PROPFAN AND TURBOFAN - ANTAGONISM OR SYNTHESIS

H. Grieb, D. Eckardt

MTU Motoren- und Turbinen-Union München GmbH

Abstract

The development of the propfan to date, especially the increasingly prominent counter-rotation propfan, has shown, on the one hand, that considerable reductions in fuel consumption are achievable. On the other hand, its integration into an aircraft creates configuration problems leading to a reorientation in commercial aircraft design. In particular, it has become clear that the noise from single-rotation or counter-rotation propfans either gives rise to complications in cabin noise-level reduction for wing-mounted engines, or to structural disadvantages involving centre of gravity and manoeuverability for tail-mounted engines, which are more suitable with regard to cabin noise. In other words, a less suitable aircraft layout with greater weight becomes necessary in every case.

Against this background, it can be shown that the geared turbofan with fixed geometry in the fan area as before, but very high bypass ratio cannot be expected to offer any advantage over the conventional turbofan of equivalent technological standard.

In contrast, it can be shown that an engine with counter-rotation shrouded front fan with variable-pitch blades allowing higher flow density in comparison with the turbofan, but higher thrust loading in comparison with the open* propfan, can be derived forming a kind of synthesis of the two basic engine concepts. Consequently, this results in an engine with very high bypass ratio and correspondingly attractive SFC as well as favourable acoustic properties, allowing for conventional underwing installation and tail installation as well.

The resulting optimal compromise between engine weight/dimensions and SFC, from the point of view of minimum propulsion weight (composed of the weight of the engine, fuel per mission, acoustic treatment, etc.), promises maximum reduction in DOC in comparison with the turbofan, whilst also bringing about further improvement over propfan powerplants.

The aerodynamic and propulsive characteristics of this concept, especially in the fan area, its operating characteristics and acoustic properties are described and comparison made with the conventional turbofan and open propfan.

* in contrast to the shrouded propfan, which is described herein

Nomenclature

Symbols

A	m^2	cross section area
c	m/s	flow velocity
c_F	-	thrust coefficient = $2F/Mc_0$
D	m	diameter
Dr	N	drag (cowl, nacelle, pylon)
F	N, daN	net thrust
H	ft	flight altitude
L	m	shroud lenght
M	kg/s	mass flow
MN	-	Mach number
N	1/min	rotational speed
P	kW	shaft power
p	bar	pressure
T	K	temperature
u	m/s	circumferential speed
x	m	axial distance from fan center plane
β	o	fan blade sweep angle
μ	-	bypass ratio
η	-	efficiency

Abbreviations

CR-OPF	open contra-rotating propfan
CR-SPF	shrouded contra-rot. propfan
DP	design point
GTF	geared turbofan
SR-SPF	shrouded single rot. propfan
TF	turbofan

Indices

ax	axial
c	cold stream (fan)
F	fan, fan outer diameter
h	hot stream (engine)
j	jet velocity
rel	relative to rotor blades
t	tangential
tot	total (stagnation)
un	uninstalled
0	atmosphere, free stream

Further symbols are explained in the context.

1. Introduction

The development of the open propfan, commenced at the beginning of the seventies in response to the fuel crisis, was concentrated initially on the single-rotation design. It is only in the last four years that the development of the contra-rotating open propfan has gained further and further in importance. This, on the one hand, is the consequence of a large number of positive aspects, such as better aerodynamic efficiency for the same disc loading, higher permissible disc loading, with wing-mounted installation lesser distortion of the airflow around the wing because there is no flow vorticity behind the propeller, avoidance of dynamic rotor reaction torque affecting the engine mountings and the aircraft, and easier management of the gearing because power and torque are transmitted via two shafts. On the other hand, analytical and first experimental investigations show that the near-field noise of the contra-rotating propfan is greater than with the single-rotation version and that the lower frequency level makes it more difficult to attenuate the noise on transition through the cabin wall, thus rendering this already considerable problem all the more serious. Further, the design expenditure and the weight of the contra-rotating propfan are greater than of the single-rotation version, although - for aerodynamic and acoustic reasons - with the contra-rotating propfan the total number of propeller blades needs not be greater than with the single-rotation version for the same performance. It is obvious that the single-rotation propfan will not be pursued much further.

Irrespective of whether the contra-rotating propfan is arranged ahead of the core engine with gear unit or behind the core engine with/without gear, it is apparent that bearing in mind the unacceptable costliness of soundproofing of the passenger cabin area, the present contra-rotating propfan will have to be exclusively tail-mounted. Accordingly, the pusher version will be preferred. However, tail-mounted installation has unfavourable effects on the general design of the aircraft, because the unfavourable weight distribution necessitates that the wings be located relatively far to the rear, resulting in a correspondingly short distance to the control fins, the surfaces of which have to be amply dimensioned; and this also gives rise to a considerable increase in weight, compare /1,2/. Moreover, with tail-mounted installations, the questions regarding the noise situation are by far from being clarified, bearing in mind the distortion of the flow upstream of the propfan caused by the flow around the wing and its wake as well as the wake of the engine pylon.

Furthermore, with every kind of installation it must be kept in mind that the question of the safety of the aircraft in the event of propeller blade damage associated with potential secondary damage in sensitive areas cannot be regarded as having been solved convincingly. In this context, in comparison with previous propulsion systems, on the one hand, the greater probability of bird strike, but on the other hand considerably higher demands in propeller and blade integrity are to be expected.

It would appear probable that considering the size of the propeller, the use of the open contra-rotating propfan will be confined to twin-engined short and medium-range aircraft seating a maximum of 150 - 180 passengers.

Fig. 1 shows the specific thrusts and SFCs of various engines representing the various generations in propulsion concepts for civil aircraft. These data, especially the wide range between propfan and turbofan engines, give rise to the question of whether propulsion concepts can be derived from the propfan and turbofan engines, which will represent a combination of the advantages of the two engine concepts, without their disadvantages. The advantages and disadvantages of the propfan and turbofan concepts are summarised in Table 1.

