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LIGHT PROPELLER AIRCRAFT NOISE STUDY : EXPERIMENTAL APPROACH TO IDENTIFY THE CONTRIBUTION OF MAIN SOURCES

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INTRODUCTION

The new regulations constraints require light aircraft noise reduction due to weaker sound pressure level limitations. Light aircraft manufacturer SO.C.A.T.A. has choosen a collaboration with Acoustic Laboratory of CERT/ONERA to carry out a research into its propeller airplanes equipped with piston engine. Noise level limitations depend on the noise standard and the country. Four general regulations are applied for this aircraft category : OACI Annex 16 chp. 6 and FAR PART 36 Appendix F which involve flyover aircraft procedure; OACI Annex 16 chp. 10 and FAR PART 36 Appendix G with take-off aicraft configuration. Each regulation gives sound pressure level limitations according to airplane mass. But limitations are generally modified by each country and lead to sound pressure level decreasing up to 8 dB(A). Consequently aircraft noise reduction is necessary because environmental protection emphasizes this tendency.
The first part of investigations is the identification of sound mechanisms generated by the studied aircraft. For this purpose, a static experiment is perfomed in order to separate and classify the main sources. Due to environmental conditions, the most appropriate method is the determination of sound power by sound intensity measurement. As a complement to these results, an analysis of flyover noise measurement is achieved based on OACI chp. 6 noise regulation.

I BIBLIOGRAPHY

I.1 Aircraft noise sources

Propeller and engine exhaust are the main sound sources of a light aircraft [1]. Discrete frequency noise in accordance with propeller shaft rotation speed is generated. A third source exists : it is a broadband noise produced by slipstream and its interaction with airframe [2]. However general light aircraft studies [1] [3] show that the most important source is the propeller.
An empirical method has been developed by Hamilton Standard Division [4]. Few propeller characteristics are required to estimate harmonics sound pressure levels which are in good agreement with standard levels. This method confirms the influence of propeller parameters, but does not give information on sound generation mechanisms.

I.2 Analytic formulation of propeller noise

The acoustic field of a propeller is expressed analytically through Lighthill's acoustic theory [5]. The sources of sound are represented by monopole, dipole and quadripole (insignificant for subsonic tip Mach numbers) sources. Lighthill's propagation equation is solved into integral form. Goldstein's formulation takes surfaces motion into account [6]. The sound pressure $p(x,t)$ emitted by a point source (y,τ) at an observer point (x,t) is given by *(1)* :

$$p(x,t) = \underbrace{\int_{-T}^{+T}\int_{S} f_i \frac{\delta G(y,\tau / x,t)}{\delta y_i} dS(y)\, d\tau}_{\text{dipole : loading noise}} + \underbrace{\int_{-T}^{+T}\int_{S} \rho V_n \frac{DG(y,\tau / x,t)}{D\tau} dS(y)\, d\tau}_{\text{monopole : thickness noise}} \qquad (1)$$

where $G(y,\tau / x,t)$ is the Green function, S the surface in motion (the blades in our case), f_i are the loads exerted by the surface S on the fluid and V_n is the normal velocity of the surface S.
Analytical solutions [7] may be written in time domain or by Fourier transform in frequency domain. This last one is the most adapted tool for parametric investigations. Two nearby solutions and parametric studies [1] [8] exist in the case of propeller.
Gounet's solution [1] uses a reference in motion on the aircraft and no chordwise source distribution while Hanson's formulation [8] is developed with both fixed reference and chordwise non compactness distribution.
Aeroacoustic windtunnel and inflight measurements studies also exist [9]. The reduction of propeller noise involves increasing number of blades, decreasing diameter and rotation speed, and moreover appropriate spanwise loading distribution and geometry.
For noise source investigations in order to reduce their sound levels, it seems important to classify and separate each source by measurement.

