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# THEORETICAL AND EXPERIMENTAL STUDY OF HELICOPTER ROTOR NOISE

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## INTRODUCTION

ONERA takes part since several years in the study of external noise from civil helicopters which constitutes, even in the absence of well defined international standards, a determining factor for their use in urban zone and their sale in some countries.

An important research program is being developed with the Turboméca Company concerning the noise due to turboengines. The objective is obviously the reduction of noise emission, but also the prediction of acoustic levels so that these might be taken into account in the overall estimation of the noise of the complete helicopter. In particular a new test rig at Uzein, near Pau, South-West France, makes it possible to improve the acoustic characterization of turbomachines. Let us mention in particular the implementation of cross analyses either between microphones in near and far field or between probes placed inside the machine (e.g. in the combustion chamber or the ejection nozzle) and microphones outside : such techniques bring to light, for every regime (take-off, fly over, approach), the main sources radiating within a given angular sector.

The present paper deals with another aspect of activities on helicopters, carried out in close cooperation with the Aérospatiale Company, and concerning the main rotor. Two kinds of study are performed in parallel. On the one hand, theoretical models are developed for the prediction of acoustic spectra ; this method is also applied to propeller noise : for this it suffices to tilt the rotor axis 90° from the vertical, which leads to several simplifications in the equations used. On the other hand, tests are carried out in wind tunnels with a view to characterizing noise sources and improving blade profiles. Such measurements are very fruitful, as they make it possible to isolate the physical phenomenon on which attention should be drawn, but they have to be confirmed by flight tests. We shall insist here on the tests performed in 1981 at CEPr (Propulsion Test Centre), in the CEPRA 19 anechoic wind tunnel, in cooperation with the U.S. Army and the Aérospatiale Company.

## 1. THEORETICAL MODELS

### 1.1 Tone noise prediction

The method used consists in solving the wave equation through the intermediary of the Green function G ($\vec{y}$, $\tau$ ; $\vec{x}$, t), according to the formalism described by Goldstein [1] : G expresses the response, at point $\vec{x}$ and time t, to the emission at point $\vec{y}$ and time $\tau$. The sound pressure p at point $\vec{x}$ is expressed by the sum of three integrals :

$$p(\vec{x},t) = \int_T \int_{\mathcal{A}} \rho_0 \, V_n \, \frac{DG}{D\tau} \, d\vec{y} \cdot d\tau + \int_T \int_{\mathcal{A}} F_i \cdot \frac{\partial G}{\partial y_i} \, d\vec{y} \, d\tau + \int_T \int_{\mathcal{V}} T_{ij} \cdot \frac{\partial^2 G}{\partial y_i \, \partial y_j} \, d\vec{y} \, d\tau ,$$

where $\rho_0$ is the air density. The region in space where the functions to be integrated are non-zero defines the source volume $\mathcal{V}$, noted by the vectors $\vec{y}$. The first two terms are reduced to a surface integral, concerning only solid surface $\mathcal{A}$ , i.e. blades.

The interpretation of these three terms, already brought to light by Lowson and Ollerhead [2] from the Lighthill equation, is schematized on figure 1.

- The first is the thickness noise, due to the volume of air displaced by the blades, and usually classed as a source of monopolar type (although the convective derivative of G introduces spatial derivatives, of dipolar type) ; $V_n$ is the relative velocity component normal to the profile at each point.

