ANIBAL: A NEW AERO-ACOUSTIC OPTIMIZED PROPELLER FOR LIGHT AIRCRAFT APPLICATIONS

T. Lefebvre, S. Canard, C. Le Tallec, P. Beaumier, F. David
ONERA, the French Aerospace Lab, France

Keywords: *aerodynamic, acoustic, optimisation, propeller, flight test*

Abstract

Among the French Civil Aviation Directorate (DPAC) funded projects, the ANIBAL project (Abaissement du NIveau de Bruit des Avions Légers) had the objective to design, manufacture and test a new propeller for light aircraft applications. The main constraint of the project was that this propeller shall equip an existing airplane (Robin DR 400-180) with a significant noise level reduction (> 8 dB(A)) together with minor penalties in aerodynamic performance.

This paper presents the work performed during this project. First an overview of its organisation and of the main partners' skills is presented. Then, the coupled aerodynamic and aero-acoustic numerical optimization performed to design the fixed pitch propeller is described. Finally, the in–flight tests are presented and analyzed in order to assess the achievement of the project's objectives.

1 Overview of the ANIBAL project

Since the late sixties, whereas many improvements were carried out on commercial transport aircraft in term of noise reduction, the power unit of light airplanes did not evolve much. Simultaneously, during the last decade, aerodrome neighbourhood communities have been longing to obtain significant aircraft noise level reductions. Like in many other European countries, the priority has been set to the development of technical solutions making it possible to reduce, to a significant degree, the noise generated by light aircraft.

The ANIBAL project (*Abaissement du NIveau de Bruit des Avions Légers*), funded by the French DPAC, was launched in 2003 with the objective to design, manufacture and test a new propeller for light aircraft applications with the objective of achieving a significant noise reduction of about 8 dB with a performance loss lower than 3% without changing the engine system.

Concerning the work breakdown structure, the first Work Package (WP) dealt with the aero-acoustic assessment starting with the selection of the conditions that were considered critical for the optimization. It also fixed the requirements for the propeller to be designed. This selection was thus carried out by taking into account the objectives of the project but also of some broader criteria (like noise reduction in "aerodrome circuit"). In parallel, the reference blade was selected and its aerodynamic and acoustic performance could then be evaluated, thereby freezing the objectives of the optimization. The impact of the geometrical constraints of the possible technology was then evaluated and led to the selection of a carbon fiber made propeller (DUC *hélices* technology). The optimization process was then conducted, in the respect of these geometrical constraints, resulting in the 5 blade ANIBAL propeller.

The second WP dealt with the manufacturing and ground testing of two ANIBAL prototypes (H1 and H2). Following the manufacturing of those prototypes, some static tests were successfully performed in order to assess the blade behaviour with respect to centrifugal force and flapping moment. In order to prepare the ground tests with the H1 prototype equipped with one instrumented blade and telemetry, the blade was calibrated and the propeller was dynamically balanced in ONERA facilities. The ground tests were performed in the DGAC/SEFA facilities, using a Robin DR400 aircraft engine, with both dynamic and aerodynamic characterization of the H1 propeller. An endurance test of 50 hours was performed and the H2 prototype was also evaluated.

The last WP dealt with the flight tests campaign, performed in October 2008. A Robin DR400 aircraft, with adequate instrumentation, experienced one week of flight tests with both the reference propeller and the ANIBAL propeller. Both aerodynamic and acoustic performances were measured and the results successfully confirmed the validity of the optimization.

ONERA led this project involving five of its scientific departments. Among the French DGAC, 2 units were also working on the project; one for ground testing and the other one for the flight tests and the acoustic measurements. The sub contractors were DUC *hélices*, manufacturer of LSA propellers, involved in many parts of the project, CGTM, responsible for the flight tests preparation and the French Gliding Association (FFVV), which has been involved in the specification phase of the project and provided the aircraft engine for the ground test, the airplane, the gliders and their pilots for the tests.

This paper essentially concerns the aeroacoustic optimization process of the propeller and the exploitation of the flight tests. Additional information about the other tasks can be found in [1].

2. Specifications

2.1 Requirements specifications

The activity started with the selection of the reference propeller and its characterisation. Using the partners' experience, the SENSENICH, 76EM8S50 – 58 was selected as the reference. It is a 2 blade propeller of 1.93 m in diameter, used for glider towing with a good climbing, and acceptable cruise performance.

The requirements were defined for various specific points of the flight domain. These points were used to define the propeller design and test cases for which the propeller should be optimized. These test cases include the certification point (in climb, full power) and level flight points from cruise power setting down to stall configuration. Some additional test cases were also defined to check for any possible loss of performance due to the acoustic optimization process.

2.2 Reference propeller performance

The next step was to assess the performance of the reference propeller with ONERA tools in order to generate a basis for further comparisons.

The retained aerodynamic method is based on the lifting–line theory. HOST, developed by EUROCOPTER, is an aeromechanics and flight dynamics code [2], widely used by the ONERA Aerodynamics Department, for helicopter and tilt rotor applications [3]. The aero-acoustic method is based on the Ffowcs Williams and Hawking's equation [4], [5] implemented in the frequency domain (PACHA) or in the time domain (KIM [6]) designed at ONERA. It predicts the loading and thickness noise radiation. The geometrical data (chord, twist, etc.) were obtained using 3D measurements of a SENSENICH propeller (Fig. 1), and the generation of 2D polars required the use of the solver MSES [7].

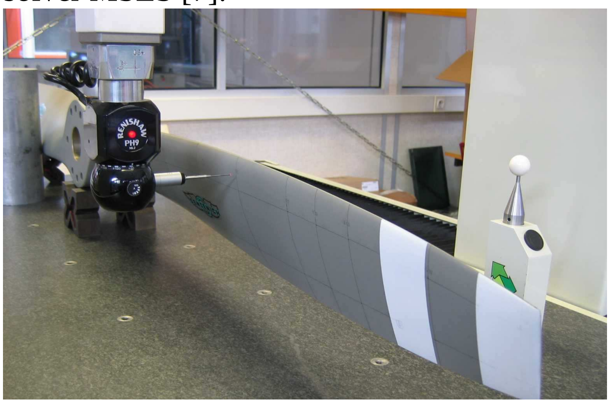

Fig. 1 Reference blade measurements

The results of isolated propeller simulations are presented in Fig. 2. The curve, characteristic of the propeller, represents the evolution of the cruise efficiency as a function of the advance ratio. One can notice that the maximum efficiency is close to 0.85, which is relatively high. Among the various points of optimization which are emphasized on the curve (blue circle), one can notice that the various points of level flight are all around the maximum efficiency. Both climb points are located at the beginning of the curve.

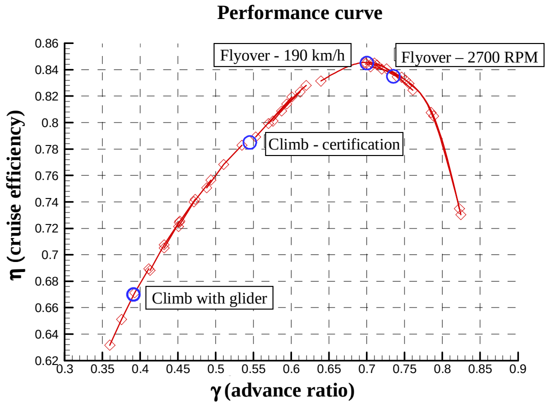

Fig. 2 Aerodynamic performance of reference propeller

The main acoustic results are presented in Fig. 3. Concerning level flight results, one can check that the noise level regularly increases with the rotation speed, which is explained by the increase of sectional velocities. The thickness noise dominates loading noise for all speeds and the difference increases with speed: 4 dB(A) at 2330 RPM, and 10 dB(A) at 2700 RPM. The thickness noise contribution can easily be reduced by reducing the tip Mach number, but the rotation speed is fixed so that the propeller diameter has to be reduced. The loading component is more difficult to reduce as the performance has to remain unchanged. Moreover, reducing the diameter increases the blade loading. Another comparison point is the one between the level flight at 2500 RPM and the certification configuration (nearly the same speed). As local Mach numbers are identical, the thickness noise is similar, but there is strong difference in loading noise, mainly due to the difference in power and required thrust.