	Open contra-rotating propfan	Turbofan
Cruise SFC	most attractive	base
Cruise Mach Number	limited to 0.76 - 0.78	not limited
Take-off thrust for given cruise thrust	very high	base
Thrust reverse	simple; fast reaction by variable pitch fan blades comp. /3, 4/	by cowl-mounted thrust reverser
Fan blade containment	high risk of secondary damage	minimum risk
Near-field noise	fuselage soundproofing and/or acoustic fatigue counter-measures, compare /1/	base
Far-field noise	possibly somewhat higher, regulations can be met	base
Engine installation	wing mounting critical with view to wing aerodynamics and cabin noise level	underwing and tail mounting feasible
Access to passenger/cargo doors on ground	partly hindered depending on engine installation, compare /1/	base

Table 1: General Operational Properties of Propfans and Turbofans

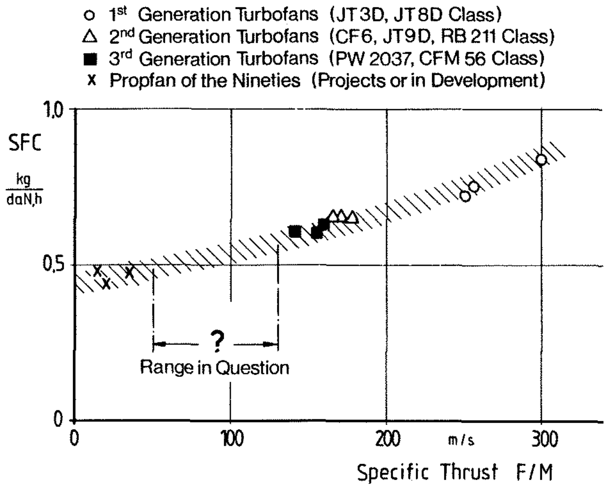

Fig.1:

Selection of Statistical Data on Specific Performance of Turbofan and Propfan Engines

(Cruise, MN = 0.80; H = 35000 ft, uninstalled)

2. Turbofan and Propfan Design Features

Fan flow with/without shroud

Consideration of the available propfan performance data leads to the conclusion that the open contra-rotating propfan, which is more favourable than the single-rotation version with regard to the permissible disc loading, permits only a very small step in the direction of greater disc loading or greater specific thrust respectively. It can be assumed that with the contra-rotating propfan under cruise conditions a specific thrust of 34.0 m/sec or a thrust coefficient of 0.30 corresponding to a pressure ratio of the propeller of around 1.12 practically represent the upper limit. Higher specific thrust is possible only with the shrouded fan version, both with the single-rotation and contra-rotating propfans. This is explained by the fact that without shroud, static pressure increase as the flow passes through the propeller is practically impossible, meaning that very high axial Mach numbers which are not acceptable occur already within the propeller with higher disc loading. In contrast, static pressure increase in the propeller is possible with the shrouded version, where the static energy of the flow is converted into flow velocity in the nozzle behind the propeller. The question of whether the shrouded propfan concept should be based on the single-rotation or contra-rotating propfan has still to be discussed. Regarding this situation, allowance must be made for the shroud drag, which according to present knowledge practically exclude low specific thrust values because of the large shroud dimensions with associated drag.

In this context, Fig. 2 illustrates for typical propfan shrouds, the strong influence of upstream and downstream flow conditions, summarised by the parameter D_0/D_{max}, on the overall shroud/nacelle drag. This is strongly influenced by the fan concept, as described later.

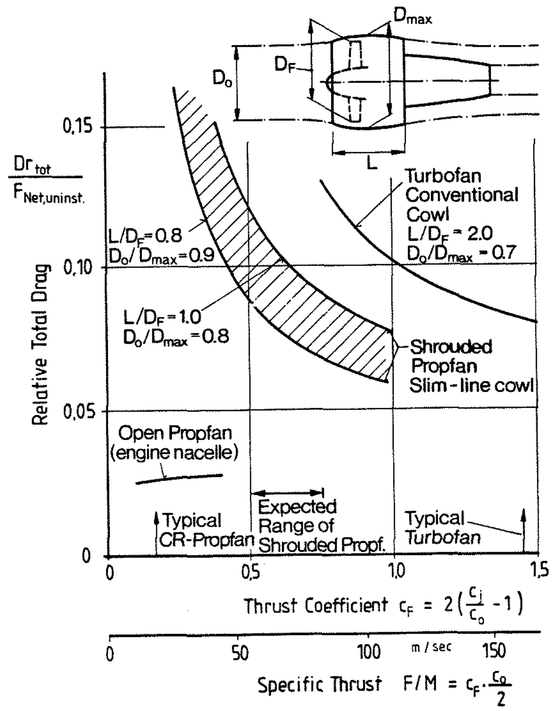

Fig. 2:

General Magnitude and Trend of Cowl and Nacelle and Pylon Drag, Related to Uninstalled Net Thrust

(max. Cruise, MN=0.76; H=35000 ft)

If, on the other hand, the turbofan is developed with a view toward appreciably lower SFC, i.e. to lower specific thrusts or higher bypass ratios respectively, it will be necessary to go for a geared version, which has not been attempted to date at first glance because of the complexity. However, closer examination reveals that it is by no means the gear alone that militates against the turbofan with smaller specific thrust, all the more so since the extra cost for the gearing can be compensated to a certain extent by the possibility of having a low-pressure turbine with higher speed, i.e. fewer stages. Much more, decreasing specific thrust or increasing flow involves greater shroud dimensions, meaning that irrespective of the rapid increase in the shroud drag as shown in Fig. 2, it is the expenditure for the nacelle including the thrust reverser which actually accounts for the unacceptable disadvantages. Furthermore, if the fan pressure ratio decreases below 1.4, that is to say with subcritical bypass nozzle in the take-off and climb phase, it becomes even more difficult with fixed fan geometry to keep the working line within the good efficiency range in the fan performance map, and to provide sufficient surge margin as well under all operating conditions (see Figs. 3 and 4).

In this connection, an essential difference must be made between fan flow with and without shroud, which represents a decisive argument in favour of pursuing the shrouded fan concept. In the open propfan concept according to Fig. 5, as it passes through the propeller the flow is accelerated such that it reaches approximately the mean between the air speed and jet stream velocity. At air speeds between Mach 0.76 and 0.8, because of the acceleration of the flow passing the propeller, the propfan inevitably reaches its choke limit, since even with only 5 or 6 blades per rotor with the present thick profiles at the hub, resulting in a blockage of the annulus cross section area of 2 - 3% corresponding to choking at an axial Mach number of roughly 0.87 will occur. Moreover, the choke limit with associated negative effect on the aerodynamic efficiency will occur at least locally - i.e. in the hub area - already at medium axial inflow velocities, that is to say of araound Mach 0.79 to 0.82.

