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Performance improvement of propulsion systems by optimization of the mixing efficiency and pressure loss of forced mixers

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Abstract

Propulsion systems featuring a mixed exhaust system, where the core and bypass flow are mixed before being expanded through a common final nozzle, offer the possibility to reduce both chemical and acoustic emissions. Especially forced mixers are used to increase the cruise performance and to reduce jet mixing noise of turbofan engines with low to medium bypass ratio. Here, the performance improvement options are focused on with respect to thrust and specific fuel consumption (SFC).

Although it is common practice to consider both pressure loss and mixing efficiency as contradicting parameters (a high mixing efficiency (positive effect) is often considered to result automatically in a high pressure loss (negative effect)), it can be shown that a reasonable compromise can often be reached by special scarfing techniques and a higher lobe number. Thus it is possible to focus on the pressure loss for optimization of the (take-off) thrust or the emphasis is laid on (cruise) SFC. Of course, a mixture can also be meaningful to a certain degree.

1. Introduction

Rolls Royce Deutschland has developed new, efficient and environmentally friendly propulsion systems for long distance corporate and for regional aircraft. However, continuous effort is necessary to further develop the engines in order to meet customer requests.

Both the BR710 and BR715 turbofan engines are equipped with forced mixers and feature a mixed flow exhaust system. Inside the jet-pipe of a mixed flow exhaust system, the cold flow from the low pressure system and the hot flow from the high pressure system of the engine are coming together and are allowed to interact before leaving the nozzle. In contrast, for a separate jets configuration, both flow are expanded separately.

For mixed flow exhaust systems, the improvement of the mixing process of the cool fan flow and the hot exhaust gas from the core engine before the mixture is expanded through a common nozzle is offering advantages, see ref. 1, both with respect to jet noise generation and performance.

Conventional mixers decrease the jet noise by approx. 1.5 deziBel (dB) EPNL. The possibility of further improving mixers with respect to jet noise have been discussed before, see ref. 2 and 3. It has been demonstrated, that additional noise reductions of more than 1dB can be achieved considering jet noise, which is usually the dominant noise source at take-off and sideline certification conditions. This jet noise reduction effect is obviously only possible for mixed exhaust systems, whereas for separate jets serrated nozzles are proposed, see ref. 4, for example.

In this paper the aerodynamic performance effects will be concentrated on. Former studies have been reported on performance aspects of mixers, see e.g. ref. 6, where systematic investigations of forced mixers were performed for a short exhaust system, compared to the system under consideration here. Ref. 7 shows systematic changes of lobe numbers, variations in mixing chamber length etc. for the Lycoming LF-500 series engine. This paper deals with the optimization of mixers for the BR700 and Tay series by further increasing the lobe number and a special scarfing.

2. Remarks on aerodynamics and performance modeling

The introduction of a mixer in the mixed flow exhaust system is introducing several aerothermodynamic effects (fig.1):

1. Radial deflection of flow: In the gullies of the mixer, a part of the fan flow is deflected radially inwards, and in the lobes a part of the core flow is deflected outwards.
2. Generation of vortices: Once the flow has passed the trailing edge of the mixer, vortices are developing. Their strength is resulting from the difference in radial momentum of the core flow in the lobes and the fan flow in the gullies. The vorticity should be high enough for good mixing, but decayed to a high degree at the end of the nozzle in order to minimize loss of momentum in the vortices.
3. Mixing: The vortices enhance the mixing process considerably comparing to confluent flow. Thus, all gradients (momentum, energy, species mass fractions) are decreased. The mixing process with respect to temperature is giving a thrust increase from a thermodynamic point of view. It can be explained in an enthalpy – entropy (or Mollier) diagram. Since the isobars are diverging for higher temperatures, a thrust increase is obtained by the mixing process. With respect to momentum, the mixing leads to a more uniform nozzle velocity profile, which improves propulsive efficiency.
4. Pressure losses: The deflection of the flow (see 1.) and the largely increased surface area of the forced mixer and the corresponding skin friction loss contribute to the mixer loss.

From a performance point of view a mixer with low pressure losses and a high mixing efficiency is desirable. The mixing process itself leads to an increase in entropy, which also can be expressed as a pressure loss (ref. 7).

Here, the performance implications are modeled as follows. The pressure loss and the mixing efficiency are input parameters for the performance model. They are determined from a scaled model experiment which was done in the cases considered here at FluiDyne, Minneapolis in Channel 11. The differences in thrust between a forced mixer configuration and an annular mixer configuration, measured with both the core and the bypass flow at the same temperature, is used to determine the pressure loss of the mixer. Since both temperatures are equal, no thrust increase from mixing can be observed. In the next step the experiment is performed with a realistic temperature ratio and thus a thrust gain is observed. By comparing this gain to the theoretically possible ideal thrust gain, the mixing efficiency is obtained.