All these performances (aerodynamic and acoustic) of isolated Sensenich propellers were considered as reference for the optimization.

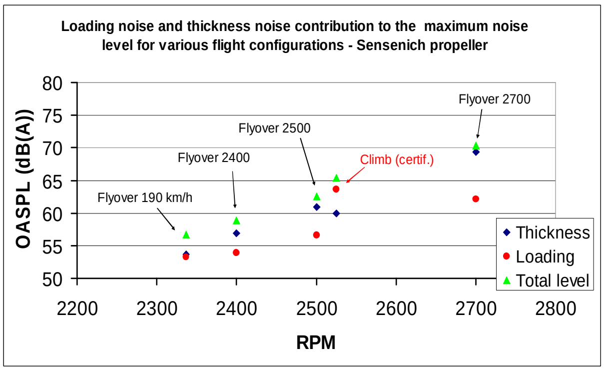

Fig. 3 Aero-Acoustic prediction of reference propeller

3.3 Selection of blade structural technology

In parallel, the impact of the geometrical constraints of the selected technologies was evaluated, especially in terms of blade thickness and led to the selection of a carbon fiber made propeller (DUC *hélices* technology). The retained structural design will be based upon DUC experience on LSA blades with reinforced characteristics to take into account the higher constraints encountered in light aircraft applications. The internal design of the blade is made of:

- composite skin (unidirectional webs) of epoxy resine and high density carbon fiber (HR type),
- body in rigid plastic foam PMI (Polymethacrylimide), used in helicopter blades manufacture).

Fig. 13 presents a section of a standard blade.

Fig. 4 Overview of blade internal structure (composite technology)

The main advantages of such a technology are its capabilities to achieve limited blade thickness with no degradation of the structural behaviour, therefore, enabling high degrees of freedom on chord and thickness laws.

The only constraint imposed by the manufacturing processes is to limit the minimum thickness at chord tip to 5 mm.

3. Optimization process

3.1 Parametric study

This parametric study was designed as an aerodynamic optimization under acoustic constraints. Actually, acoustic improvement directions can be obtained from the loading and thickness noise formulae which indicate that:

- reducing the helicoidal speed implies reducing the blade diameter as the engine rotational speed can not be modified much,
- modifying the blade shape by reducing the thickness and the loading near the blade tip implies moving the thrust more inboard.

One can note that all these modifications point toward an increase of the number of blades. Some additional gain could also be obtained using the sweep effect to dephase the noise sources, but studies have shown that only minor improvements could be obtained using this technique.

The parametric study was run, modifying the blade number (up to 5), the propeller diameter (down to 1.64 m), the airfoils location, the twist and the chord distributions.

For a 3 blade propeller, Fig. 4 presents the acoustic gain obtained with the candidates for the certification point compared to the reference propeller. As expected, all propellers present strong improvements for thickness noise but small ones for loading noise and do not fulfil the noise reduction objective.

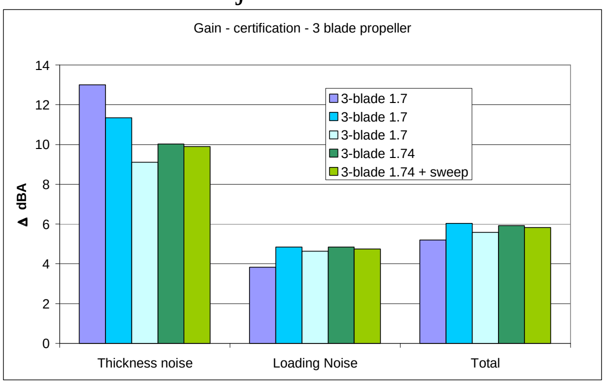

Fig. 5 Noise component on certification point – 3 blade propeller

Concerning the aerodynamic performance, Fig. 5 presents the expected improvement compared to the Sensenich propeller. It shows a small reduction in climb flight (within the objective) and some improvement in level flight.

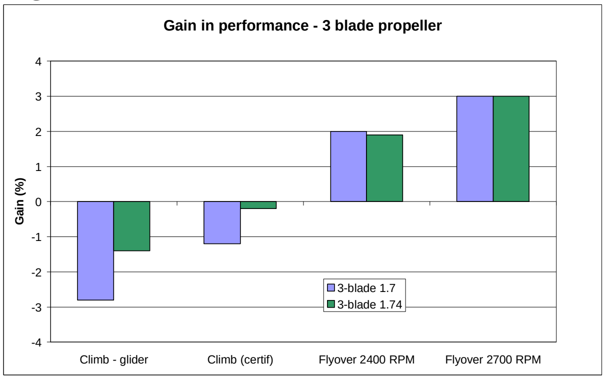

Fig. 6 Performance–3 blade propeller

The 4 blade solution was not deeply investigated as a 4 blade propeller for a 4 strokes engine is be problematic from the acoustic point of view: the engine acoustic tones can combine with the propeller acoustic tones and increasing the noise level up to 6 dB(A).

The main interest of a 5 blade propeller is the expected reduction of the loading noise component compared to the 3 blade designs. Figure 6 presents the acoustic results for the certification point. Compared to a 3 blade propeller, the small improvements found for the thickness noise component, can be explained by both diameter and thickness at blade tip had to remain constant. On the contrary, a strong gain on the loading noise component is obtained, mainly due to the increased number of blades. As a result, the expected reduction of the total noise level is higher than 9 dB(A). As far as aerodynamics performances are concerned, a 5 blade design enables to obtain similar performance as the reference propeller for initial climb, while keeping the gain for level flight, as shown in Fig. 8.

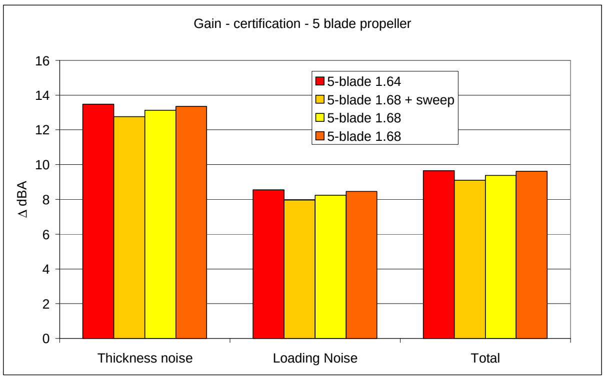

Fig. 7 Noise component on certification point – 5 blade propeller

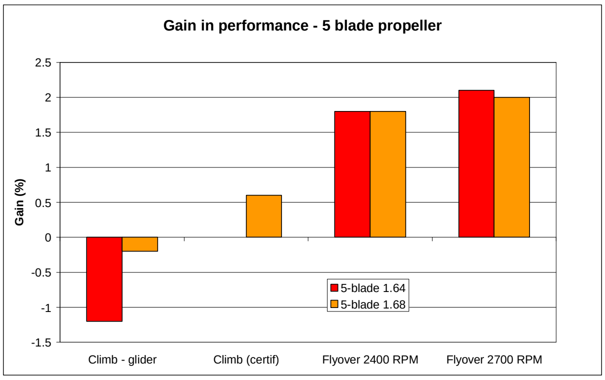

Fig. 8 Gain on performance – 5 blade propeller

3.2 ANIBAL design

Starting 5 blade propeller of 1.68 m in diameter, some modifications were made according to DUC *hélices* recommendations, in order to fit the manufacturing process: the thickness law was smoothed and the leading edge location was made straight. Moreover the manufacturing process implied a constant thickness of the trailing edge (0.5 mm). This constraint was used during the airfoil optimization. Figure 9 presents the final ANIBAL blade design.