II EXPERIMENTAL PROCEDURE

II.1 Inflight and static noise

Some inflight and flyover pressure measurements have been already achieved [3] [10]. A sound pressure spectrum doesn't allow to obtain the characteristics of each sound source. It is not the case of sound intensity measurement which provides the sound power radiated by each source.
As the determination of sound power by inflight sound intensity measurements would lead to experimental difficulties, static aircraft operating set-up is choosen. This experimental procedure avoids atmospheric absorption which exists for flyover case, and besides excludes any influence from other sources.
Sound generation mechanisms are different for flight and static procedure : Doppler effect acts on wave propagation, flight speed effect influences propeller loads and its distribution. Lastly for aircraft static operating, ground vortex intake leads to the appearance of some unsteady loads. As long as the differences are well known, sound power determination by run-up tests remains a good approach to separate aircraft sources of sound.

II.2 Determination of sound power

Definition : In our case, the principle relies on the integration of sound intensity on a surface which encloses the source. It is based on Gauss theorem and all outside sources are not taken into account when there is no absorption in the defined volume *(Fig. 1)* [11].
The measurement consists in discretizing the whole surface into N elementary surfaces S_i, in the purpose to calculate overall sound power by the following formulation *(2)* :

$$W = \sum_{i=1}^{N} I_{ni} S_i \qquad (2)$$

where I_{ni} is the normal intensity of the element S_i.
Sound intensity measurement : Sound Intensity is defined as the energy flow per elemental area. This vector is expressed by the product of sound pressure by acoustic velocity *(3)* :

$$I_n(t) = p(t).u_n(t) \qquad (3)$$

Using acoustic and signal processing properties, the mean sound intensity can be approached by *(4)*:

$$I_n(\omega) = -\frac{\mathrm{Im}\, G_{AB}(\omega)}{\rho\, \omega\, \Delta r} \qquad (4)$$

where $\mathrm{Im}G_{AB}(\omega)$ is the imaginary part of the pressure cross spectrum between two microphones A and B, ρ is the air density, $\omega = 2\pi f$ is the pulsation, Δr is the distance between the two microphones.

This formulation induces some frequency limitations : for low frequencies due to phase between microphones and for high frequencies due to finite difference approximation of pressure gradient.

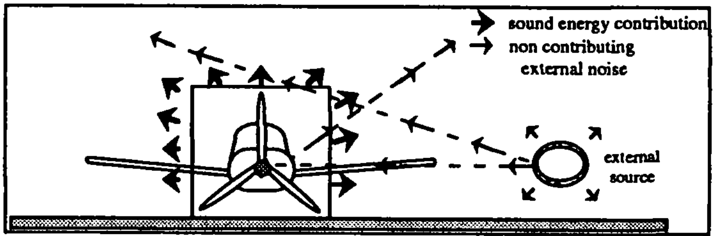

Fig.1 : Sound power determination by intensity measurement

II.3 Separation of noise sources

To obtain the sound power of each source, three measurement volumes should be defined each enclosing the propeller, the exhaust and the engine. Due to both the proximity of sources and the propeller slipstream, a single volume enclosing all these elements has to be choosen. Thus, three aircraft configurations are selected in order to separate each source :

- Standard airplane
- Standard with sound covering engine cowling
- Same as above with exhaust radiation removed of the measurement volume (on the following assumed as exhaust off).

III DESCRIPTION OF TESTS

III.1 Aircraft

- engine : 4 cylinders P = 149 KW.The sound covering of engine cowling is achieved according to space, temperature and acoustic constraints.
- exhaust : collector + short pipe, Ø = 75.10^{-3} m.The exhaust is extended with a pipe insulated acoustically in order to reject from the volume the exhaust radiation.
- propeller : 3 blades, Ø = 1,78 m, constant speed (low pitch).

III.2 Measurement volume and mesh

The choice of the volume and the number of elementary surfaces must deal with source size and distance from source. The volume consists in five measurement faces and a reflective one *(Fig. 2)*. The total number of measurement points is 124 and Si ≈ 0,25 m^2. The assumptions are :

- the tar ground is fully reflective.
- the mesh is adequate to obtain constant normal intensity from each elementary surface.
- backside the propeller plane, the presence of slipstream involve the discretization with only few points (outside flow) and wider elementary surface than other faces. The sound intensity measurement is difficult in non uniform and turbulent flow [11].