The general expectation leads to the assumption, that higher mixing efficiency also conditions higher pressure losses. Of course, this is correct as a trend, but care can be taken to minimize the pressure loss increase. To do this, the exchange parameters with respect to SFC have to be evaluated. For different flight conditions, the impact of both performance parameters is different. At typical take-off conditions (low flight velocity) the mixing efficiency plays only a small role for performance, but the pressure losses are more important for SFC and thrust, respectively. To the contrary, at high altitude cruise conditions (high flight velocity) the mixer pressure losses have a lower importance, and the mixing efficiency is the major parameter for SFC. This is explained by the fact, that at these conditions not only the thermodynamic contribution but also the improvement of the propulsive efficiency is of importance.

Thus if take-off conditions are of importance, i.e. if this should be the aerodynamic design point, the pressure loss should be minimized at a constant or even lower mixing efficiency. From an aerodynamic design point of view, this is possible by a small increase in lobe number, and the inverse scarfing technique. Here, every second lobe is cut back to a high degree. Thus, deflection and skin friction losses are minimized. The mixing efficiency can be kept at approx. the same level as before.

On the other hand, for cruise conditions, which are normally the aerodynamic design points, the mixing efficiency has to be maximized at constant or even higher pressure losses. It is important to study the breakeven between increased mixing efficiency and increased pressure loss for every different engine. In the case described in ref. 6 an approx. 35% mixing efficiency gain would be off-set by a total pressure loss ($\Delta p/p_t$) increase of 1%. For the BR710 the corresponding values are approx. 20% and 1%, respectively. Thus, if a mixing efficiency increase can be achieved with a lower pressure loss increase than in the above mentioned ratio, a net SFC improvement results. This is achieved by increasing the number of lobes to a higher degree than described before and the complex scarfing technique. Here, alternating gullies and lobes are cut back, respectively, which can be done in either a symmetrical or periodic manner.

3. Experimental simulation

In the past mixer performance was measured at ARA in Bedford and FluiDyne in Minneapolis/St. Paul (USA). Acoustic behavior was measured at the DERA/NTF in Pyestock and at FluiDyne, were recently an acoustic treatment and microphones were installed at channel 11. The best quality data came from FluiDyne for performance and the NTF for acoustic. The mixer study presented here deals with small changes in mixer loss and efficiency and thus FluiDyne performance data will be presented here.

Fig.2 shows a schematic picture of the facility. The pressurized air form the tanks is put on conditions (total pressure and total temperature) before reaching the model and model adapter which are decoupled from the rest of the facility to measure axial and side force. The core flow is heated by leading the core flow through a heat pebble bed exchanger. Two venturies are used to determine the fan and core mass-flows. The model adapter includes a small chamber and screens to eliminate incoming disturbances. Flight velocity is not simulated.

The model is a 1/5 scale model of the bullet, mixer, LPT fairing and partly modeled bypass-duct and nozzle. The model is highly instrumented. Total pressure rakes, total temperature rakes and wall statics are used to determine fan and core total pressure and total temperature.

As described before the mixing efficiency and mixer loss is calculated from thrust coefficient measurements. Discharge coefficients are measured to derive the final nozzle effective flow area.
The coefficients are referenced to the so called mixing plane. Since the mixer exit geometry and flow field is complex, especially in case of scarfed mixers, the mixing plane is defined and used as a common reference for the experiment and the performance model.

Thrust coefficient C_v is defined as the ratio of measured thrust to ideal thrust. The ideal thrust is the sum of both, fan and core flows, expanded separately and ideally to ambient pressure. The discharge coefficient C_d is defined as the ratio of measured effective fan and core areas, referenced to nozzle throat area, to geometric nozzle throat area. Table 1 shows the mixing efficiencies and mixer loss for the BR710 16 lobe mixer and the new 18 and 20 lobe mixers as measured at FluiDyne.

BR 710	Mixing effic. η [%]	Mixer loss $\Delta p/d$ [%]
16 lobe	Datum	Datum
18 lobe	-3%	-60%
20 lobe	+8%	-14%

Table 1

It is clear that the 18 lobe mixer is the better choice for improved (take-off) thrust and the 20 lobe is the better choice for cruise SFC.

