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AEROACOUSTIC CHARACTERISTICS OF EFFICIENT AUTOMOTIVE ENGINE COOLING FAN SYSTEMS

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ABSTRACT

Recent studies on automotive engine cooling fan systems carried out in partnership between LEMFI and Valeo have led to the definition of a range of efficient stator designs. It was shown that an adequate rotor-stator coupling could yield significant efficiency gains over the whole range of Valeo fans with diameters ranging from 280 mm to 460 mm. Efficiency gains ranging from 12 percentage points for the 350 mm fan diameter to 2 points for the 460 mm were estimated by using a simplified radial equilibrium design (SRE). These predictions have been verified experimentally by recent designs for various fan system diameters. The present study then describes a newly developed aeroacoustic test facility dedicated to automotive fan systems. The influence of the rotor-stator coupling is then shown by comparing the rotor alone and rotor-stator configurations, not only on the overall performances and velocity fields at the system outlet measured by a 5-hole probe, but also on the noise generated by the fan systems for various flow conditions. At the nominal flow rate, the efficient stators are shown to bring little or no extra noise if the number of stators and the rotor-distance are carefully chosen. At other flow rates, additional noise might be expected.

INTRODUCTION

In today's automotive vehicles, the engine compartment is becoming more and more crowded and additional components are integrated like, air conditioning loop, power steering system, automatic gear box, particle filters, etc... These new components should not have any significant impact on the overall weight and car energy budget. Consequently, an improvement of all performances including those of the cooling systems, are required while maintaining strong constraints such as tighter axial packaging and reduced sound emission with smaller tonal content. The necessary optimization of the underhood airflow management must closely associate computer simulations and dedicated experiments. These tests constitute a complementary phase, which enables us to adjust and validate computational simulations. This approach allows a reduction in the number of prototypes required designing a new system and consequently the product development cost. For Valeo Motors and Actuators, CFD (Computational Fluids Dynamic) now plays a key role as a design tool in the optimization of its fans as shown in [1-3]. This allows reaching high maximum fan static efficiency in the range of 55% systematically with reduced self noise. The next challenge has been to address installation effects found in the engine block compartment on the fan aeroacoustic performances. A first step towards this goal has been to consider the rotor-stator interaction of the fan with its support made of struts and stators. Dimensional analysis and simplified radial equilibrium (SRE) parametric study, undertaken on the range of fans used in automotive cooling systems, presented respectively in [4] and [5], showed significant potential efficiency gains with the use of well designed stators. The present paper shows an extensive experimental and numerical validation of these initial calculations. It then gives some extensive results on the noise associated with such high efficiency fan systems.

NOMENCLATURE

C_a	Axial chord length
C_u	Tangential velocity
I	Loaded motor intensity
I_0	Unloaded motor intensity
q_v	Fan system volumetric flow rate
r	Motor internal resistance
Δp	Fan system pressure rise
U	Loaded motor voltage
U_0	Unloaded motor voltage
η_g	Fan system static efficiency
η_s	Fan static efficiency
ρ	Air density

STATOR DESIGN BACKGROUND

In [5], the parametric SRE study on a large range of fan diameters and operating points used for automotive engine cooling applications showed that the maximum efficiency gain that a stator can achieve is about 12 to 15%. The latter is only obtained with an optimized set of chord length, stagger angle and aerodynamic camber. Slighter gains of about 5% are achieved for the larger diameter fans. The optimal aerodynamic camber (based on NACA65 profiles) is about 2.5 and the optimal stagger angle is between 25° and 30°. An angular reaction rate between 50 and 60% corresponding to a 60 mm axial chord length, C_a, (the *dominant* parameter) is found to be optimal. Moreover any aerodynamic benefit could only be expected beyond 20 mm. To further optimize the stationary blade, a twisted blade from hub to tip (variable stagger angle) with a variable chord length might be considered to yield an additional efficiency gain of 2 to 3 points.

