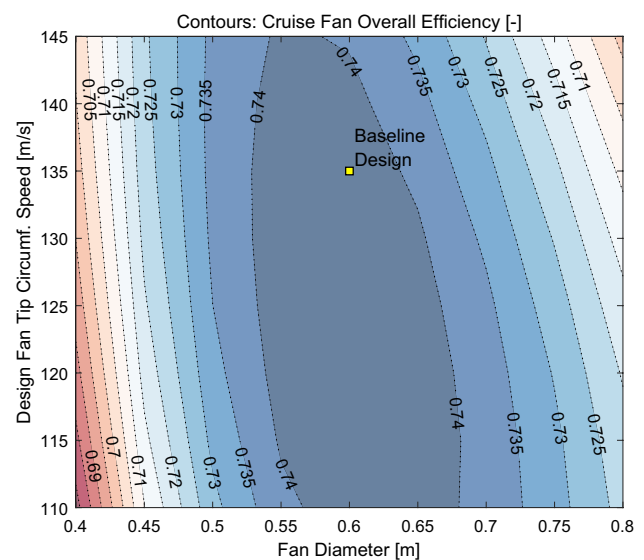


**Fig. 9** Influence of fan diameter and blade tip speed on the overall efficiency at cruise

The blade tip speed only has a minor influence on the cruise efficiency. However, it affects the aerodynamic stability of the fan stage. A lower blade tip speed, as well as a smaller fan diameter, result in an increased blade loading and reduced stability. An evaluation of blade loading and thus stability, using the de Haller number, is presented by Weintraub et al. [35]. Higher blade tip speeds are preferable for the aerodynamic design of a ducted fan, but the stability also depends on additional factors, such as the flow at the hub and tip. These are subject to a detailed design and are not evaluated in this paper. In summary, for such an application, studies are required to ascertain the optimum diameter for maximum efficiency, as well as the blade tip speed for acceptable stability.

Figure 10 shows the influence of the aerodynamic fan stage design variables on the overall sound power level.

As fan diameter and blade tip speed both increase, the blade loading decreases, and the blade surface boundary layers become thinner. Given the smaller velocity deficit of the wakes, the unsteady lift of the stator vanes decreases. As a consequence, the sound excitation and the overall sound power level are reduced.

In this study, the ratio of the axial gap to rotor chord length is kept constant. As the fan diameter grows, the axial gap between rotor and stator increases. Because of the larger propagation distance, the wakes and potential fields decay to a greater extent. As a result, there is a further reduction in the unsteady excitation and sound power as the diameter increases.

For smaller fan diameters and blade tip speeds, blade loading increases. This results in larger radial variations of the rotor outflow angle and a greater tilt of the wake. The
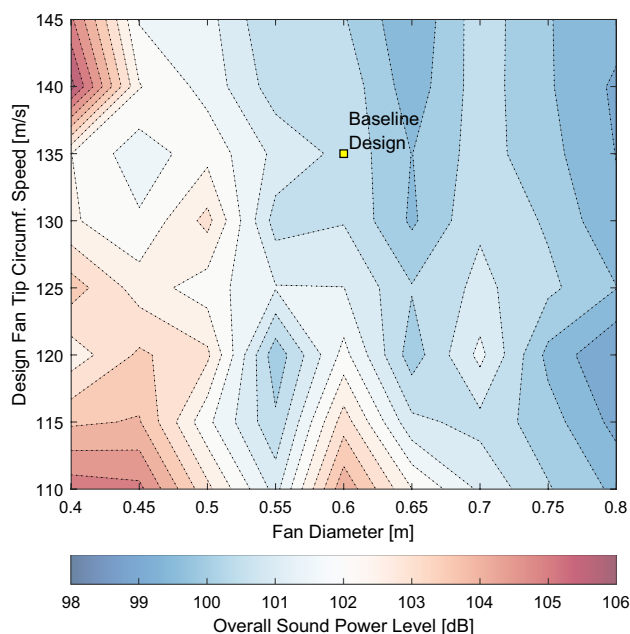
**Fig. 10** Influence of fan diameter and blade tip speed on the overall sound power level at sea level initial climb required thrust



**Fig. 11** Influence of fan diameter and axial rotor stator gap on the nacelle drag at cruise

fan diameter and blade tip speed therefore have an influence on both the amplitude and phase of the sound excitation. Destructive radial interference is intensified by the wake tilting and reduces the overall sound power level [16]. As a result of the blade loading affecting the radial interferences, the overall sound power level in Fig. 10 increases at higher blade tip speeds for a small fan diameter.