III.3 Tests configurations

Operating point : The noise radiated from the propeller depends on rotation speed, loads and geometry. The operating point must be kept constant during measurement of each configuration. The speed rotation is checked with a stroboscope and confirmed from spectrum analysis. Shaft power is given from both manifold pressure and speed rotation. The manifold pressure is regulated according to the temperature. In the *Table 1*, experimental set-ups are given with different aircraft configurations and operating points.

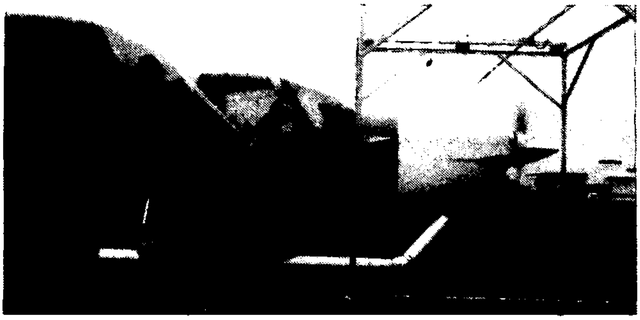

Figure 2 : Measurement set-up with aircraft, delimited volume and special exhaust pipe

Test	Airplane	Rotation Speed(RPM)	Shaft Power (kW)
1	Standard	2640	134
2	Sound covering engine cowling	2640	134
3	Same as above + Exhaust off	2640	134
4	Standard	2500	97

Table 1 : Airplane tests configurations

Measurement equipment : Sound intensity measurement is carried out with a B&K intensity probe 3519. It is equipped with two B&K 1/2" microphones Type 4134, 5.10^{-2} m spacer. The frequency validity domain is 31,5 Hz - 1,25 kHz due to frequency limitations mentioned above [11]. Analyzer B&K Type 2032 is used for spectra analysis. Some preliminary measurements provide averaging record duration according to stationarity of acoustic field and confirm the stability of operating point. Acquisitions and sound power calculations are executed by Star Acoustic software.

IV RESULTS

IV.1 Standard airplane - Test 1

The sound power spectrum *(Fig. 3)* consists in some high level discrete frequencies *(Table 2)* with negligeable broadband noise. These frequencies are determined by speed rotation and represent harmonics from exhaust and propeller noise generation. The rotation frequency is $f_0 = N/60$ where N is the rotation speed expressed in RPM, so that the exhaust harmonic frequencies are $2nf_0$ and those of the propeller are Bmf_0, where n and m are integers and B is the number of blades (3 in our case). Other discrete frequencies in accordance with $1/2nf_0$ are generated by engine radiation.

The axis are scaled with arbitrary units (U). The sum of the sound power levels of the first three harmonics is 101U for the propeller and 95U for the exhaust. In comparison with overall sound power level 103U, propeller noise appears to be the predominant one, in agreement with the bibliography.

n° har. propeller		1		2		3	4	
n° har. exhaust	1		2	3	4		6	
f (Hz)	88	132	176	264	352	396	526	overall
Lpw (U)	95	100	79	93	80	87	84	103

Table 2 : Sound power levels from propeller and exhaust harmonics - Standard airplane - 2640 RPM, 134 kW

IV.2 Propeller sound power - Test 3

Test 3 aicraft configuration is achieved to confirm the origin of each discrete frequency. The propeller harmonics appear clearly *(Fig. 4)* and their levels *(Table 3)* can be compared with previous ones *(Table 2)*. The exhaust noise has been actually rejected : -15U for its fundamental and -10U for its fourth harmonics. In the same way, engine discrete frequencies and broadband noise have significantly decreased.

This configuration allows the determination of propeller sound power : the sum of propeller harmonic levels is the same as overall sound power one.