To verify these conclusions, three stator vanes with a realistic axial chord length of 40 mm adapted to a Valeo 380 mm fan were first designed in [6]. An efficient 320 mm fan system, shown in figure 1, was then designed in [7], which provided a detailed comparison with CFD predictions. In both cases, the optimum number of stator blades is found to accommodate the fan system operating point and tonal specification. More recently several such efficient systems have been developed for specific automotive specifications. They provide further verification of the above theoretical predictions. The rotor stator distance is kept about the same percentage of the rotor axial depth for all assemblies.

Figure 1: New efficient stator design (320 mm).

EXPERIMENTAL SET-UP

Most experiments in the present study have been carried out on the Valeo-LEMFI test rig (figure 2). This test rig has been designed according to the ISO DP 5801 international standard. It allows a complete characterization of stand-alone fans and fan systems. Its main features and instrumentation are described in details in [8].

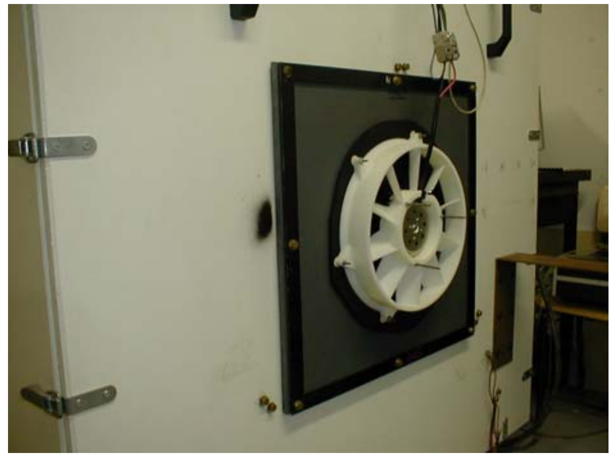

Figure 2: Valeo-LEMFI test facility.

The rotational speed is set by the frequency variator. For each diaphragm of diameter Φ, the voltage supply U, the electrical intensity I and the static pressure rise in the box Δp are measured. The following overall values are then calculated:

- The flow rate given by the relation:

$$q_v = 0{,}6\Phi\sqrt{\frac{2\Delta p}{\rho}}$$

- The overall fan system efficiency η_g given by:

$$\eta_g = \frac{\Delta p.q_v}{U.I}$$

- The fan static efficiency η_s expressed by;

$$\eta_s = \frac{\Delta p.q_v}{U.I - U_0.I_0 - r.I^2}$$

where U_0 and I_0 are respectively the voltage and the electrical intensity measured separately on the unloaded motor without the fan. r is the internal resistance of the motor.

Additional information on the three-dimensional nature of the flow through the fan is provided by probes such as 5 hole probes or hot wires that can be traversed in the radial direction in the wake of the fan system at the exhaust of the plenum.

For acoustics measurements, the front panel where the fan system is mounted, shown in figure 2, is now reversed, such that the fan is pushing air within the plenum. This allows sound measurements on axis, 1 m away from the hub face of the fan system, without being in the fan wake. Similarly sound power levels can be estimated by performing pressure measurements on a quarter of a sphere according to the ISO-5136. Sound pressure levels are recorded with a GRAS ½' microphone type 40AE at various flow rates. The corresponding pressure rise through the fans in this pusher configuration are slightly lower than in the puller configuration for a given diaphragm diameter (at most -10% at high flow rates). Finally, the present measurements are made in a room with hard walls, closer to a reverberant room. Each measurement was compared to the background noise measured with the fan system off and kept

when there was at least a 10 dB difference over the whole useful frequency range (0-10000 Hz).
Additional measurements have been performed in the Valeo semi-anechoic chamber (a 4 m x 3.2 m x 2.5 m useful volume with a hard floor) shown in figure 3, on engine cooling module configurations which set the operating condition to the nominal design one. The sound pressure levels are measured with a B&K ½' microphone type 4190 and the spectra are recorded with the B&K Pulse 3560 software, in a position with respect to the fan system according to the car manufacturer specification. All measurements have an uncertainty of ± 1dB. The spectra shown here have a fixed constant bandwidth of 2 Hz and obtained from an FFT over a frequency range (0-6.4 kHz).