Fig. 3 to Fig. 5 show the thrust coefficients for all three mixers at conditions similar to cruise (choked nozzle flow). The annular mixer is the reference for the mixer loss. The closer the thrust coefficient of the forced mixer for cold fan and core flow is to the one of the annular mixer the lower the loss is. As can be seen the 18 lobe mixer has a significantly higher thrust and thus lower loss than the datum 16 lobe mixer whereas the 20 lobe mixer is close to the 16 lobe mixer.

The mixing efficiency is in simple terms the difference in hot and cold thrust coefficient at identical nozzle pressure ratios. The difference between hot and cold is biggest in case of the 20 lobe mixer.

While the differences for loss and mixing efficiency are easy to see, the increase of hot thrust, which is the combination of both, is close to the experimental repeatability of 0.1% C_v for both mixers. The new mixers are both better than the 16 lobe.

Table 2 shows the mixing efficiency and mixer loss for the Tay 611 12 lobe mixer and the new 16 lobe mixer as measured at FluiDyne. Only one mixer was designed for SFC improvement.

Tay 611	Mixing effic. η [%]	Mixer loss $\Delta p/d$ [%]
12 lobe	Datum	Datum
16 lobe	+7 %	+18%

Table 2

Fig. 6 shows the thrust coefficients for the new Tay 16 lobe mixer. The mixing efficiency increased by 7% and the loss increased by 18% resulting in a 0.1% increase in hot thrust coefficient. Fig. 7 shows a flow visualization of the new complex scarfed 16 lobe Tay mixer. Flow visualization is performed also with core engine mounting devices to check if the flow is attached in the gullies and lobes.

4. Numerical simulations

The flow over the different mixers and the mixing in the jet-pipe has been analyzed using a commercially available Navier-Stokes method. The code Fluent (ref. 9 and 10) solves the Navier-Stokes equations using unstructured meshes. The realizable k-ε model was chosen to simulate the turbulent flow behavior. A steady state condition was assumed.

Many more configurations were checked using this method, but here the restriction is made to the mixers which were tested at FluiDyne. The typical mesh size is around half a million cells. The total temperature and the x-vorticity contours on several cross sections are depicted in fig.8. The last plane is the mixed nozzle exit. The boundary conditions relate to a high altitude cruise condition. From the total temperature plots, a better mixing can be clearly observed compared to the original.

The calculations on triangular meshes (boundary layers not physically resolved) were used to calculate mixing efficiencies. Thrust coefficients could not be simulated accurately on this kind of meshes. Thus instead of thrust coefficient the averaged total temperature at the nozzle exit and the ideal mixed total temperature was used to calculate mixing efficiency. This technique is an alternative if total temperature traverses instead of thrust measurement is available, but the technique is known to be inaccurate. The tendencies were predicted right but the absolute values do not match the measurements.

In the meanwhile hybrid meshes which resolve the boundary layers are also used to calculate mixer metal temperatures and to identify regions with wall shear stress close to zero (indication for possible separation). A typical hybrid mesh is shown in fig. 9. The flow visualization of an inverse scarfed mixer investigated during a research program indicated a horseshoe vortex in front of the lobe (see fig. 10). This could be reproduced by CFD qualitatively as shown in fig.11.

Studies were performed, that showed, that the mixing itself is not very sensitive to turbulence modeling indicating that vorticity and deflection (convection) are the dominant factors. The k-ε realizable model implemented in Fluent showed the best results for confluent flows without forced mixer as shown in ref. 10. For mixer loss calculations more emphasis has to be laid on turbulence modeling in the future.

5. Conclusions

Compared to conventional aerodynamic mixer designs, performance improvements are possible by going for higher number of lobes and new scarfing techniques. Some theoretical comments are given on the background and the implications for different flight regimes. The expected performance improvements are confirmed by CFD results and thrust measurements on model scale, which have been discussed. A positive side effect is the reduction of jet-noise, which is normally expected and observed with better mixing efficiency. Thus the important aspects of environmental concerns, exhaust emissions and noise, are addressed.