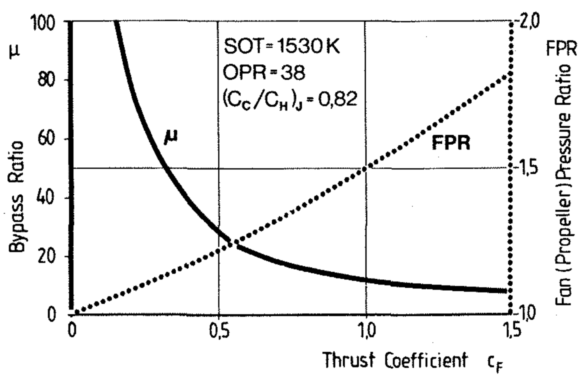

Fig.3:
Bypass Ratio and Fan Pressure Ratio Versus Thrust Coefficient
(Max. Cruise, MN=0,76; H=35000ft)

With the conventional turbofan according to Fig. 5, the shroud forms a diffuser in front of the fan, which decelerates the incoming flow from the air speed to an axial velocity that is acceptable at the entry to the fan. Moreover, the blockage of the annulus cross section area by the fan blades, which in this case is in the region of 8 - 9% because of the larger number of blades, produces a choke Mach number in the annulus cross section of around 0.71. In view of the greater blockage in the fan hub area inlet axial Mach numbers of up to 0.67 are acceptable. The axial velocity is reduced further as the flow passes through the fan, especially since the axial inflow Mach numbers of the

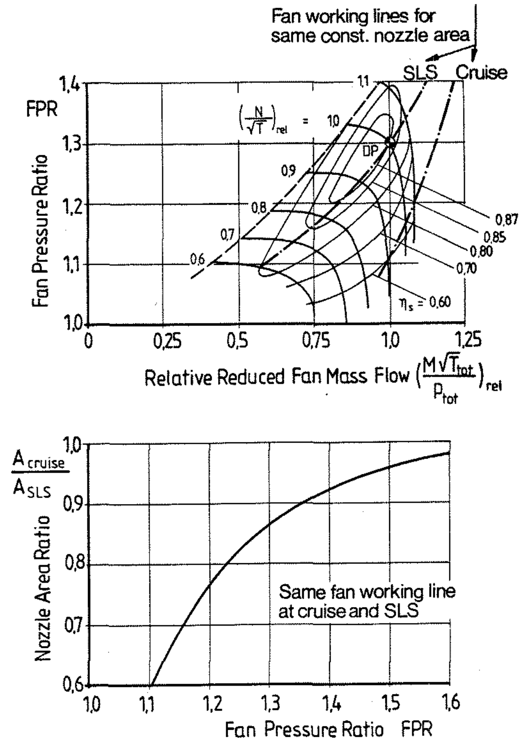

Fig.4:
Effect of Fan Pressure Ratio and Nozzle Area on Fan Working Line at Cruise and SLS
(Fixed fan geometry, cruise at MN=0,76; H=35000ft)

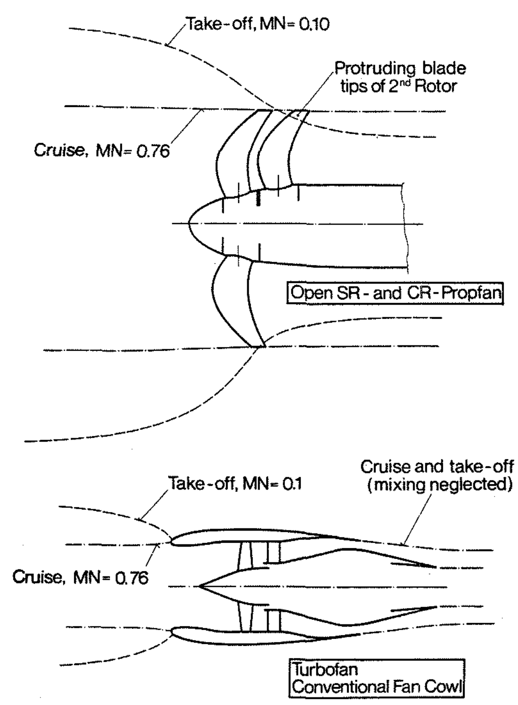

Fig.5:
Stream Tube Contours for Cruise and Take-Off Conditions, Interaction with Propfan Blade Tips and Turbofan Cowl Entry Lip

outlet guide vane and the following transition duct to the nozzle have to be kept low, i.e. in the region of Mach 0.40 to 0.45, in view of flow losses. In principle, these arguments also hold good for the single-rotation shrouded propfan as well, which will be gone into later. Fig. 6 shows a comparison of the typical axial velocities occurring with the flow through the propfan and turbofan.

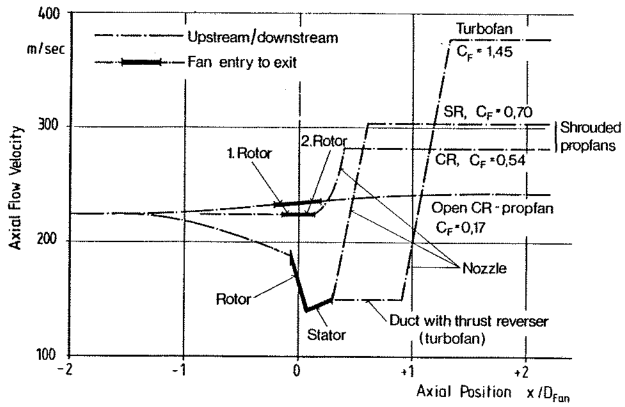

Fig.6:
Mean Axial Velocity Distribution for Open Propfan, Shrouded Propfan and Turbofan
(max.Cruise,MN=0,76; 35000ft)

Just as with the turbofan, with the single-rotation and contra-rotating shrouded propfans it is decisive that at high air speeds, i.e. at cruise the axial Mach number at the fan entry is not rising with the air speed anymore, because of the given airflow characteristics with critical nozzle, but is determined by the configuration of the shroud. Consequently, in contrast to the unshrouded version, the shrouded propfan is not limited to a flight Mach number of 0.76 - 0.80, but can also be used in the region above this, which is desirable especially for long-haul aircraft.

Blade configuration

With the single-rotation shrouded propfan the need for matching of the blades for various flight conditions, including thrust reversal, calls for particular care in the design of the hub section of the impeller. This means that in contrast to the turbofan, the pitch must not be too small. Here provision has to be made to ensure that the blades do not overlap too much at the hub, i.e. at pitch/chord ratios around 0.6 - 0.7, with the result that for thrust reversal only the blades in the outer, particularly effective part of the flow cross section can be varied such that reversal of the mass flow is achieved. Furthermore, considering the mechanical integrity of the hub and the strength of the blade pinions, but also in view of noise generation, the tip speed has in any case to be restricted to roughly 280 - 300 m/sec, meaning that with the recommended fan pressure ratio of 1.30 - 1.34 being in line with acceptable shroud dimensions and drag (compare Figs. 3 and 4), but also in view of the aerodynamic loading of the blades and vanes, hub/tip ratios of less than 0.40 - 0.45, are not feasible.