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Figure 3: Valeo semi-anechoic chamber

AERODYNAMIC MEASUREMENTS

The three initial 380 mm efficient fan systems all achieved a maximum 5% efficiency gain at the nominal flow rate as shown in figure 4. The more twisted blade did not bring any significant gain, which most likely hint at the limitations of the SRE approach. More recent stator developments also stress that CFD is also needed for a proper adjustment of the stator mean stagger angle. Figure 5 shows the static efficiency as a function of flow rate for the 320 mm fan system shown in figure 1. The rotor tested on two different facilities is compared to the rotor-stator topology in terms of flow rate at the nominal speed. At the nominal flow rate, a 10% efficiency gain is achieved slightly beyond the theoretical prediction shown in figure 4. Several tests were made to assess the uncertainty and the repeatability of these efficiency measurements: for both configurations the same 3% variation was assessed yielding the same overall gain. Repeatability between the different test rigs is also verified. The efficiency gain or the associated pressure gain then tends to zero as the transparency point is approached ($\Delta p=0$). This is verified for all efficient fan system designs. The consequent recent fan stator designs for 380, 280 and 420 mm ultra slim fans yield a 3%, 8% and 2% efficiency gain respectively, with axial chord lengths being respectively 30, 40 and 20 mm. They all confirm the above SRE predictions as shown in figure 4.

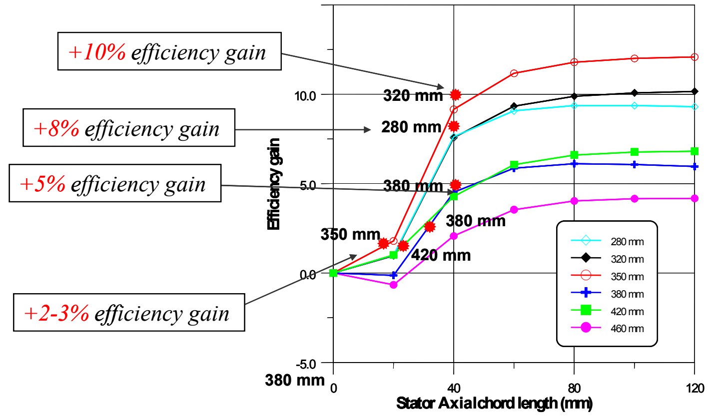

Figure 4: Effect of C_a (axial chord length) on efficiency.

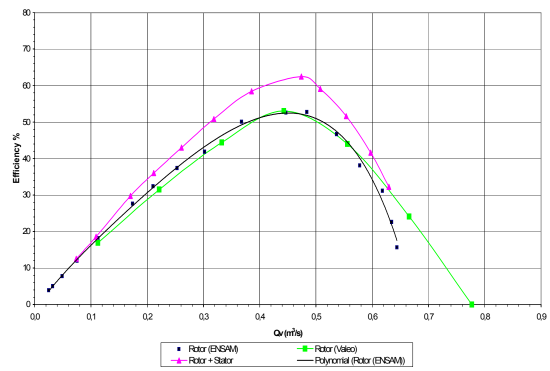

Figure 5: Efficiency vs flow rate for the 320 mm fan system

The local measurements in figure 6 clearly shows that a high reduction of the tangential velocity component is achieved by the long chord stators, which explains the above reduction of overall velocity magnitude and a high deflection and a consequent straightening of the flow. The transformation of swirl kinetic energy into static pressure is thus verified.