6. References

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7. Figures

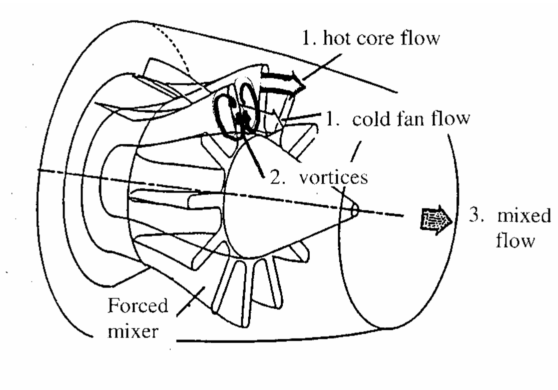

Fig. 1 Nozzle with forced mixer

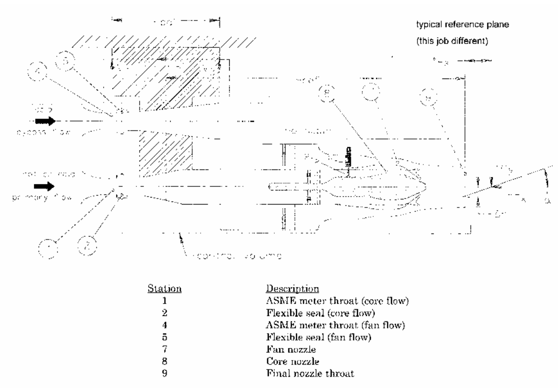

Fig. 2 Schematic view of the FluiDyne channel 11

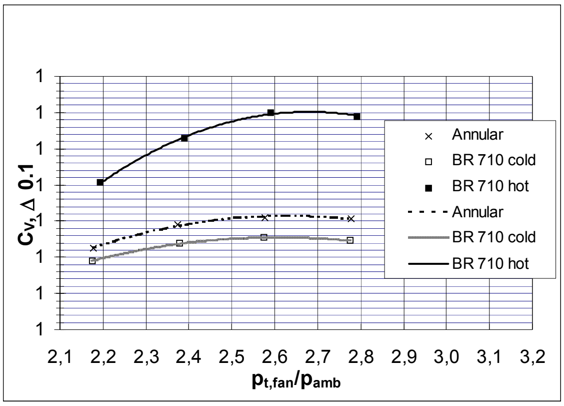

Fig. 3 BR710 16 lobe mixer thrust coefficient

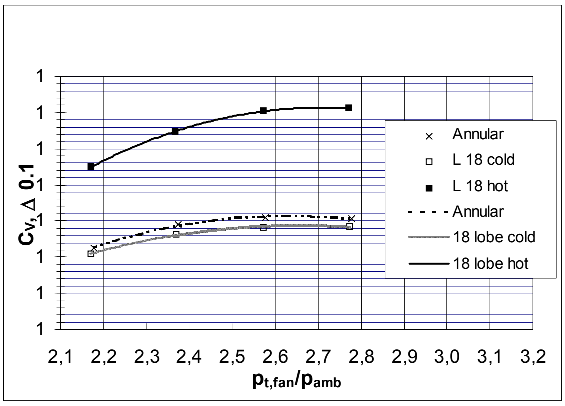

Fig. 4 BR710 18 lobe mixer thrust coefficient

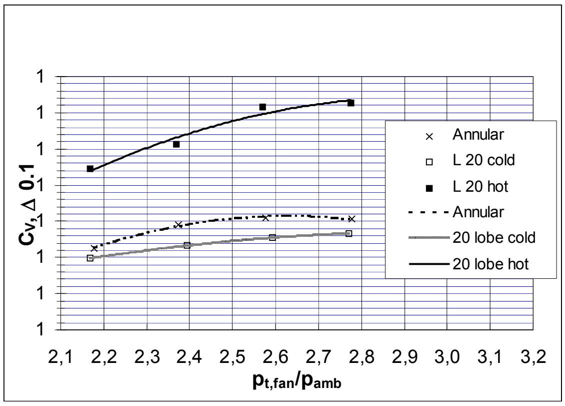

Fig. 5 BR710 20 lobe mixer thrust coefficient