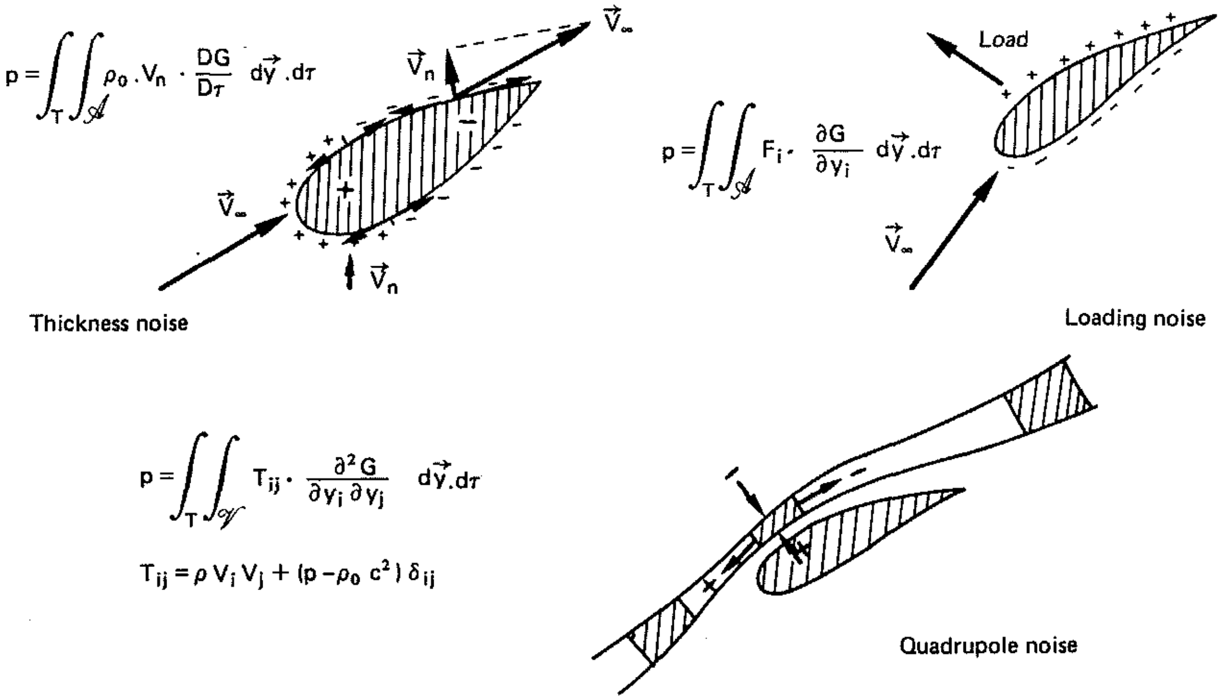


Fig. 1 — Pure tone noise sources on a rotor.

- The second is the loading noise, produced by the mean and fluctuating forces $\vec{F}$ exerted by the blades, and of dipolar type.

- The third is the noise attached to the tensor $\overline{\overline{T}}$, expressing the effect of the Reynolds stresses, of quadrupolar type.

This last term has not yet been taken into account, as it is negligible compared to the other two in subsonic regime. On the contrary, it becomes important when the Mach number of the advancing blade tip becomes transonic (see section 2.2).

The thickness noise evaluation requires only the knowledge of the blade geometric parameters and of the rotation and forward velocities. As for the loading noise, it is deduced from the forces on the blades. Up to now these were provided by calculation [3], but the number of load harmonics deduced from these charts is insufficient for a correct prediction of the level of acoustic tones of high order. The information collected by pressure transducers on the blades will allow an improvement of the quality of these predictions (see section 2.3).

### 1.2 Survey of previous results

The first two terms of the above equation are calculated, with the far field approximations, in the frequency domain, for the successive harmonics of the blade passing frequency. The complete equations are given in Ref. [4]. From the geometric and aerodynamic characteristics of the rotor, the acoustic spectrum is obtained as well as the temporal signature, by inverse Fourier transform. Let us notice that other calculation methods exist : in particular Farassat [5] integrates the equations directly in the time domain ; the directivity of the sound field is easily deduced, for instance in a horizontal or vertical plane. The results presented in Ref. [4] show that the thickness noise radiates principally forward of the rotor, with a dissymmetry between the advancing and the retreating blade sides, while the load generates higher levels laterally.

For their validation, these calculations must be compared with experiment.