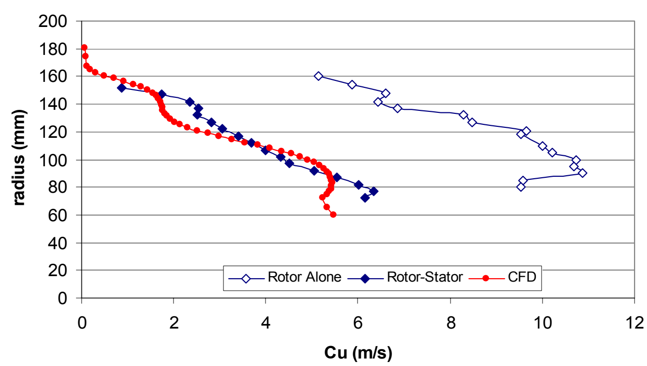

Figure 6: Tangential velocity: comparison of 5 hole probe and CFD results on the 320 mm fan system

ACOUSTIC MEASUREMENTS

The global sound pressure levels measured in the Valeo-LEMFI test rig on the first two efficient fan systems are reported in figure 7. This plot compares the rotor alone configuration with the rotor-stator configuration as a function of flow rate. The arrows correspond to the nominal flow rates of such fan systems. For both systems, similar sound pressure levels are obtained at the nominal flow conditions. At smaller flow rates, the 320 mm fan system makes again similar noise as the fan alone whereas the 380 mm rotor-stator configuration is significantly louder. The trend is inverted at high flow rates. For the larger 320 mm stators, flow separation may occur then and yield a larger global noise. Yet these results are only indicative as they represent point sound pressure level in a noisy environment and the conclusions might be biased by the many reflections in the room.

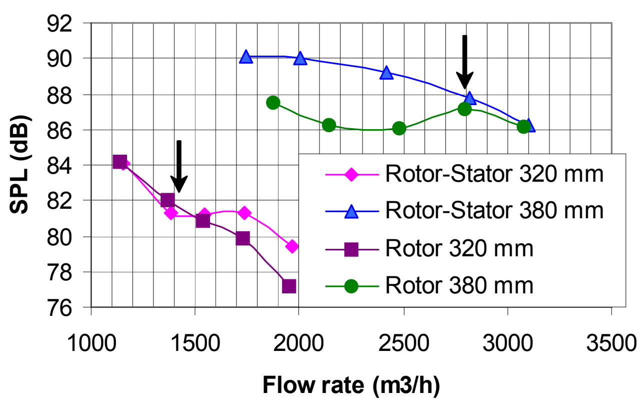

Figure 7: Sound Pressure Level vs flow rate.

More definite and conclusive results can be drawn at the design conditions by the measurements on the module in the Valeo semi-anechoic chamber. Figures 8 and 9 are comparisons of the noise generated by the same 380 mm motor and fan assembly associated with different supports at two different rotational speeds. All the sound pressure levels are measured in a direction normal to the fan system center. The same rotor-stator distance is kept for all assemblies. The “18 stators” label corresponds to a current classical support with *short* stators (axial chord length less than 20 mm) that do not achieve any significant flow deflection or straightening: the simulation of [10] confirmed the 4° found by PIV in [9]. The “12 and 13 stators” labels refer to the same long efficient stator vanes (axial chord length of 30 mm in figure 4). For all assemblies the overall sound pressure level is within 1-1.5 dB with very similar broad band noise, which confirms the previous finding. Yet the tonal content is very different. For instance, at high speed, the 12 stators reduce the H14 harmonics significantly, suppress H21 and increase the fundamental blade passing frequency H7 yielding the most favorable sound quality at this critical condition. From this case it can then be concluded that the long stators do not change the overall fan system noise level and improves its tonal content. It should be emphasized that the two speeds yield two different operating conditions and loadings of the fan system.