Additionally, the fan diameter influences the excitation phase through the twisting of the blades and the size of the axial gap. As the diameter increases, a larger blade becomes more twisted, resulting in a stronger wake tilting. Likewise, a greater axial gap and so too, convective distance for a large diameter, amplifies the tilt of the wake as it impinges on the stator vane leading edges. For the diameter in total, the influence of blade twist and axial gap on destructive radial interference predominates when compared to blade loading. Consequently, a larger fan diameter results in increased destructive radial interferences and reduced sound power.

When consideration is given to both amplitude and phase of the excitation, the key influences are the increase in the axial gap and the blade twisting with the fan diameter. In contrast, these quantities are not, or only slightly, affected by the blade tip speed. The influence of the fan diameter on the overall sound power level is thus greater than that of the blade tip speed.

For those designs investigated as a part of this study, the helical tip Mach number varies between 0.3 and 0.5. With lower blade tip speed and lower axial flow velocity for larger fan diameter, the helical tip Mach number decreases.
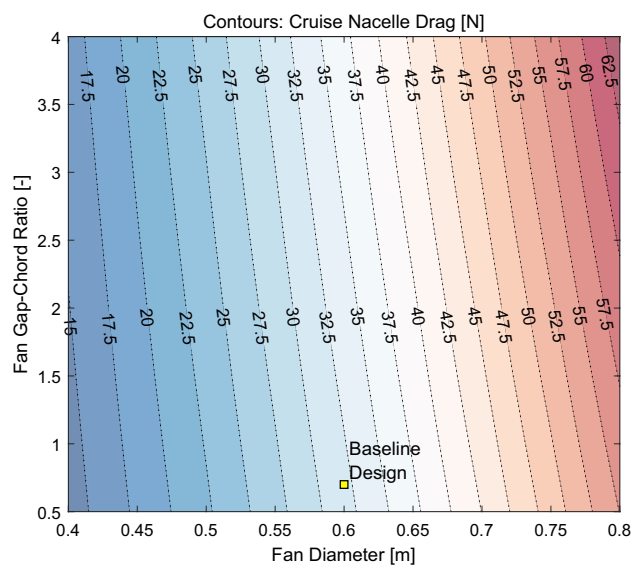
The influence of the helical tip Mach number on the overall sound power, shown in Fig. 10, is therefore only minor. This small effect results from the predominant excitation of sound at the stator vanes by the wakes. On account of the wake excitation, the unsteady lift of the stator vanes and the sound generation show only a slight dependence on the helical tip Mach number of the rotor blades.

For this study, pitch-to-chord and aspect ratios of rotor and stator are kept constant, so the number of blades decreases with a larger fan diameter. Given the restriction to integer blade numbers, discontinuous curves of the overall sound power level occur for the fan diameter. The significant influence, which the blade numbers have on the sound emitted, presented in Sect. 3.1, is visible here.

In summary, large fan diameters seem to be acoustically advantageous. In light of the ambiguous tendencies caused by the destructive radial interferences, no design trends are forthcoming for the blade tip speed. For each new design and application, it is therefore beneficial to conduct a study into the effect of the aerodynamic fan stage design variables on the acoustics. Taking into account the contrary trends of aerodynamics when compared to acoustics, a comprehensive evaluation concerning both targets is of great value for the design of a ducted fan.

### 3.4 Fan diameter and axial gap

The nacelle design of the ducted fan is determined primarily by its diameter and axial length, which in turn is driven by the axial gap between rotor and stator. Here, this axial gap is indicated relative to the chord length of the rotor blades. First, the influence of these design variables on the nacelle

aerodynamics is analyzed in Fig. 11 on the basis of the cruise nacelle drag. The drag increases with the fan diameter and the axial gap by up to 30% of the required cruise thrust. In particular, this is due to the larger wetted surface and greater aftbody drag. Compared to the axial gap, the fan diameter has a greater influence, since the wetted surface and aftbody drag are proportional to the square of the fan diameter. To minimize nacelle drag, it is necessary to choose small diameters. A further reduction is possible by selecting short axial gaps.