Another interest of this configuration is the origin of coupled harmonics. The most part of their energy comes from propeller source due to no level difference between the two tests (*Table 2* and *Table 3*).

f (Hz)	88	132	264	352	396	526	overall
Lpw (U)	80	100	93	70	87	83	101

Table 3 : Sound power levels from propeller and exhaust harmonics - sound engine covering and exhaust off - 2640 RPM, 134 kW

IV.3 Influence of aircraft operating point - Test 4

Lower operating point test (n°4) shows, in one hand, decreasing of harmonic frequencies and, on the other hand the same importance for the two sources. Due to lower rotation speed, the figure of sound power spectrum moves through low frequencies. The difference of levels between propeller and exhaust fundamentals goes from +5U *(Table 2)* to +2U *(Table 4)*. Tip Mach number and shaft power are influential parameters of propeller sound generation [1], so that the propeller noise decreases faster than the exhaust one when rotation speed and shaft power are decreasing.

n° har. propeller		1		2		3	4	
n° har. exhaust	1		2	3	4		6	
f (Hz)	83	124	166	250	332	374	500	overall
Lpw (U)	94	96	72	89	76	83	78	99

Table4 : Sound power levels from propeller and exhaust harmonics - Standard airplane - 2500 RPM, 97 kW

The application of ponderation A (greater for low frequencies) produces (for this configuration) and emphasizes (for high operating point) the difference between the two sound sources.

IV.4 Critics

Each configuration verifies field indicators provided by provisional standard NFS31-100 [13]. For exhaust off configuration, external source influences the measurement. Analysis of exhaust radiation close to back face explains the appearance of negative sound power level for few discrete frequencies. Another test with exhaust radiation removed farther should be performed to improve the results.

V COMPARISON WITH FLYOVER TESTS

To complement the run-up tests, some flyover measurements are carried out. On one hand flight noise generation effect can be taken into account and on the other hand, the correlation with regulation procedure is necessary to confirm the sources classification.

Experimental set-up : It is the same as OACI Annexe 16 Chp. 6 [12]. The airplane flies at an altitude of 300 m. The microphone is located at 1,2 m above ground. The aircraft performs several flights with different operating points. Recorded signals are analyzed with frequency analyzer B&K Type 2032. The presented operating point is 2700 RPM and 144 kW shaft power, in comparison with static operating point.

Results : For regulation purposes, the sound pressure spectrum which gives the maximum overall level expressed in dB(A) must be kept. But in order to compare with static measurements, presented spectrum *(Fig. 5)* corresponds to the aircraft location just above the microphone. In this case, the rotation speed is 2700 RPM so that $f_0 = 45$ Hz, the propeller fundamental is 135 Hz and the exhaust one is 90 Hz. In the following table *(Table 5)* the sound pressure levels of exhaust and propeller harmonics are presented in U and U(A) *(Fig. 6)*.

f (Hz)	90	135	180	270	405	overall
Lp(U)	35	45	29	38	32	47
Lp(U(A))	14	30	17	30	27	37

Table5 : Sound pressure levels from propeller and exhaust harmonics - flyover test - 2700 RPM, 144 kW

Comparison with run-up tests : It deals with the shape of the spectrum and the influence of each source, but not directly with the level due to different quantities (sound power level and sound pressure level). A difference of level between high order harmonics of propeller appears. For static configuration, the presence of both steady and unsteady loads provides two slope of harmonic decreasing (on both sides of the fourth harmonic) *(Fig. 2)* while for flyover measurement the first three harmonics only exist due to steady loads.

The sound sources classification is preserved and analysis of lower operating point flyover spectrum confirms the evolution of sound sources with airplane operating point.

VI CONCLUSION

In the purpose of qualifying the noise sources of light aircraft, an experimental set-up is performed through the sound power measurement of run-up operating aircraft. As in bibliography results, most part of energy is provided by both propeller and exhaust radiation. The results of the different airplane configurations lead to consider that this one with both sound covering of engine cowling and exhaust off allows to eliminate a large part of engine-exhaust contribution and to put in a prominent position the most important source, namely the propeller. The environment of the measurement remains complex due to non precise discretization of back face and other sources which are still present in the volume. But comparative studies will be able to achieve with this configuration whereas flyover or inflight measurements underlie too many parameters. For investigations of noise sources, flyover measurements confirm the predominance of the propeller for results expressed in U and in U(A). A parametric study of propeller noise generation has already been undertaken. Hanson's formulation allows, on one hand, to realize both static and inflight comparisons due to fixed reference and, on the other hand, to take both the geometry and the aerodynamics of the propeller into account. In addition investigations of propeller aerodynamic performances are also realized because any modification of propeller design affects the performances and must be checked. In the future, an exhaust noise study will be performed to analyze this second main source and to reach a decreased aircraft overall noise level.