We shall see in section 3 the exploitation of measurements in the anechoic wind tunnel. Before these tests were performed, we made use of flyover noise recorded by the Aérospatiale Company. In this case the formulas for the prediction should account for the relative motion between source and observer ($\vec{x}$ depends on t in a reference frame linked to the helicopter). The effect of interference between the direct wave and that reflected by the ground should also be included. Lastly, a special treatment of the signals provided by the microphones makes it possible to get free of the frequency shift by Doppler effect, and thus to follow the level of each tone during the whole flyover. The comparisons obtained this way are satisfactory [4] : the thickness noise dominates before overhead and the levels measured are well predicted. Elsewhere, the discrepancies may be attributed to a faulty prediction of the loading noise, because of the limited number of harmonics deduced from the force charts used (see end of section 1.1).

### 1.3 Approach to the study of broadband noise

Although the rotor tones dominate the spectra, the acoustic power of broadband noise contributes in a non-negligible manner to the overall level. Unfortunately the exact origin of this component is still poorly known : airframe noise, interaction between rotor and atmospheric turbulence [6], quadrupolar emission of blade wakes, diffraction of wake fluctuations by the trailing edge [7] or wall pressure fluctuations on the blades.

This last aspect has been investigated, as the boundary layer should have a rather important influence on the overall broadband noise. An experiment has been performed in the S3 Ch wind tunnel of ONERA, which presents the interest of reaching transonic Mach numbers. A fixed profile, equipped with pressure transducers, was mounted on the wall ; the measurement of fluctuating pressures constitutes a data bank for the acoustic source considered.

The synthesis of these measurements is made of a curve providing a reduced power spectral density as a function of the Strouhal number $S_t = f.\delta_1/V$, relative to the displacement thickness $\delta_1$ of the boundary layer. The important conclusion is brought to light that the evolutions in incompressible conditions (low velocities V, large $S_t$), similar to those published elsewhere, should not be extrapolated to the compressible domain (high V, small $S_t$). Finally, the Aérospatiale Company introduced these results for predicting the broadband noise level, and compared these modified predictions with experiment [8].

## 2. WIND TUNNEL STUDIES ON ROTORS

### 2.1 Objective of these researches

It is obviously very instructive to study precise phenomena on a wind tunnel model, on condition that the experiments be representative of what happens in flight. The research concerns more specially the configurations generating the worst nuisance, i e. those in which the noise has a very impulsive character [9], as its spectrum covers a broad frequency range.

This impulsivity may have two different causes :

- in fast flight, the Mach number of the advancing blade tip is high and the peak of thickness noise is very brief ;

- in descending flight, if a blade-vortex interaction occurs, this entails rapid force fluctuations which generate a harmonic-rich loading noise.

## 2.2 Study of transonic phenomena

It was already indicated in section 1.1 that noise prediction in these conditions should take into account the quadrupolar noise and the shock wave effect, which become important in some angular sectors of radiation.

At the present time, at ONERA, velocity charts are calculated around the advancing blade. The introduction of these data in a program of acoustic radiation is just beginning. Difficulties are due either to integral convergence problems around Mach one or to calculations of the velocity within a large enough source volume [10].

Studies of theoretical aerodynamics have been complemented by tests in the S2 Ch [11] and S1 MA wind tunnels of ONERA, with a view to improving rotor performance and to defining blade tip shapes reducing at best the supersonic pocket. The S2 Ch wind tunnel has a diameter of 3 metres, S1 MA one of 8 metres, which allows large models (4.2 m in diameter, Fig. 2). During such experiments, a few microphones were used to provide acoustic information. However, it should be remembered that these wind tunnels are of guided section type and that, up to now, no acoustic treatment was applied to their walls. So the interpretation of the noise measurements they allow is mainly oriented towards comparisons of various types of rotors operating in identical conditions.