With the contra-rotating shrouded propfan the blades necessary for energy conversion are so to speek distributed on two rotors, meaning that with the anticipated 10 - 12 blades per rotor with slim hub profiles, the resulting blockage of the annulus cross section area is only about 2 - 3 %. Furthermore, the design for contra-rotating rotors, i.e. without outlet guide vane, allows for axial flow downstream of the fan with the result that high axial inflow Mach numbers similar of the unshrouded propfan are possible without deceleration, but rather with slight acceleration of the flow through the rotors to the immediately following nozzle, compare Fig. 6.

With the contra-rotating shrouded propfan, which is preferably to be designed for pressure ratios of around 1.23 - 1.25 corresponding to acceptable shroud dimensions etc. and tip speeds of around 250 m/sec, axial Mach numbers of the flow through both rotors in the order of Mach 0.75 - 0.78 can be accepted without harm. This results in a considerable reduction in the aerodynamic blade loading, and consequently with a hub pitch/chord ratio of around 0.8 desirable in view of the blade setting at the hub regarding thrust reversal, in hub flow conditions that are very favourable from the aerodynamic aspect. Thus with the contra-rotating shrouded propfan, concerning the mechanical integrity of the hub and the required cross section of the blade pinions for 10 - 12 slim profile blades at the hub, hub/tip ratios of 0.25 are possible.

For the single-rotation and contra-rotating shrouded propfan with the same thrust, the same shroud outer diameter and same state of the art of the core engine and bearing in mind the still-to-be discussed propfan efficiencies, this results in the main fan design data as summarised in Table 2, used as the basis for further shrouded propfan design considerations. This comparison makes it particularly clear that with the contra-rotating propfan, as opposed to the single-rotation model, the higher permissible axial inlet Mach numbers and the smaller realisable hub/tip ratios make possible an appreciably greater mass flow per fan entry fontal area.

With the given maximum shroud diameter, this leads first to lower specific thrust or higher bypass ratio respectively, and consequently for given cruise thrust to greater take-off thrust. In combination with the improved fan efficiency, which

			Contra-rotating CR-SPF	Single-rotation SR-SPF
Fan outer diameter	D_F	m	2.50	2.50
Fan mass flow	M_F	kg/s	396	312
Fan pressure ratio	FPR	-	1.24	1.31
Axial entry Mach number	MN_{ax}	-	0.775	0.65
Entry hub/tip ratio	D_i/D_F	-	0.25	0.45
Blade tip speed	U_T	m/s	229	242
Rotor blade number		-	12 + 12	22
Stator vane number		-	-	28
Mass flow per frontal area	$\frac{M_F}{\pi/4 D_F^2}$	kg/s,m^2	63.5	49.6
Fan isentr. efficiency	$\eta_{F,isentr.}$	-	0.92	0.89

Table 2: Main Layout Data of Shrouded Propfans for 2200 daN Net Thrust (installed)
Max. Cruise, MN = 0.76; H = 35000 ft

has still to be discussed, it also leads to considerably greater propulsive effectiveness as a major indication for better SFC of the complete engine.

Shroud Aerodynamics

When designing the nacelle for the shrouded propfan it must be borne in mind, that for the contra-rotating model in particular, the flow to the fan entry does not have to be decelerated and has to be only slightly accelerated towards the nozzle exit, as shown in Fig. 6. Hence it is possible to have a relatively short slim-line fan shroud, at least as far as climb and cruise conditions are concerned. In the case of the single-rotation version, the deceleration of the flow to the fan entry as well as through the fan, is unavoidable, see Fig. 6. Consequently, the aerodynamic of the flow around the shroud and of the flow to the fan are less favourable, especially with short slim-line shroud.

On the whole, with both shrouded propfan versions it is the conditions during take-off and initial climb in association with the corresponding flow around the leading edge of the shroud, as well as the flow conditions with cross wind and gusts, with resultant danger of boundary layer separation at the inside which are decisive for the design. The question of whether it will be necessary to have variable geometry in the shroud leading edge area for controlling the flow during the take-off phase has still to be clarified.

For these reasons, the main shroud dimensions of the propfan and turbofan were chosen in the frame of nacelle dimensioning and drag analysis (compare Fig. 2) regarding the following geometrical relationships:

	Shrouded Propfan CR	Shrouded Propfan SR	Turbofan
D_{max}/D_F	1.1	1.1	1.3
L/D_F	0.8	1.0	2.0

Moreover, the aerodynamic conditions around and inside the shroud during thrust reverse require intensive investigation. Some problems encountered with thrust reverse by shrouded variable pitch fans are commented in /3, 4/.

Shrouded Propfan Efficicncy

Regarding the operating characteristics and attainable efficiency, it is to be noted that with the single-rotation propfan the aerodynamic loading conditions of the blade and vane cascades are similar to those prevailing in the conventional turbofan, although the lower pressure ratio of the propfan means that the blade tip velocities are considerably lower and, thus, also the relative entry Mach numbers are lower. In contrast to this, in the contra-rotating propfan the situation concerning aerodynamic losses is such that the sum of wetted blade surfaces is appreciably smaller and the blades are subjected to considerably lower aerodynamic loads. Also, considering the higher axial velocity, the somewhat lower blade tip speed and the blade sweep mean that the aerodynamic losses are appreciably lower than in the single-rotation model. Concerning this, however, the aerodynamic behaviour of the near-tip profiles with large pitch/chord ratio in the order of 3 at transonic relative entry flow Mach numbers and static pressure rise between the cascade entry and outlet has still to be clarified in detail, since it will not be possible to make use of the experience gained with the open contra-rotating propfan.