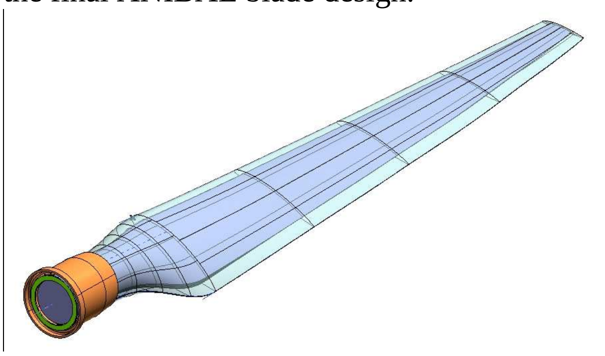

Fig. 9 3D view of the ANIBAL

The cruise efficiency of the ANIBAL propeller is presented in Fig. 10 as a function of the advance ratio. Thanks to a larger area of cruise efficiency (> 0.85) compared to the reference blade (Fig.3), all level flight configurations show good performance. Moreover, the 2 climb points (with / without glider) have a comparable efficiency compared to the reference blade.

Concerning the acoustic evaluation of the ANIBAL propeller, the main results are presented in Fig. 11. A 10 dB(A) noise reduction is achieved in all flight conditions compared to the reference propeller, the higher gain is obtained for high speed cruise. As expected, the thickness noise is strongly reduced (14 dB(A)) whereas the loading noise is less influenced and now represents the main noise contribution for the certification point.

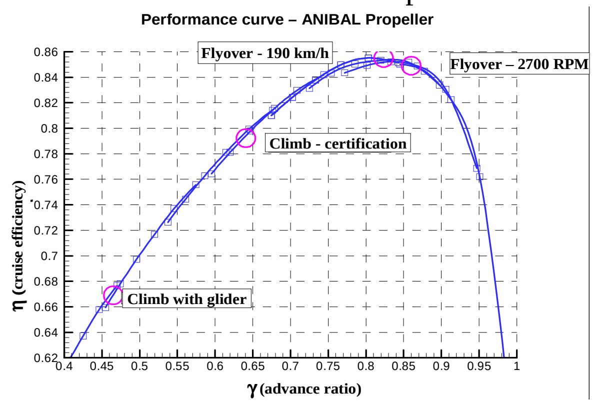

Fig. 10 Aerodynamic performance of ANIBAL propeller

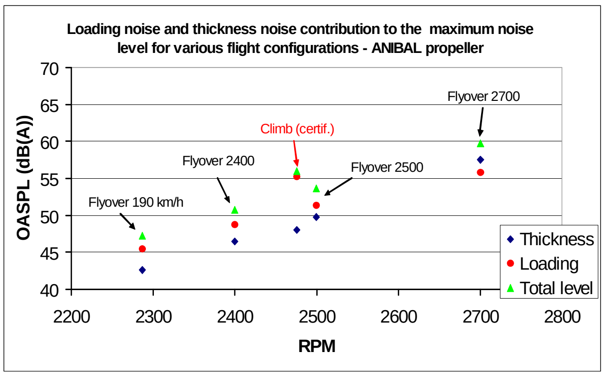

Fig. 11 Aero-acoustic prediction of ANIBAL propeller

The selected ANIBAL propeller theoretically meets the requirements of the project with a noise reduction exceeding 8 dB(A) and slightly enhanced aerodynamic performances.

4. Flight tests

According to the project objectives, the flight tests had to ensure the evaluation of both the noise reduction for various configurations and the aerodynamic performance, especially during the initial climbing. These tests should also allow assessing the code capability to predict aerodynamic and acoustic properties of actual propellers.

4.1 Flight tests preparation

The airplane, a Robin DR-400 180 R, was equipped with measurement equipments by CGTM, giving access for example to the admission pressure; the RPM and fuel consumption (see Fig. 12). The trajectory, obtained through D-GPS, enabled a precise restitution of the performance of the airplane and of the flight conditions synchronized with the microphone measurements.

Fig. 12 DR400 during instrumentation

4.2 Flight tests execution

The test campaign took place at Aire sur l'Adour, located in the South West of France. This aerodrome was selected for its 1000 m asphalt runway, its low traffic and the presence of a glider flying club. Figure 13 presents a Google Earth view of the aerodrome with the two microphones locations indicated by a red spot along the runway. Figure 14 shows the STAC truck used as the test direction office to coordinate both airplane trajectory and microphone measurements.

Fig. 13 Overview of the aerodrome

Fig. 14 Test direction – STAC truck

Concerning the campaign schedule, the test program was limited to 4 days and 5 hours of flight for the ANIBAL H2 propeller. It started by the evaluation of the Sensenich propeller aerodynamic and acoustic performances. For aerodynamic performances, typical airplane characteristics like climb rate in initial climb as well as flight speeds at various RPM were measured. For acoustic tests, measurements were conducted during the initial climb (ICAO annex 16 procedure [8]) but also for level flight in order to cover the full range of RPM. The ANIBAL prototype was then mounted on the DR 400 airplane as shown in Fig. 15.

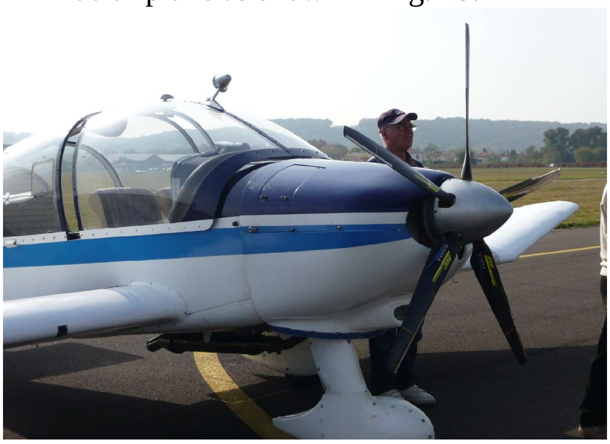

Fig. 15 DR400 equipped with ANIBAL propeller

The ANIBAL propeller behaviour was first evaluated with the opening of the flight domain and, after a pitch reduction, the evaluation of aerodynamic and acoustic performances was performed for the same configurations as for the reference blade. Eventually, both propellers were evaluated when towing a double seater Janus C glider for aerodynamic and acoustic performances during take off and initial climb, in order to evaluate the actual reduction of noise for the airfield neighbours.

4.3 Aerodynamic performance results

Concerning the aerodynamic performance, the recorded data (atmospheric conditions, static and dynamic pressure, rotation speed, airplane location, etc.) for each tests were post-processed in order to compare the propeller performances in terms of climbing rate, average flight speeds and cruise efficiency. During the post-processing, some assumptions had to be considered to compute the cruise efficiency of the propellers. For example, the aerodynamic polar curves provided by the airplane manufacturer were used to compute the required thrust, and the engine model (from Lycoming) was used to obtain the required power through the measured pressure and RPM. One has to note that some problems occurred during the test campaign as, for some tests, the RPM sensor was disconnected and the dynamic pressure sensor and its back-up sometimes did not work. Yet, the amount of gathered data was considered sufficient enough to obtain a reliable database.

Four different flight test cases were considered for the performance analysis: the performance at take – off, the level flight conditions (at fixed RPM), the initial climb (full power) and the climb towing a heavy glider. On the 3 last will be considered here.

4.3.1 Levels flights conditions

The level flight test cases were performed for four engine speeds: 2700 RPM / 2500 RPM / 2100 RPM and an engine speed corresponding to 130 km/h. Figure 16 presents the average speed reached by both propellers for the three first engine speeds. With the retained test pitch (after a decrease), the average speed using the ANIBAL propeller was found to be approximately 10 km/h lower than the one reached with the reference propeller. Nevertheless, with the initial pitch (selected after ground testing), the average speeds are similar. Actually, the test pitch was precisely evaluated after the campaign and the pitch is reduced by 1.7 ° (18.3° pitch), which explains the speed reduction.