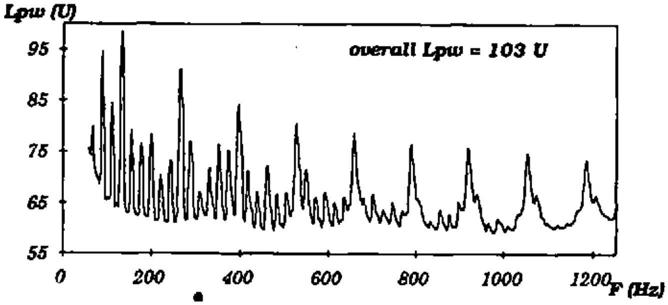

Figure 3 : Sound power spectrum - Standard airplane - 2640 RPM, 134 kW

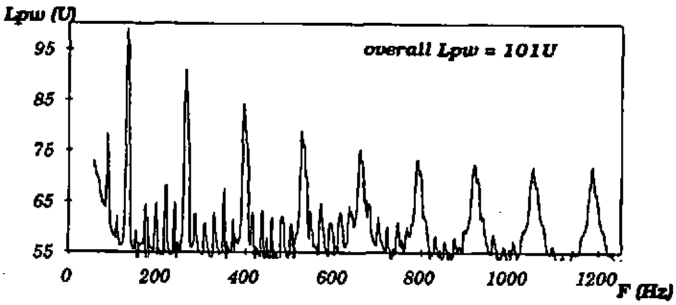

Figure 4 : Sound power spectrum - Sound engine covering and exhaust off - 2640 RPM, 134 kW

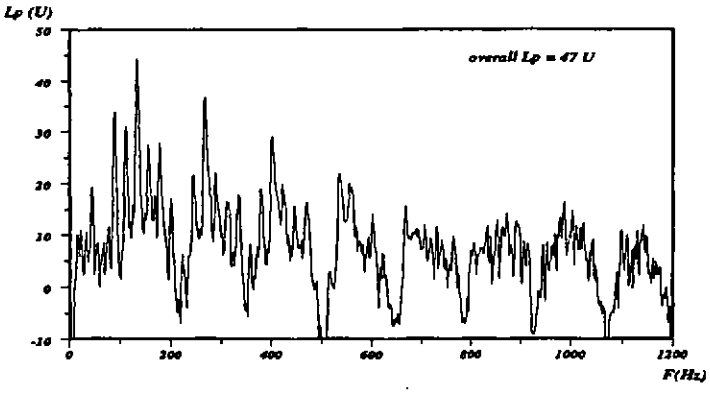

Figure 5 : Sound pressure spectrum in U - flyover test - 2700 RPM, 144 kW

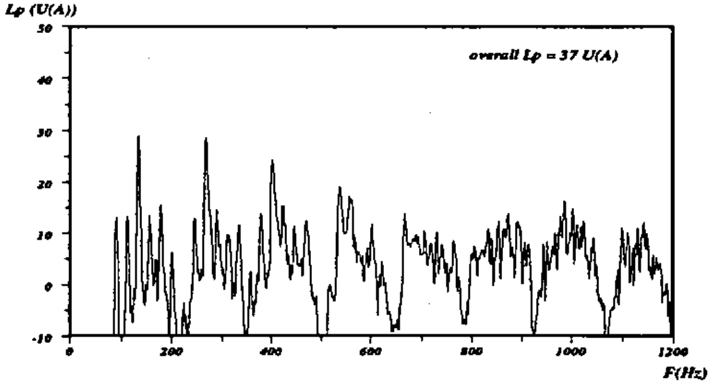

Figure 6 : Sound pressure spectrum in U(A) - flyover test - 2700 RPM, 144 kW

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