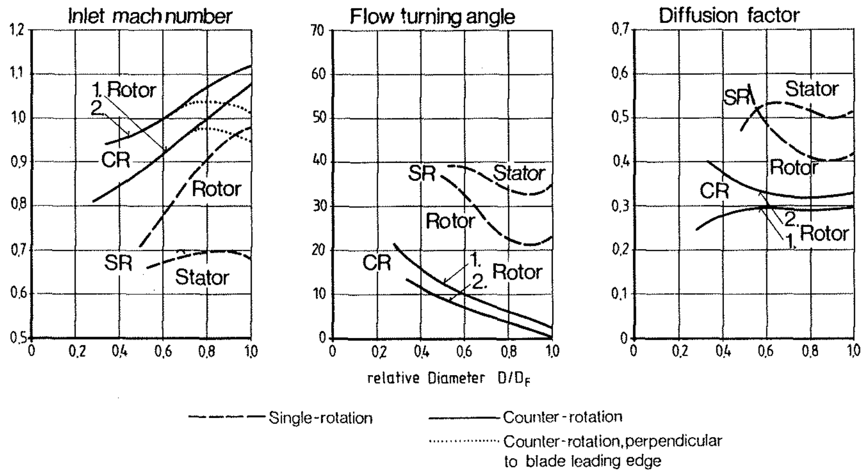

Fig.7:

Aerodynamic Cascade Data of Single-Rotation (SR) and Counter-Rotation (CR) Shrouded Propfans (Examples)

For the main data of the single-rotation and contra-rotating propfans as listed in Table 2, the main flow data determined for the two concepts and the aerodynamic loading of the cascades are given in Fig. 7. Concerning the comparison of efficiencies, it should be noted that the axial struts required in the contra-rotating propfans for shroud location give rise to losses amounting to roughly 0.4% of the fan efficiency.

As a summary, Fig. 8 gives the overall propulsive efficiency in the cold air stream, derived from the Froude propulsive efficiency, the isentropic fan efficiency and the nacelle drag, related to the shaft power required by the fan.

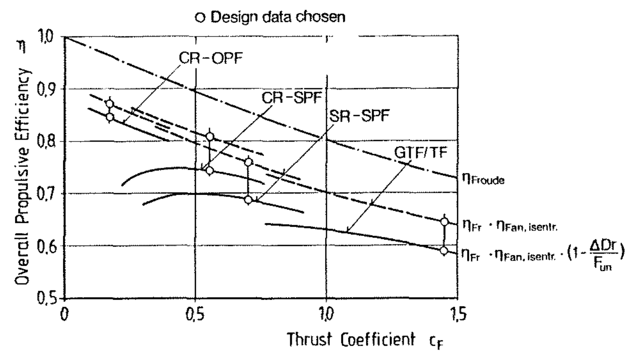

Fig. 8:

Fan Stream Propulsive Efficiency

$P_{prop} / P_{shaft} = \eta_{Fr} \cdot \eta_{Fan,\,isentr.} \cdot (1 - \frac{D_r}{F_{un}})_{Shroud}$

Max Cruise, MN = 0,76; H = 35000 ft

3. Design Data and Installation Conditions of Shrouded Propfans

With respect to the various fan concepts, the propulsion concepts shown schematically in Fig. 9 were investigated, going into important aspects such as cruise SFCs including nacelle drag, main dimensions, weights, installation conditions and particularly the noise data.

Regarding this, for the same state of the art of the core engine and the gear, expected in the mid-ninetees, Table 3 first gives a general view of the main cycle data chosen such as turbine entry temperature, overall pressure ratio, bypass ratio and fan pressure ratio, in each case with optimised jet stream velocities in the area of the fan and the core engine corresponding to a ratio of $(C_c/C_h)_j$ = 0.80 - 0.85.

The remarkable aspect here with the contra-rotating propfan and given nacelle dimensions is the high mass flow attainable, which in conjunction with the low specific thrust and improved fan efficiency leads to lower shaft power. The consequence is - among other things - a smaller and lighter core engine and gear unit.

Based on the relevant case of engines for a 150-seat short- and medium-haul aircraft with an installed thrust per engine at cruise of 2200 daN corresponding to a take-off thrust of 11.000 - 13.000 daN, the engines are considered for the case of underwing installation. In view of the flow around the nacelle and wing as well as of the required ground clearance, there results an upper limit for the nacelle diameter or fan diameter respectively. This is illustrated in Fig.10 for the engine concepts under review. From this it can be recognised that the shrouded propfan requires a thrust coefficient in excess of 0.55 - 0.70 corresponding to a specific thrust of 62 - 78 m/sec in order to be able to maintain the above installation conditions. As an example, Fig. 11 shows the main dimensions and general arrangement of the contra-rotating shrouded propfan concept designed for the installation case described here with main design data according to Table 3.

			Open contra-rotating propfan CR-OPF	Shrouded contra-rot. propfans CR-SPF	Shrouded single rot. propfans SR-SPF	Turbofan TF
Fan diameter	D_F	m	4.05	2.50	2.50	1.60
Fan mass flow	M_F	kg/s	1160	396	312	147
Specific net thrust*	F_{un}/M_F	m/s	19.4	60.4	77.8	162.5
Thrust coefficient*	c_F	-	0.17	0.54	0.70	1.45
Nacelle drag related to net thrust*	$\frac{Dr}{F_{un}}$	-	0.025	0.095**	0.082**	0.082**
Turbine entry temp.	SOT	K	1530	1530	1530	1530
Overall pressure ratio	OPR	-	38	38	38	38
Bypass ratio	BPR	-	90	26.1	19.6	8.2
Fan pressure ratio	FPR	-	1.07	1.24	1.31	1.75
Cold/hot stream jet velocity relation	$(c_c/c_h)_j$	-	0.83	0.83	0.83	0.83
SFC, installed***		kg/daN,h	0.436	0.508	0.543	0.596

*) related to uninstalled net thrust
**) pylon included
***) nacelle drag included

Table 3: Main Layout Data of Engine Concepts Considered for 2200 daN Net Thrust
Max. Cruise, MN = 0.76; H = 35000 ft