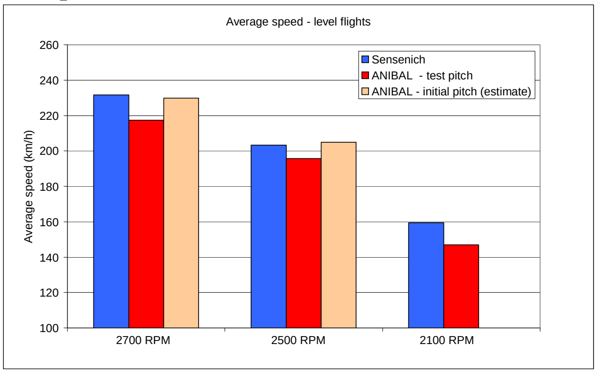

Fig. 16 Comparisons of level flights speeds

Figure 17 presents the evolution of the cruise efficiency as a function of the advance ratio for both propellers for level flights conditions. In this figure, S1 and S2 respectively refer to the main dynamic pressure sensor and to the back-up one. The ANIBAL efficiency is a few counts lower (3-4 counts) than the reference one for all test conditions.

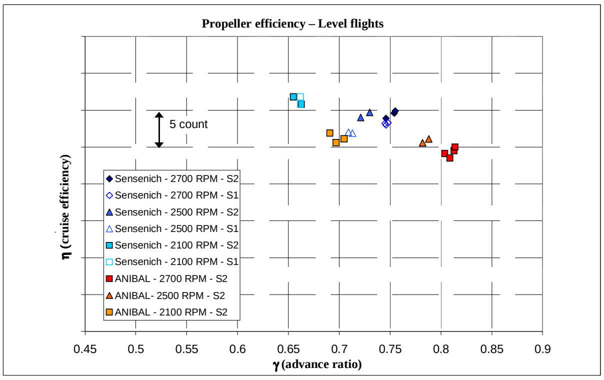

Fig. 17 Comparison of cruise efficiency – level flights

As for speed reduction, the explanation for this difference with expected performance is related to the pitch reduction which led to a test pitch lower than the targeted one, as presented Fig. 18 below.

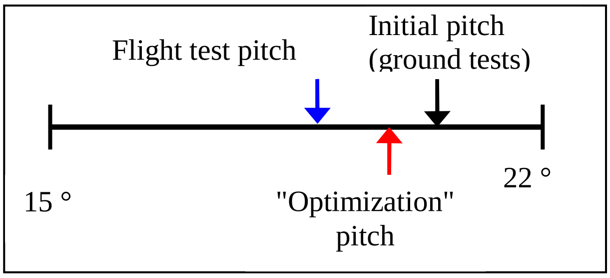

Fig. 18 Gain on performance – 5 blade propeller

As a consequence, the high speed performance is lower than expected but the low speed performance (like in climb) should be increased

4.3.2 Climb conditions

The previous assumption can be checked by analysing the initial climb conditions (ICAO annex 16 procedure). Each propeller experiences eight flights for this test case. The mean and maximum values of the vertical speed during climb are summarized in Fig. 19 for both propellers.

Climb	Sensenich	ANIBAL
Vz - Mean Value	3.8 m/s	4 m/s
Vz - Max Value	4 m/s	4.4 m/s

Fig. 19 Comparison of vertical speed – climb

One can check that the ANIBAL propeller provides a slightly better performance than the reference propeller both for mean and maximum values. The comparison of the cruise efficiency for both propellers (Fig. 20) confirms this behaviour in all cases. The average efficiency of the optimized propeller is roughly 2 counts higher than the Sensenich propeller.

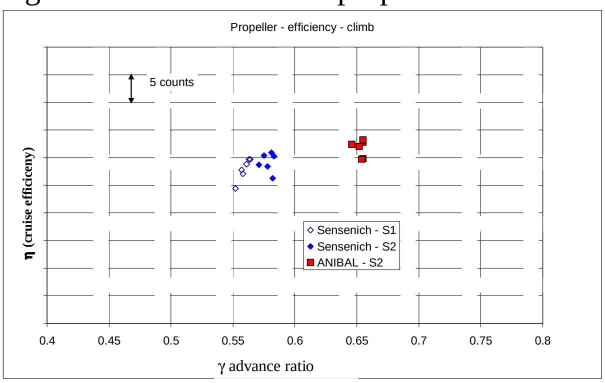

Fig. 20 Comparison of cruise efficiency – climb

Therefore the ANIBAL propeller experiences a performance slightly higher than expected, considering the optimization process, but it seems logical assuming the reduced pitch (lower than the target one).

Concerning the towing test cases, the trajectory speed is reduced compared to the initial climb (130 km/h instead of 170 km/h) and the advance ratio is lower. For these flight conditions, each propeller was evaluated three times.

Here again, the best performances are associated with the ANIBAL propeller, especially for the maximum value with a Vz reaching 2.45 m/s instead of 2.1 m/s for the reference propeller. For this flight test, the airplane equipped with the ANIBAL propeller brought the glider at the altitude of 1500 ft 30 s earlier than the reference airplane (more than 10 % of gain on time). Figure 21 compares the cruise efficiency for both propellers for this flight condition. Only two flights per propeller were retained and one can check that the best cruise efficiency was reached by the ANIBAL propeller with a gain of 5 counts compared to the reference propeller. This better performance confirms the effect of the reduced pitch.

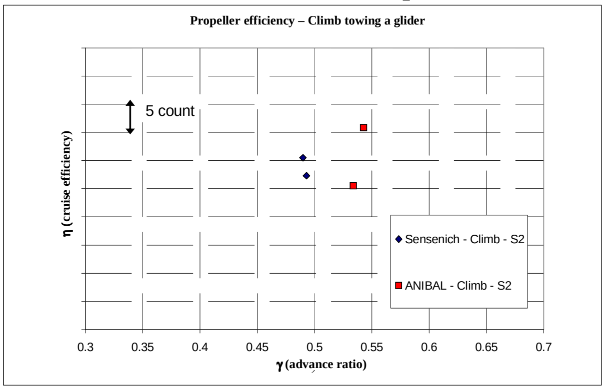

Fig. 21 Comparison of cruise efficiency – climb with glider

4.3.3 Post test calculations

Some additional computations were performed to check the effect of pitch modifications on the propellers expected performance. Three level flight conditions (2700 RPM / 2500 RPM / 2100 RPM) were used to correlate the theoretical performance curves with the test data, in terms of thrust for a given flight speed and RPM, using pitch modifications. Figure 22 present the correlation obtained for the ANIBAL propeller.

Concerning the Sensenich propeller, the theoretical pitch had to be slightly increased to match the test data. Considering that similar airfoils polar were used for the ANIBAL propeller in the same lifting line code, the difference between the theoretical optimized pitch and the flight pitch should have been be similar to the Sensenich propeller. Actually, for ANIBAL propeller, the theoretical pitch had to be reduced (by more than 1.1 °) to match the test data thus confirming the pitch reduction of the flight tests, leading to a lower pitch than the optimized one.

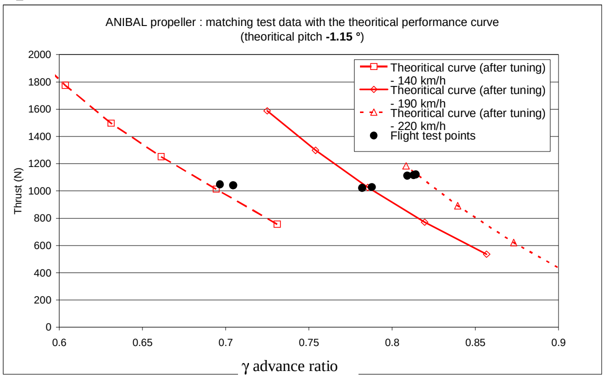

Fig. 22 Comparison test /computation (after theoretical pitch modification) - ANIBAL

Eventually, Figure 23 shows the propellers "corrected" theoretical curves with the locations of the flight test configurations in flyovers and in climbs.