The influence of fan diameter and axial gap on the aerodynamics of the fan stage is analyzed in Fig. 12, based on the cruise overall efficiency. For the optimum diameter, the relationships presented in Sect. 3.3 are still valid. A larger axial gap leads to greater end wall friction losses between the rotor and stator, causing the overall efficiency to decrease by up to two percentage points. From a fan stage aerodynamic point of view, it is therefore mandatory to choose small axial gaps and to determine the optimum diameter of the fan stage.

To examine the influences of fan diameter and axial gap on the ducted fan acoustics, the overall sound power level is shown in Fig. 13. The dependencies between the acoustics and the fan diameter, discussed in Sect. 3.3, are still valid. The overall sound power level decreases for larger axial gaps. Because of the longer propagation distance towards the adjacent blade row, the wakes and potential fields decay to a greater extent. As a result, the unsteady flow perturbations and the sound excitation decrease.

For axial gaps smaller than one rotor chord length, the stator potential field decays only slightly before interacting with the rotor. The outcome is major unsteady lift forces, with a resultant strong excitation of sound. Since the
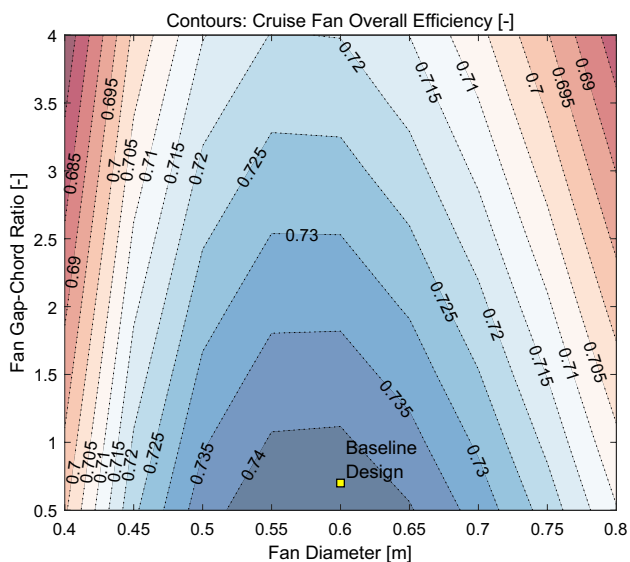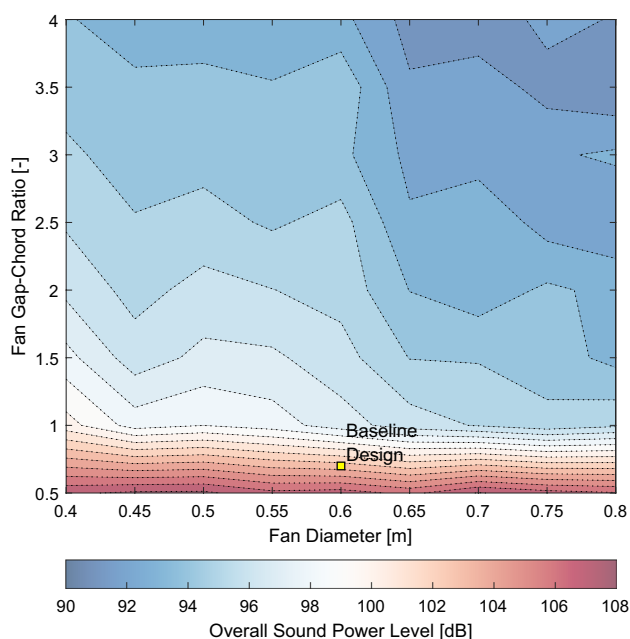


**Fig. 13** Influence of fan diameter and axial rotor stator gap on the overall sound power level at sea level initial climb required thrust



**Fig. 12** Influence of fan diameter and axial rotor stator gap on the overall efficiency at cruise

potential fields decay faster than the wakes, a larger axial gap diminishes the influence of the potential fields compared to the wakes. As such, in the case of axial gaps greater than one rotor chord length, the sound is predominantly excited by the wakes. As the axial distance increases yet further, the mixing only marginally improves, and the wakes decay more slowly. Consequently, the drop in the overall sound power level decreases.