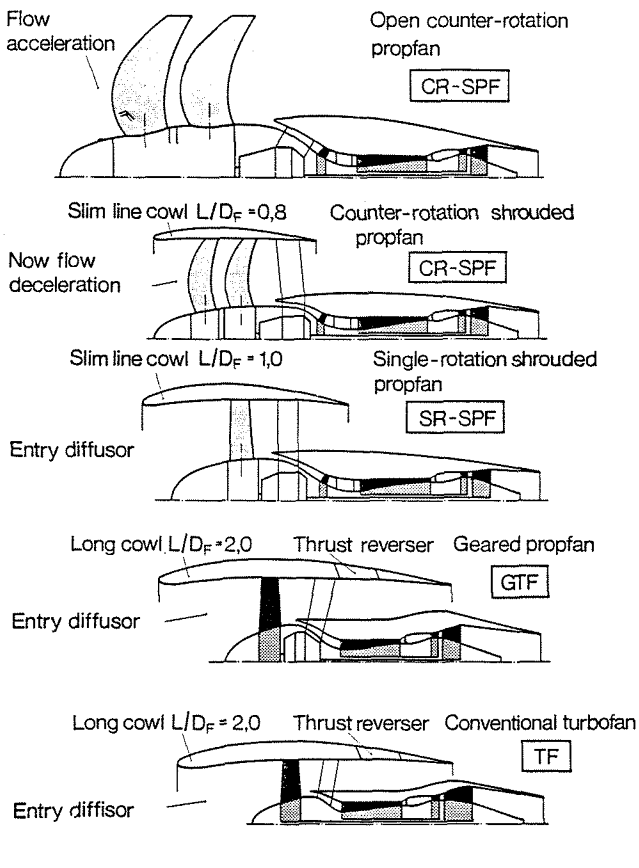

Fig.9:
Propulsion Concepts Considered
(Main Dimensions for Approx. Same Cruise Thrust
(Schematic)

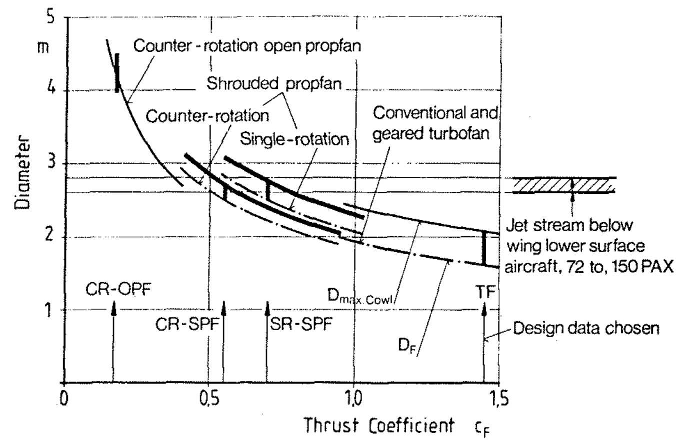

Fig.10:
Turbofan and Propfan Diameters F-2200 daN (Installed)
(MN=0,76, H=35000ft, ISA)

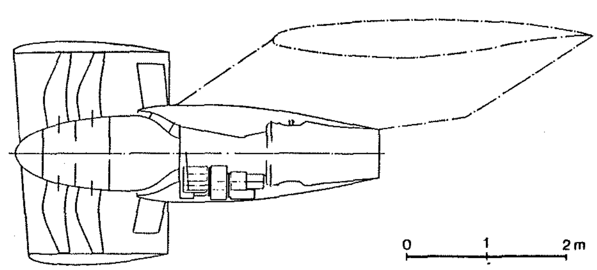

Fig.11:
General Arrangement of Counter-Rotation Shrouded Propfan for 150-PAX Short/Medium-Haul Aircraft in Underwing Installation

In addition, Fig. 12 shows the underwing installation of the contra-rotating shrouded propfan for the described example of a future 150-seat short- and medium-haul aircraft with 2200 daN thrust per engine at cruise in comparison with that of a turbofan of equivalent state of the art. The contours plotted for the incoming air flow and the jet stream to be passed under the wing make it clear that the question concerning the engine/wing interference is particularly important, irrespective of which shrouded propfan concept is used, and requires the utmost careful geometrical arrangement of the engine under the wing. Despite of the greater massflow, but because of the appreciably lesser deceleration (thickening) and lesser reacceleration (thinning) of the stream tube passing the wing lower side, with the shrouded contra-rotating propfan (shown here) as well as qualitatively with the single-rotation shrouded propfan (not shown), more or less favourable aerodynamic conditions are to be expected (in comparison with the turbofan).

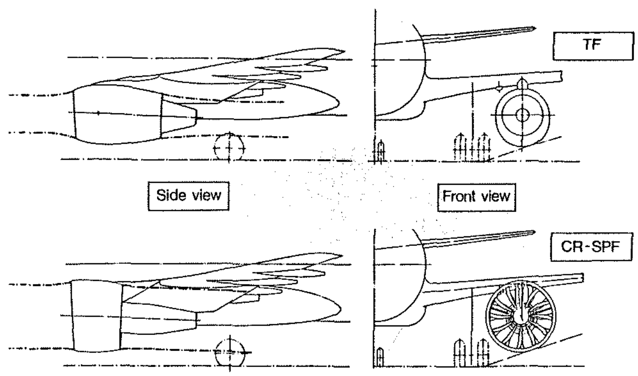

Fig.12
Wing/Engine Arrangement for a Aicraft, 72 to, 150 PAX (Turbofan and Counter-Rotating Shrouded Propfan)

4. Near-Field and Far-Field Noise

As mentioned at the beginning, one of the aims of the shrouded propfan is to limit noise emission to such an extent that

- Concerning the near-field noise, the engines can be installed under the wings without the need for additional soundproofing measures to the airframe, analogous to the turbofan installation, and
- Concerning the far-field noise, at the least, the noise limits according to the latest regulations can be complied with.

In fact, because of the low fan pressure ratio and the moderate fan blade relative entry Mach numbers, the noise generated by the shrouded propfan is lower than that generated by the turbofan. On the other hand, with the shrouded propfan the possibilities for soundproofing measures inside the shroud are considerably more limited for physical and geometrical reasons, where the following design features are determinative:

- The primary frequency is appreciably lower in the propfan than in the turbofan, meaning that sound-absorbing cladding needs to be thicker and is less effective, all the more since the shroud does not extend as far to the front or rear of the shrouded propfan as with the turbofan, compare Fig. 9.
- The sound directivity to fore and aft is considerably less than with the turbofan because of the lower primary frequency, with the result that the areas to the side of the engines, and thus also the cabin wall, are exposed to more noise than with the turbofan.
- Because of the lower primary frequency, soundproofing of the cabin wall is considerably more complicated, i.e. requires more mass.

On the one hand, just as with the unshrouded version, with the contra-rotating shrouded propfan the fan blade sweep and lateral inclination at the outer sections offer an excellent opportunity of reducing the noise emitted. On the other hand, the narrow pitch of the blades in the single-rotation concept avoids the feasibility of blade axial and tangential sweep. Compared with this, the contra-rotating shrouded propfan with axial and tangential sweep of the blades result in a reduction of the noise emitted by the fan to the order 3 dB. Concerning this, Table 4 gives a summary of the design parameters characterising the noise generation, propagation and attenuation in the turbofan, shrouded propfan and unshrouded contra-rotating propfan engines for the same thrust at cruise.