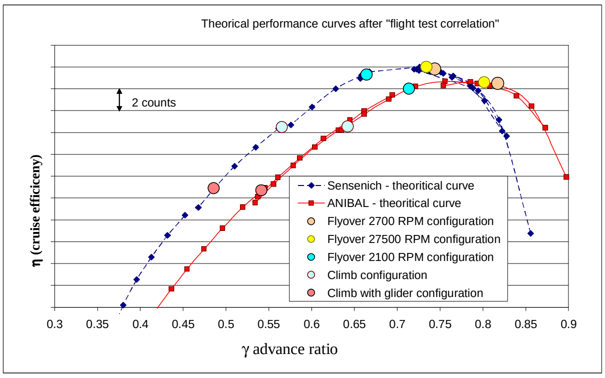

Fig. 23 Theoretical performance curves with flight configurations (Anibal vs. Sensenich)

Some remarks can be done from this figure:

- for level flights, located around the maximum cruise efficiency of the propellers, the expected efficiency of the Sensenich propeller should be higher than the ANIBAL one, which was observed during the flight campaign,
- for the climbing configuration, without glider, the efficiency of the ANIBAL propeller is expected to be slightly higher than the Sensenich one, which was also observed during the flight campaign,
- for the climbing configurations towing a glider, the theoretical curves predict a similar efficiency for both propeller, whereas, during the flight test, ANIBAL propeller has obtained the highest efficiency, even though the test results were scattered for this flight configuration. Nevertheless, one has to note that these flight configurations are located in a steep part of the performance curve and the uncertainty on advance ratio can have a strong impact on the cruise efficiency (+/1.5 counts).

Therefore, the post – test calculations confirmed that the retained flight pitch was lower than the targeted one, thus reducing the optimum advance ratio and lowering the efficiency. Nevertheless, from the performance point of view, the ANIBAL objective is fulfilled with improvement in initial climb.

4.4 Acoustic results

In the following, each flight case is analyzed separately. It is to note that for each case, several independent measurements have been recorded. Thanks to the stable meteorological conditions and to the quality of the piloting, the results from one attempt to the next are very similar. Therefore, no specific correction of the acoustic results had to be made.

4.4.1 Analysis of acoustic measurements

The STAC measurements provided to ONERA are instantaneous narrowband spectra, gathered every 300ms, during the course of the airplane. The typical STAC measurements (slip mean spectrum in third of an octave) were also analyzed by the STAC in accordance with the certification process. Examples of noise spectra are shown in Fig. 24 and Fig. 25 for the two propellers. This type of analysis enables to separate the noise sources of airplane in the course of the flight.

Light aircraft noise is mainly composed of two noise sources which are due to the exhaust and to the propeller. These noise sources produce tone noise, a phenomenon linked to the engine rotation speed. N being the rotation frequency, the exhaust tones frequencies correspond to a multiple of 2*N because of the engine and the propeller tones appear every multiple of B*N with B, the number of blades. The noise spectrum of the airplane equipped with the Sensenich propeller (two blades) is composed of propeller tones every multiple of 2*N, all mixed with the ones due to the exhaust. On the other hand, the noise spectrum of the airplane equipped with the ANIBAL propeller (five blades) is composed of propeller tones multiples of 5*N. Except for tones 10*N, 20*N,…, which combine exhaust and propeller noise, exhaust and propeller tones are dissociated thus enabling a validation of the propeller noise computations.

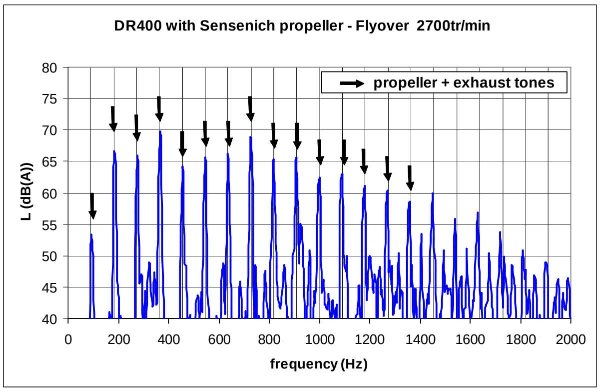

Fig. 24 Measured noise spectrum – typical with a two blade propeller

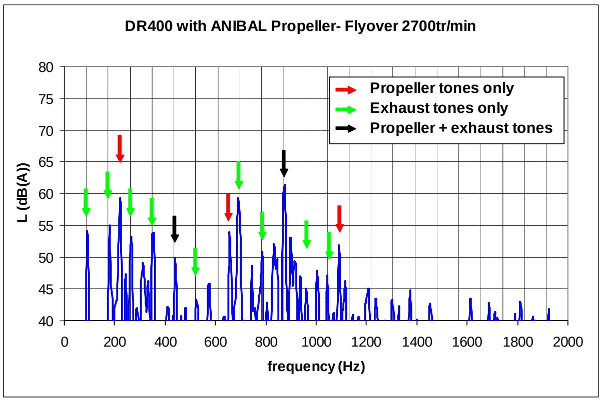

Fig. 25 Measured noise spectrum – typical with a five blade propeller

Also, concerning the acoustic performance, the analysis of the results have been made both through the global sound level variation of the airplane and the acoustic spectrum at maximum sound level. In addition, post test computations are presented in order to assess the propeller noise contribution to the total noise level.

4.4.2 Comparison of global sound level time trace of the airplane

Figures 26 to 29 respectively present the comparison, between the Sensenich and the ANIBAL propellers, of the global sound level time trace during flyover test for initial climb (Fig. 26), at maximum engine speed (2700 RPM) (Fig. 27), at 2500 RPM (Fig. 28) and for flight at 130 km/h (Fig. 29). The time t=0 corresponds to the airplane passing over the microphone. For these flight conditions, when the airplane is flying above the microphone, the acoustic gains achieved with the airplane equipped with the ANIBAL propeller are the following : - 7 dB(A) for flyover at 2700 RPM, - 5 dB(A) for flyover at 2500 RPM, - 2 dB(A) for flyover at low speed and – 3 dB(A) for climb conditions.