In summary, the axial gap directly reduces the excitation amplitude of the predominant tonal sound sources of the ducted fan. Furthermore, the axial gap affects the amplitude almost independently of the blade loading. The influence on the overall sound power compared to the fan diameter is, therefore, greater. For an infinitely large axial gap as the upper limit, no rotor-stator interactions will occur and only rotor-alone noise will be excited, since the unsteady flow perturbations will completely decay up to the adjacent blade row. As rotor-alone noise is cut-off, no tonal sound will be radiated from a ducted fan with an infinitely large axial gap.

In conclusion, for a ducted fan, primarily tonal sound is excited deterministically by rotor–stator interactions. As a result, the number of rotor blades and stator vanes determines the excited azimuthal orders of the acoustic modes, which in turn strongly influence the overall sound power emitted through their propagation capabilities and directions. Further design features, which strongly affect sound emission through the excitation amplitudes and the radial interferences, are the lean and sweep of the stator vanes, the fan diameter, and the rotor–stator gap. For the reference

case, a cut-off or low radiation efficiency design, a large stator vane lean in the rotor rotation direction, a large stator vane sweep when the tip is displaced downstream, a large fan diameter, and a wide rotor–stator gap are acoustically advantageous.

However, a large fan diameter and axial gap have adverse effects on the aerodynamics of the fan stage and nacelle. Given these interdisciplinary relationships, it is necessary to adopt a comprehensive approach to the low-noise pre-design of a ducted fan, taking into account the various targets and boundary conditions. Depending on the top-level aircraft requirements of the specific application, the design trade-offs between efficiency of the fan stage, nacelle drag, and overall sound power emitted will result in varying design optima for the ducted fan. The selection of these design variables for the ducted fan has to be a compromise when it comes to improving efficiency, drag, and sound emission. In particular, concessions may have to be made in terms of conceptual drawbacks, such as nacelle drag or reduced efficiency, if minimum noise levels are to be achieved. Based on parametric studies, trade-offs in the design of ducted fans have to be established for the specific application.

## 4 Summary and outlook

The models presented and the studies conducted in this publication highlight that analytical and physics-based methods, which do not require calibration, are necessary when analyzing novel propulsor configurations, such as the ducted fan. These methods and the comprehensive evaluation, combined with a profound overall understanding, facilitate a mission-optimal design of ducted fans. Sufficient depth and scope of modeling and knowledge are required, especially for acoustics, to take into account all effects.

The studies presented in this paper establish that the tonal sound sources caused by the rotor–stator interactions predominate for a ducted fan, while the rotor-alone noise is cut-off for subsonic ducted fans, due to the nacelle. The tonal interaction sound sources are excited deterministically by the potential fields and wakes of the blades. Consequently, the blading parameters varied in this publication—the rotor blade and stator vane numbers, the lean and sweep of the stator vanes, the fan diameter, and the rotor-stator axial gap—strongly affect the sound power emitted. A potential for reducing propulsion noise by up to 20 dB overall sound power level is identified, compared to free propellers. The ducted fan therefore represents a promising propulsion system for applications that require low noise emission, such as air taxis in urban and regional air mobility.

For most design variables investigated in this publication, there are no clear trends on how to achieve low sound emission. While clear trends are evident in terms of the impact of these design variables on the aerodynamic excitations of the tonal sound sources, this is due to their frequently ambiguous influence on the radial interferences of the tonal sound sources. Both effects are of the same order and partially counteract each other. As such, detailed acoustic analyses, using methods such as those presented in this publication, are required to reduce the tonal sound sources systematically and identify quiet designs.

Future publications will extend the acoustic analyses to include more operating points relevant for the mission. Further design variables of the blades will be considered, and the results and models will be validated using high-fidelity methods.

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