The sound emission is particularly great with the propfan when the fan blade relative entry Mach numbers perpendicular to the leading edge exceed 1. However, reduction of the tip speed, which leads simultaneously to reduction of the primary frequency, can be used only to a limited extent for reducing the noise level in the cabin, because frequency reduction is accompanied by loss of effectiveness of the soundproofing.

Analysis of the near-field noise in the configurations under review reveals that one of the main requirements, i.e. marked reduction of the noise emission of the propeller, which is extremely high with the unshrouded propfan, can be fulfilled by the shrouded design.

			Open contra-rotating propfan CR-OPF	Shrouded contra-rot. propfans CR-SPF	Shrouded single-rot. propfans SR-SPF	Turbofan TF
Fan diameter	D_F	m	4.05	2.50	2.50	1.60
Blade tip speed	U_T	m/s	198	229	242	431
Blade tip sweep at leading edge						
axial	β_{ax}	°	40	25	-	-
tangential	β_t	°	20	30	-	-
Blade tip relative entry Mach number	MN_{rel}		1.04	1.095	1.038	1,58
ditto, perpendicular to leading edge	$MN_{rel,\beta}$		0.75	0.90	1.033	1,58
Blade number			6 x 6	12 x 12	22	22
Primary frequency	f	1/s	93	350	676	1910

Table 4: Relevant Acoustic Fan Data for Engine Concepts Considered
Max. Cruise, MN = 0.76; H = 35000 ft

Altogether, according to Fig. 13 it is expected that with the shrouded propfan, both the single-rotation and contra-rotating versions with internal shroud cladding with corresponding attenuation effect and normal fuselage structure, the noise level inside the cabin can be kept within the limit of 80 dBA set by the fuselage external flow boundary layer noise, and simultaneously kept to roughly the same noise level as with the turbofan. The determinative factors here are the design of the shrouded propfan with greater number of blades and smaller diameter with consequently higher frequency, the avoidance of the sound propagated by the blade-tip vortices at the unshrouded contra-rotating propfan, the (admittedly small) shielding effect of the fan shroud and the (likewise small) noise attenuation by the cladding inside the shroud.

Contrary to this, with the same airframe structure and cladding, according to Fig. 13 the noise level for the unshrouded contra-rotating propfan is at least 25 dBA greater, disregarding the theoretically difficult-to-determine but intensive sound emission of the blade-tip vortices.

In the case of the 150-seat aircraft with open contra-rotating propfans in wing-mounted installation, the attenuation of its unacceptably high noise level would necessitate an extra weight of approximately 1100 kg in cabin soundproofing materials per engine.

As shown in Fig. 14, the far-field noise with both shrouded fan concepts can be kept approximately within the limits that will be decisive in future.

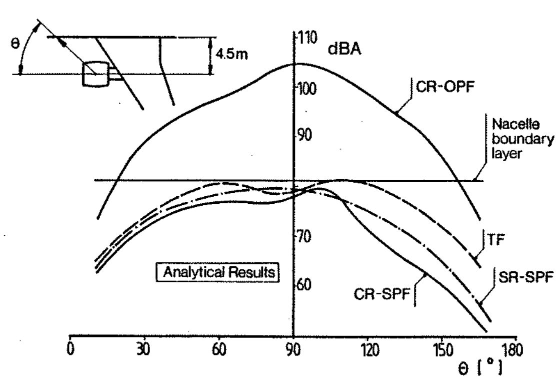

Fig.13:
Noise Levels (dBA) Inside Passenger Cabine With Various Propulsion Concepts Conventional Nacelle Structure
(Max. Cruise, MN=0.76; H=35000ft, F_{NET}=2200 daN)

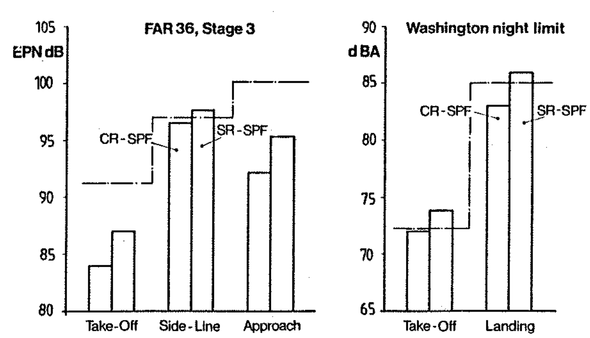

Fig.14:
Estimated Far-field Noise Levels for Aircraft, 72to, with 2 Engines
(Single-rotation and Counter-rotation shrouded Propfans)
- Analytical Results -

5. Overall Propulsion Weight

In answering the questions raised in the beginning, the investigation leads to the conclusion that in the wide range of the specific thrusts or thrust coefficients, between the open propfan and conventional turbofan lie other propulsion concepts, namely the shrouded propfan and geared turbofan, of which the contra-rotating shrouded propfan in particular forms an attractiv synthesis of the favourable characteristics of the open contra-rotating propfan and conventional turbofan, determinative for operational behaviour and economy. Concerning the latter, Fig. 15 gives the engine weights determined for the concepts considered, as shown schematically in Fig. 9 and designed for the same state of the art expected in the mid-nineties. In the shrouded engines including the turbofan, the sound-attenuating measures are integrated in the engine nacelle itself, and are thus included in the installed engine weight; whereas the extra weight of the cabin soundproofing required with the wing-mounted open propfan is shown specifically. In contrast to this, the extra measures required for cabin soundproofing with tail-mounted open propfan is not known. Similarly unknown are the extra airframe weights for the tail-mounted arrangement in comparison with the wing-mounted engines. However, studies by others, compare /1,2/, have shown that the overall weight of the airframe plus engines is hardly less with the tail-mounted propfan than with wing-mounted installation and complete cabin soundproofing. Furthermore, the extra weight of the fan blade containment for all shrouded engines is included. Particularly with the shrouded propfan, this blade containment represents a safety factor that is not to be underestimated in comparison with the open version.