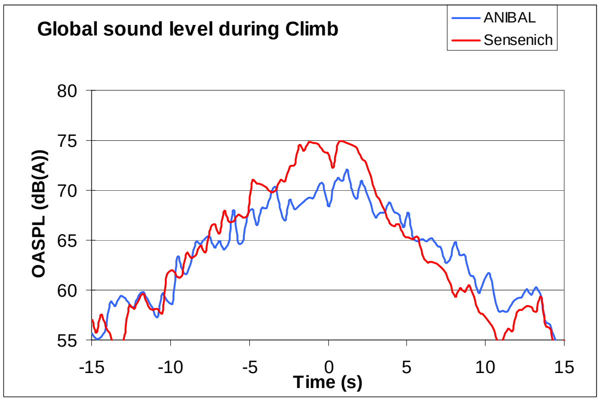

Fig. 26 Global sound level variation - climb

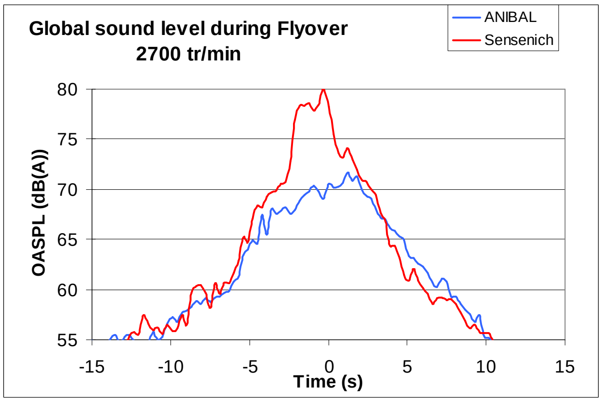

Fig. 27 Global sound level variation – Flyover 2700 RPM

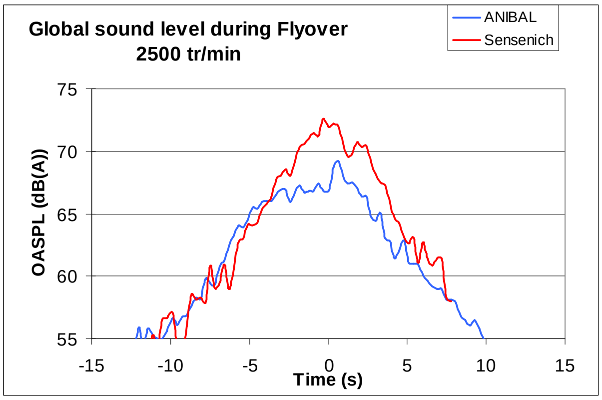

Fig. 28 Global sound level variation – Flyover 2500 RPM

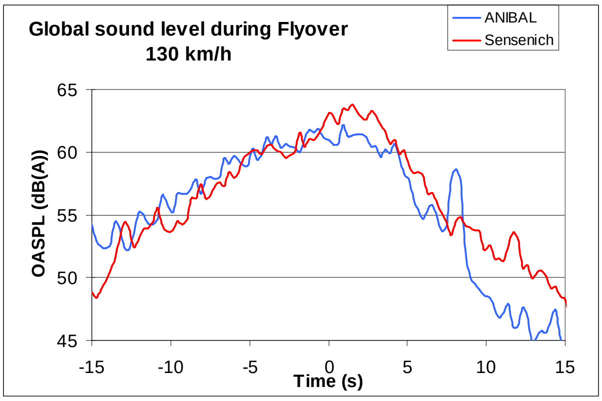

Fig. 29 Global sound level variation - 130 km/h

Even though the acoustic gains are important, they appear to be lower than expected from the optimization process (recalled in Fig. 30).

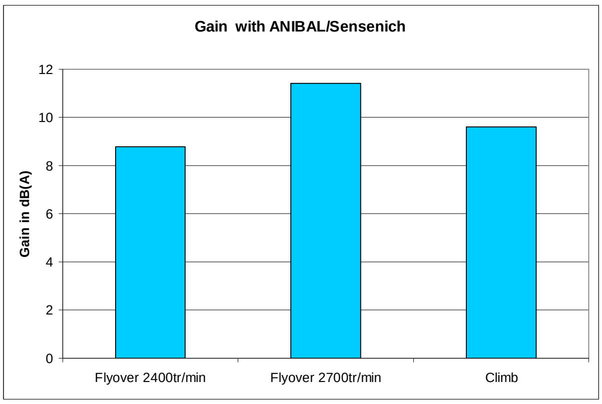

Fig. 30 Expected acoustic gain for ANIBAL

Actually, these predicted and expected gains only concern the isolated propellers whereas the measured gains in global sound level concern the complete airplane. Therefore, to estimate the ANIBAL noise improvements, exhaust and propeller noise have to be considered separately.

4.4.3 Comparison of the two propellers – experiment and computation

All noise spectra presented below are instantaneous spectra measured when the global noise level is maximum in dB(A).

The propeller noise is computed using real flight conditions and the trajectory of the flight. The only uncertainty for the comparison with measurements is the rotation speed variation for the different flights (especially for Sensenich propeller).

The computed tone levels for each propeller can be compared to the measured ones which are due to the propeller only for certain tones and due to the propeller+exhaust for other tones.

Climb initial, take off simulations at 160 km/h

For the certification flight configuration, climb at 160 km/h, computed propeller tone levels (red cross) and measured propeller + exhaust tone levels (green triangle) match very well for the Sensenich propeller (Fig. 31) and for the ANIBAL propeller (Fig. 32).

The measured spectrum for the DR400+ANIBAL propeller (Fig. 31) shows the level of the two first tones (blue squares) which are only due to the exhaust (79 dB and 72 dB). The levels of these tones measured with the Sensenich propeller (Fig. 32) are quite high (85 dB and 80 dB). It means that for this flight condition, the sound generated by the DR400 with a Sensenich propeller is largely dominated by the propeller noise.

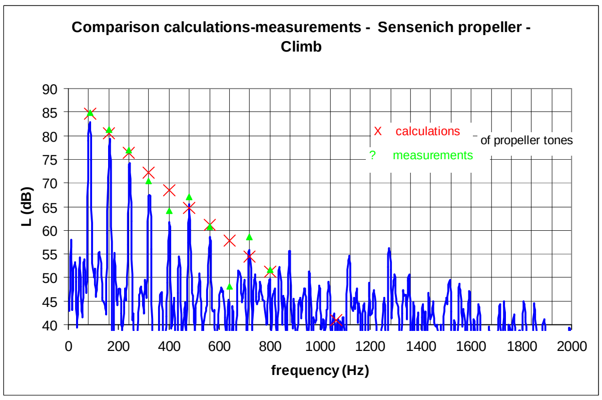

Fig. 31 Sensenich acoustic spectrum at max sound level (climb – 160 km/h)

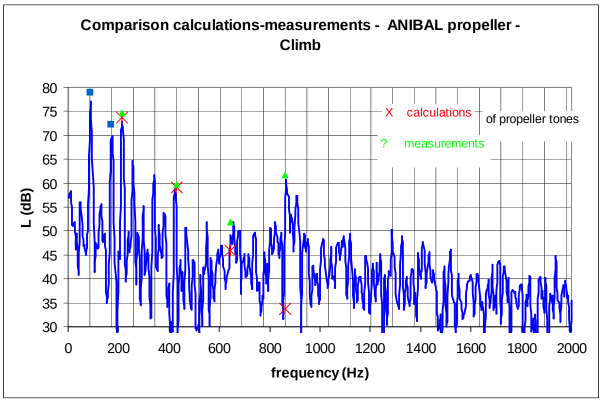

Fig. 32 ANIBAL acoustic spectrum at max sound level (climb – 160 km/h)

Concluding from this flight case, the exhaust noise is lower than the propeller noise and the computational results are in good accordance with the measurements for the Sensenich and for the ANIBAL propeller. Numerical tools hereby used are therefore well suited to the aeroacoustic prediction of light aircraft propellers.

On Fig. 33 and Fig. 34 are compared the measured sound level of the airplane and the predicted sound level of the isolated propeller for the same configuration: For the Sensenich propeller, the predicted propeller noise level is of the same order as the airplane noise; this confirms that the propeller is therefore the dominant source of noise. For the ANIBAL propeller, the predicted propeller noise is 2 dB(A) below the airplane noise, thus confirming that the propeller contribution is of the same level as the exhaust. Thus, the acoustic gain brought by the ANIBAL propeller "alone" – compared to the reference-for this climb case can be evaluated at more than 7 dB(A).