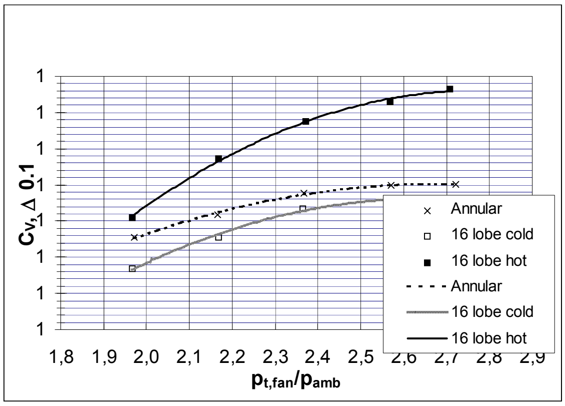

Fig. 6 Tay 611 new 16 lobe mixer thrust coefficient

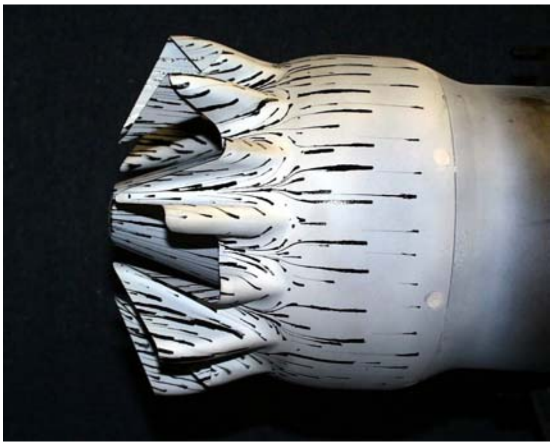

Fig. 7 Tay 611 new 16 lobe mixer flow visualization

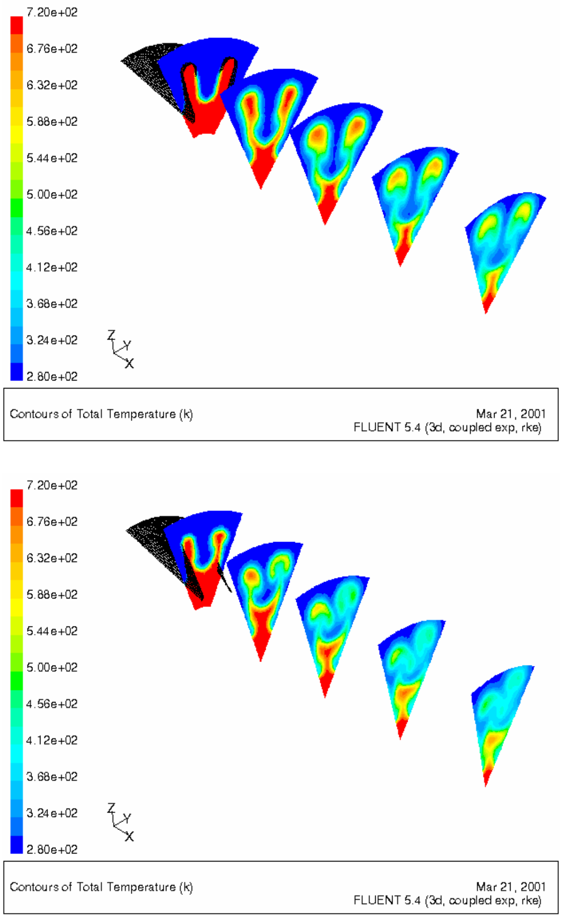

Fig. 8 Tay 611 12 lobe and new 16 lobe total temperature distribution.

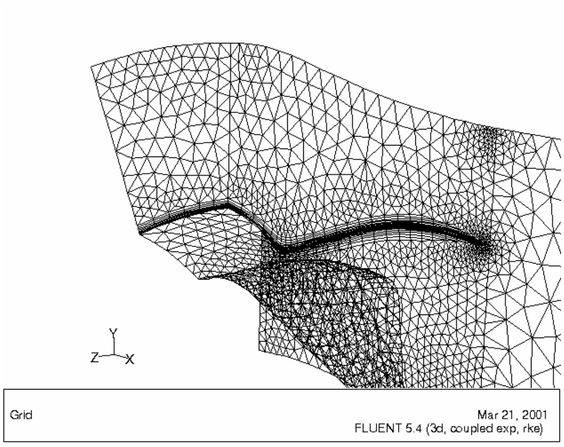

Fig. 9 Hybrid mesh for BR715 inverse scarfed research mixer

Fig. 10 Flow Visualization on inverse scarfed mixer

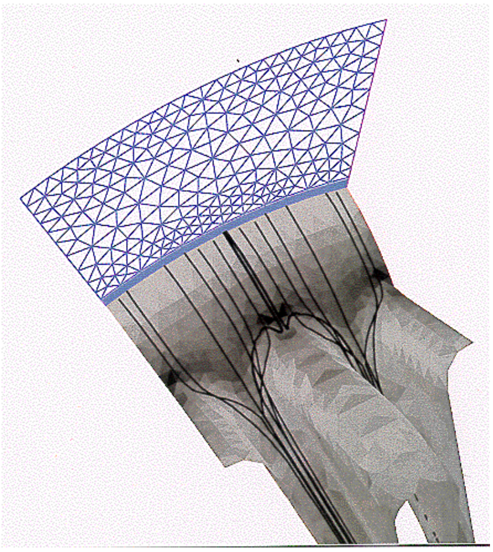

Fig. 11 CFD simulation on hybrid mesh