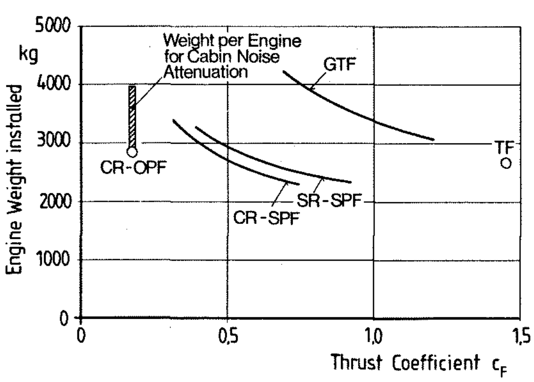

Fig.15:

Turbofan and Propfan Weights (Installed *)

F=2200 daN, Installed, MN=0,76; H=35000 ft

*EBU, Nacelle, Cabin Noise Attenuation Included

To provide a proper comparison of the open propfan with the other (shrouded) engine concepts, including the turbofan, the installed SFCs at cruise attainable by the engine concepts described are shown in Fig. 16, bearing in mind the installation, especially the nacelle drag. According to this, it goes without saying that the absolutely most favourable SFC is attainable with the open contra-rotating propfan.

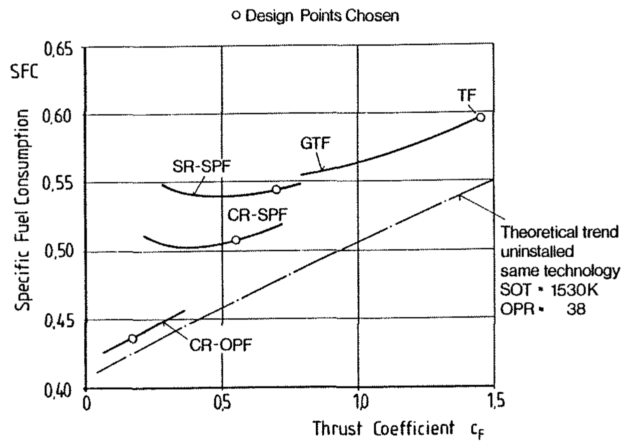

Fig.16:

Specific Fuel Consumtion (Installed)

(Max. Cruise, MN=0,76; H=35000ft, Nacelle Drag Included)

However, beside other factors such as procurement costs, maintenance costs, failure rates etc., the investigation of which lies beyond the scope of this study, the parameter which gives a distinct indication of the economy of the propulsion system is the overall propulsion weight, consisting of the weight of the engine plus soundproofing, if applicable, plus fuel per engine and mission. Fig. 17 shows this by way of the example of a 150-seat short- and medium-haul commercial aircraft with a design range of 2300 NM. It can be seen that with the single-rotation

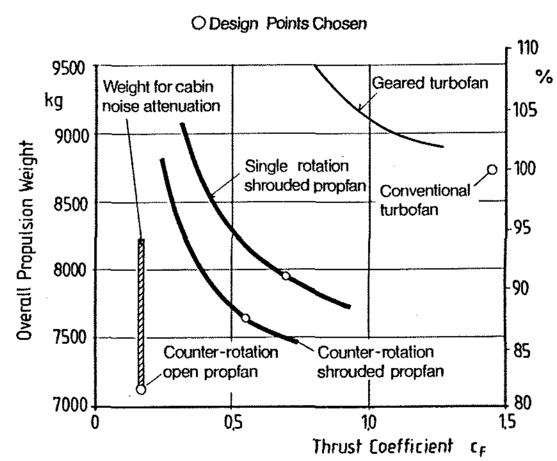

Fig.17:

Overall Propulsion Systems Weights of Various Propulsion Concepts

(2300 nm; F=2200daN at max.cruise; MN=0,76; H=35000ft) or the contra-rotating shrouded propfan respectively, a clear reduction in the overall propulsion weight in the range of 8 - 13% is attainable in comparison with the conventional turbofan, and 4 - 7% in comparison with the open contra-rotating propfan. Contrary to this, no reduction in the overall propulsion weight is expected with the geared turbofan.

This finding is regarded as being a decisive starting-point for the clear reduction in direct operating costs, attainable above all with the contra-rotating shrouded propfan in comparison with the other concepts.

6. Conclusions

The investigations carried out here show that the desired combination of the positive properties of the turbofan, namely

- Moderate transverse dimensions permitting aerodynamically favourable under-wing or tail-mounted installation
- Low noise emission level, meaning that even with under-wing installation no unusual cabin soundproofing measures are required
- Protection against secondary damage in event of fan blade loss due to blade containment in fan shroud
- Economic operation in air speed range greater than Mach 0.8

with the advantages of the open contra-rotating propfan, namely

- Extremely favourable installed specific fuel consumption by low specific thrust
- Favourable thrust characteristics, i.e. high take-off thrust for the given thrust at cruise, meaning that the engine can be throttled on take-off, reducing maintenance costs, and
- Simple thrust reversal by variable pitch fan blades

leads to an engine concept which, in addition to superior operating characteristics, promises a clear reduction in the overall propulsion weight, i.e. a significant reduction in the direct operating costs.

The development of the shrouded contra-rotating propfan and the slim-line shroud admittedly will be demanding in every respect especially considering that the aerodynamic needs of the shrouded contra-rotating propfan go well beyond current experience with the open contra-rotating propfan, and the airflow around the slim-line propfan shroud under all operating conditions represents a new aerodynamic territory.

7. Acknowledgements

The authors wish to express their appreciation to the Ministry of Research and Technology at the Federal Republic of Germany and MTU Motoren- und Turbinen-Union München GmbH for permission to publish this study. They would also like to thank Mr. G. Schill, Mr. R. Gumucio and Mr. M. Dupslaff for making available the aerodynamic and thermodynamic data, and Mr. K. Heinig for preparing the acoustic data.

References

/1/ H.G.Schulz, Messerschmitt-Bölkow-Blohm GmbH
Entwurfsüberlegungen zu Transportflugzeugen mit modernen Propellertriebwerken
DGLR-Nr. 84-083
Jahrestagung der DGLR, Hamburg 1984

/2/ I.M.Goldsmith, Douglas Aircraft Co., Long Beach, Ca.; and J.V.Bowles, NASA Ames Research Center, Moffett Field, Ca.
Potential Benefits for Propfan Technology on Derivatives of Future Short-to-Medium-Range Transport Aircraft
AIAA-80-1090
16th AIAA/SAE/ASME Joint Propulsion Conference, Hartford, Co., 1980

/3/ G.Rosen, Hamilton Standard Div., United Aircraft Corp.
Prop-Fan - A High Thrust, Low Noise Propulsor
SAE 710470
National Air Tranportation Meeting Atlanta, Ga., 1971

/4/ R.M.Denning, Rolls-Royce (1971) Ltd., Bristol Engine Division
Variable Pitch Ducted Fans for STOL Transport Aircraft
ASME 72-GT-61
ASME-Conference San Francisco, Ca., 1972