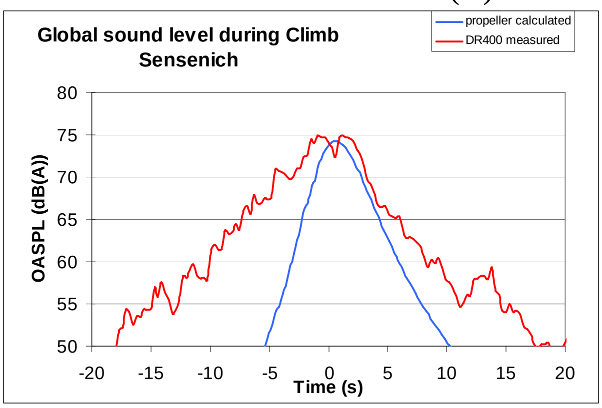

Fig. 33 Comparison between the airplane noise level and the Sensenich predicted noise level

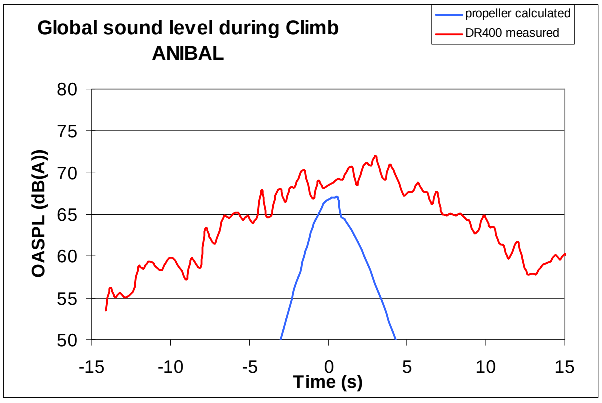

Fig. 34 Comparison between the airplane noise level and the ANIBAL predicted noise level

Flyover at 2700 RPM

During the flyover of the Sensenich propeller at maximum speed (Fig. 35), one can see that, except for the propeller first tone, the predicted propeller noise levels (red cross) are slightly over-estimated when compared to their measured counterparts (green triangle). It can be due to the uncertainty in the rotation speed for the Sensenich propeller which is an important parameter for the accuracy of aero-acoustic predictions.

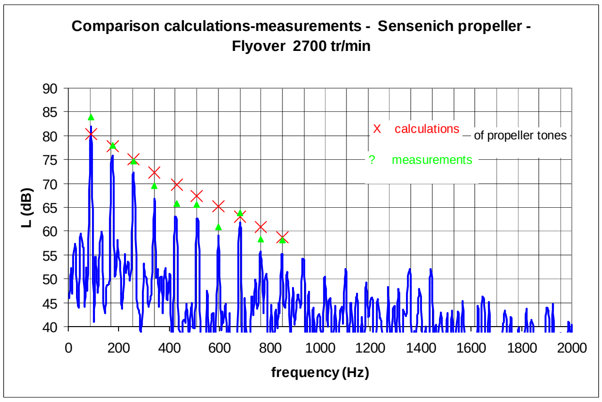

Fig. 35 Sensenich acoustic spectrum at max sound level (flyover 2700 RPM)

For the ANIBAL propeller (Fig. 36), the predictions are in good agreement with the measurements for the first three harmonics. The exhaust noise is dominating. This spectrum highlights many high frequency tones which essentially relate to the exhaust and largely contribute to the total noise.

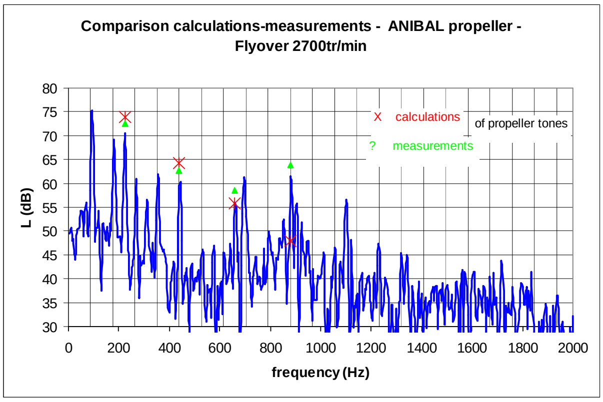

Fig. 36 ANIBAL acoustic spectrum at max sound level (flyover 2700 RPM)

Also, prediction of propeller noise levels during flyover at 2700 RPM have been made and compared to measurements of airplane noise levels (Fig. 37 and Fig. 38). For the Sensenich propeller, the comparison shows that the propeller is the dominant noise source (Fig. 37), and for the ANIBAL propeller (Fig. 38) the exhaust noise overcomes the propeller noise by approximately 2 dB(A).

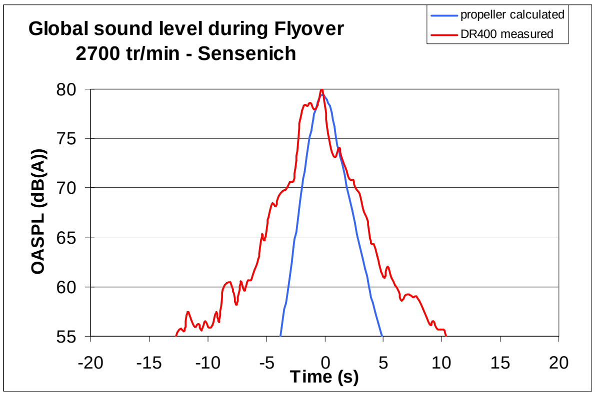

Fig. 37 Comparison between the airplane noise level and the Sensenich predicted noise level

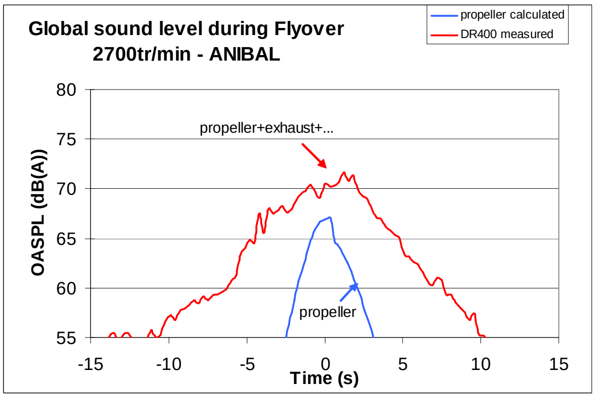

Fig. 38 Comparison between the airplane noise level and the ANIBAL predicted noise level

The comparison of the blue lines in Figs. 37 and 38 shows that the expected gain from computations using the ANIBAL propeller is more than 12 dB(A) whereas the actual measured gain is 7dB(A) (red line).

Flyover simulating the « aerodrome circuit »(backward wind, 133km/h) at 2100 RPM

This flight case is interesting because it simulates the « aerodrome circuit » conditions which is at the heart of the airfield neighbours claims concerning noise reductions.

The acoustic spectrum at maximum sound level using the ANIBAL propeller shows high amplitude tones which come from the exhaust (black arrows) (Fig. 39). The comparison between predictions and measurements of propeller tones is good as long as the propeller is the main source of noise (tone 5 or first harmonic). For higher frequency tones, the exhaust becomes the dominant source.

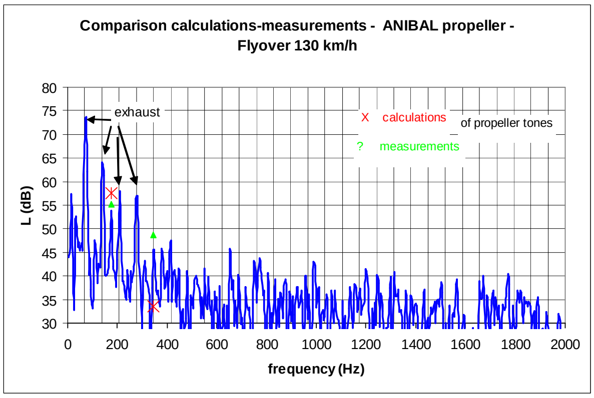

Fig. 39 ANIBAL acoustic spectrum at max sound level (flyover 130 km/h)

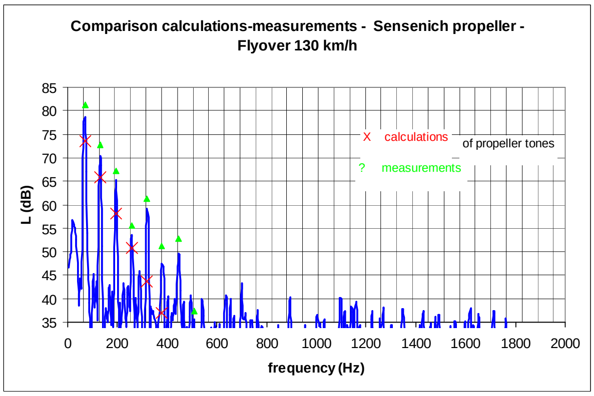

Fig. 40 Sensenich acoustic spectrum at max sound level (flyover 130 km/h)

This last result is confirmed by the acoustic spectrum at maximum sound level using the Sensenich propeller (Fig. 40). All tones being a combination of the propeller and the exhaust contributions, the predicted tone levels are underestimated.