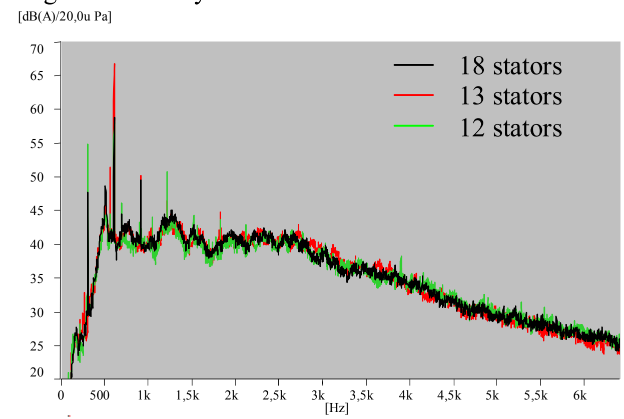

Figure 8: High speed sound pressure spectra.

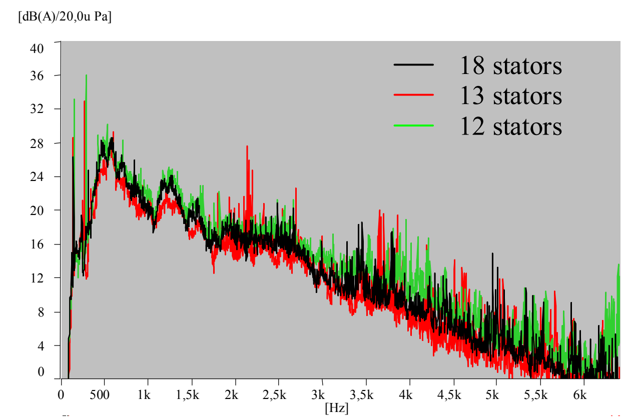

Figure 9: Low speed sound pressure spectra.

Similar results were found on a 420 mm single fan system. The original four thick struts support was compared to a 10 efficient stator vanes. No significant noise difference was observed. Finally a recent dual fan system that compared again a classical support with 15 thin stator vanes with 10 long efficient stator vanes similar to the one shown in figure 2, yielded the same overall sound pressure and a similar broadband spectrum decay with frequencies. In this case the microphone is placed normal to the center of the dual fan system. Only the tone distribution was affected with weaker tones at high frequencies for the efficient stators. These conclusions were not only verified at several rotational speeds but also in different test configurations: two different shrouds, with additional heat exchangers such as the charge air cooler or the oil cooler or without them (the transparency point at $\Delta p=0$). More operating conditions were therefore studied covering different incidences or loads on the blades. In this particular case, the noise increase at high flow rates shown in figure 7 is not observed.

CONCLUDING REMARKS

From the preliminary parametric design of efficient stators by SRE, several new efficient supports with stators having a constant maximum axial packaging of 40 mm have been built. These stators vanes have been tested with the newly produced Valeo ultra-compact rotors. The overall measured performances confirm the gain of static efficiency foreseen by the previous calculations. It should be noted that the pressure gain is centered on the peak efficiency of the fan and then it goes to zero as the transparency condition is approached. The 5-hole probe investigation then showed that the tangential velocities are strongly reduced with these stators compared to the original short ones, which explains the above additional overall pressure and static efficiency gain. The 320 mm set of experimental data has then served as a validation of the stator portion of the simulation based design for automotive engine cooling fan systems used by Valeo. A good comparison is found for all velocities components using the more realistic stage interface. The new validated CFD capability has then helped Valeo developing several high efficiency fan systems.

Finally several noise results have been obtained with these newly developed stage assemblies. At the design condition, for similar rotor-stator distance, they yield similar global sound pressure level as the rotor alone or a classical assembly with struts or short stators. However, the tonal content is significantly impacted emphasizing the role of this noise source. By properly selecting the number of stator blade, the tonal content and sound quality of the fan system can be improved. Some impact might be expected away from the design conditions when the airflow patterns are significantly altered with the long stator vanes. This should be expected when some significant change of flow topology occurs yielding new important noise sources.

ACKNOWLEDGMENTS

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