The computed sound levels due to the propellers alone are much lower than the global sound level for both propellers (Fig. 41 and Fig. 42). The exhaust noise therefore overcomes the Sensenich propeller noise by 10 dB(A) and the ANIBAL propeller noise by 20 dB(A). For this reason, the actually measured acoustic gain is reduced to approximately 2dB(A). It is to note that if the propellers were to be considered alone the gain would reach almost 9dB(A) for a flyover at 130 km/h with backward wind.

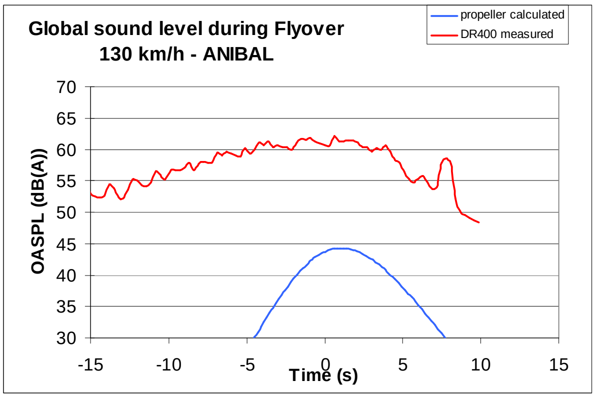

Fig. 41 Comparison between the airplane noise level and the ANIBAL predicted noise level

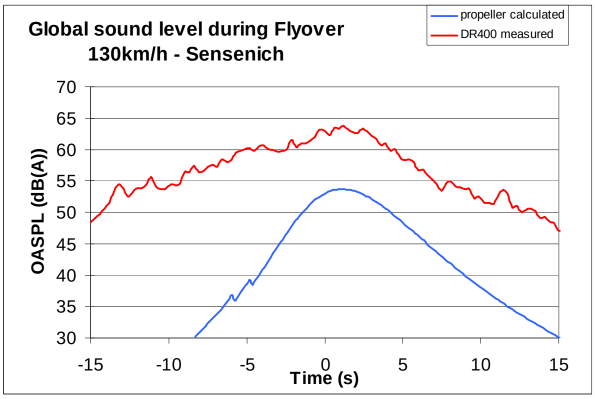

Fig. 42 Comparison between the airplane noise level and the Sensenich predicted noise level

4.4.4 Summary

Following the analysis of these flight tests results, it appears that the ANIBAL propeller reduces the noise made by the airplane DR400 for all flight cases. The most important gain is obtained when towing a glider (8dB(A)). However the expected acoustic gain was not reached because of the exhaust which prevails for all flight cases when using the ANIBAL propeller. Fig. 43 below summarizes the gain brought by the ANIBAL propeller for all the test cases

Acoustic gain	2700 RPM	2500 RPM	130 km/h *Aerodrome circuit*	Climb *certification*	Climb with glider
Global sound level (airplane)	7 dB(A)	5 dB(A)	2 dB(A)	3 dB(A)	8 dB(A)
Propeller noise contribution	> 12 dB(A)	10 dB(A)	9 dB(A)	> 7 dB(A)	10 dB(A)

Fig. 43 Overview of acoustic gain

In addition, these tests have shown that at maximum speed (flyover at 2700 RPM and climb), the airplane DR400+ Sensenich propeller noise is dominated by the propeller contribution. At lower speeds -flyover at 2500 RPM- the noise levels due to the propeller and to the exhaust are close. At very low speeds – (flyover 130 km/h with backward wind), the exhaust noise largely prevails.

Finally, it should be noted that when propeller noise prevails, a good agreement between measured and predicted tone levels is observed, showing that the numerical tools used during this study are well suited to the design of light aircraft propellers.

5 Conclusion

The ANIBAL project (*Abaissement du NIveau de Bruit des Avions Légers*) was launched in 2003 with the objective to design, manufacture and test a new “low noise propeller” for light aircraft applications.

During the first phase of the project, the optimization process led to the selection of a 5 blade propeller of 1.68 m diameter. According to the computational results, this propeller was to meet the requirements of the project with more than 8 dB of noise level reduction and slightly enhanced aerodynamic performance.

Flight tests showed the achievement of the requirements of the project in terms of aerodynamic performance and acoustic levels:

From the performance point of view, the ANIBAL propeller is better in climb conditions (with and without glider). Even if flyover speeds are reduced, the variable pitch of the

ANIBAL propeller enables it to recover high performance at high speeds if needed.

From the acoustic point of view, the ANIBAL propeller alone provides close to 8 dB(A) gain in initial climb compared to the reference propeller and up to 9 dB(A) for flyover at low speed (aerodrome circuit). Unfortunately, this gain on the propeller contribution to the airplane noise can not be fully measured during flight tests due to the contribution of the exhaust noise, prevailing over the ANIBAL propeller contribution for most of the flight conditions.

According to the authors, further attempts to reduce noise emissions of light aircraft should now focus on the exhaust. This study shows that it is a significant noise source, and overcomes the propeller in many conditions.

6 Acknowledgments

The present work was funded by the *Direction des Programmes de l'Aviation Civile* (DPAC) of the French Civil Aviation Authority (DGAC). Authors would like to thank all the ANIBAL partners for their implication in the project and especially the FFVV (French Soaring Society) for providing the airplane as well as the test pilot for the flight tests.

6 Caontact author e-mail address

Thierry.Lefebvre@onera.fr

References

[1] Lefebvre, T., Canard-Caruana, S., Le Tallec, C., David, F. and Neuville, N., "*ANIBAL: a new aero-acoustic optimized propeller for light aircraft applications*" AIAA/ATIO, Hilton Head (USA) ,September 2009.

[2] Benoit, B., Dequin, A.M., Kampa, K., Grunhagen, W., Basset, P.M., Gimonet, B., "*HOST, A General Helicopter Simulation, Tool for Germany and France*", 56th Annual Forum of the American Helicopter Society, Virginia Beach (USA), May 2002.

[3] Lefebvre, T., Beaumier, P.,Canard-Caruana, S., "*Aerodynamic and aero-acoustic optimization of modern tilt-rotor blades within the ADYN project*," ECCOMAS 2004, Jyväskylä (Finland), July 2004.

[4] Goldstein, M.E., *Aeroacoustics*, Mc Graw-Hill International Book Company, 1976.

[5] Ffowcs Williams J.E., Hawkings D.L.,"*Sound Generation by Turbulence and Surfaces in Arbitrary Motion*". Philo. Trans. Royal Society of London, Vol. 264, A1151, pp321-342, May 1969.

[6] Prieur J., Rahier G., "*Comparison of Ffowcs Williams-Hawkings and Kirchhoff rotor noise calculations*". 4th AIAA/CEAS Aeroacoustics Conference, Toulouse, May 1998.

[7] Drela, M. and al.., "*A two-dimensional viscous aerodynamic design analysis Code*" AIAA paper, 87-0424, 1987.

[8] Aircraft Noise Certification, Annex 16, Volume 1, Environmental Protection, OACI.

Copyright Statement