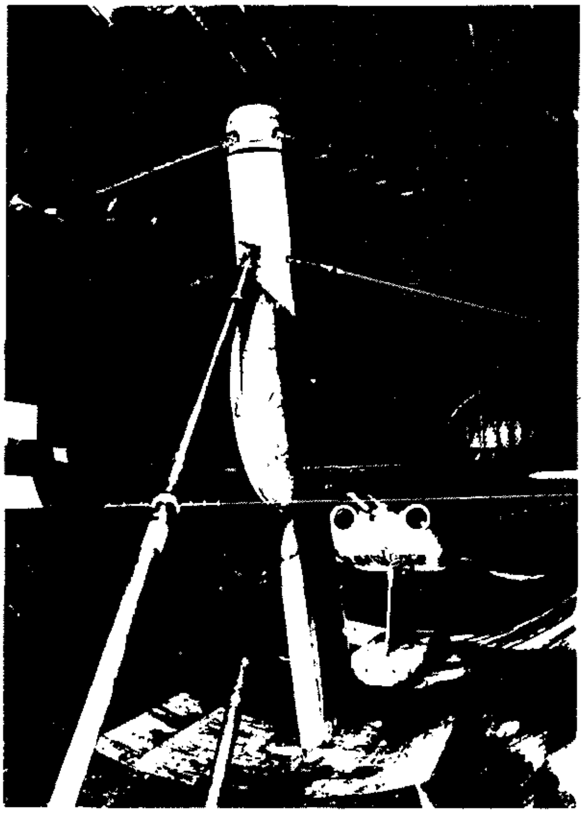


Fig. 2 – Test of Aérospatiale four-bladed model rotors, 4.20 meters in diameter, in S1MA wind tunnel (January-February 1981).

## 2.3 Study of blade-vortex interaction

This theme has been the object of in-depth experimental research in 1981 within the framework of a French-American M.O.U. (Memorandum of Understanding) on helicopter dynamics. Model of Aérospatiale four-bladed rotors and U.S. Army two-bladed rotors have been tested jointly by these organisms and ONERA.

The experiments took place in the CEPRA 19 wind tunnel (Fig. 3) of CEPr, at Orsay near Paris. It is made of an anechoic chamber of quarter-sphere shape, 9 metres in radius. The cut-off frequency is of the order of 200 Hz. The free jet is 12 m long. The nozzle used for these tests is 3 m in diameter, a dimension necessary for the rotor to be entirely within the potential core of the jet. The velocity can thus reach 60 m/s (with a 2-m convergent, the maximum value is 100 m/s).

The rotor test stand (Fig. 4) was that used at NASA Ames. Moreover, the U.S. Army studied also their rotor in 1982 in the DNW anechoic wind tunnel, in the Netherlands [12], in order to compare measurements made in two different test facilities.

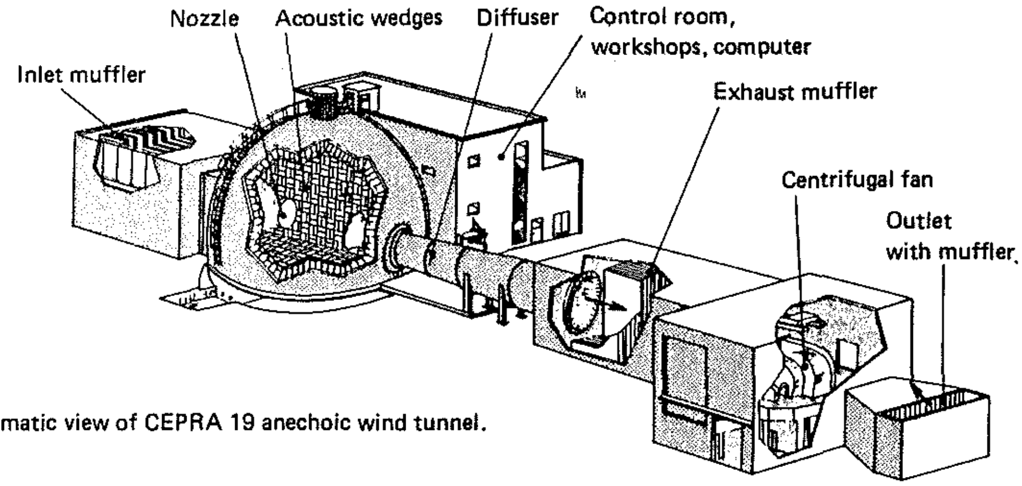


Fig. 3 – Schematic view of CEPRA 19 anechoic wind tunnel.

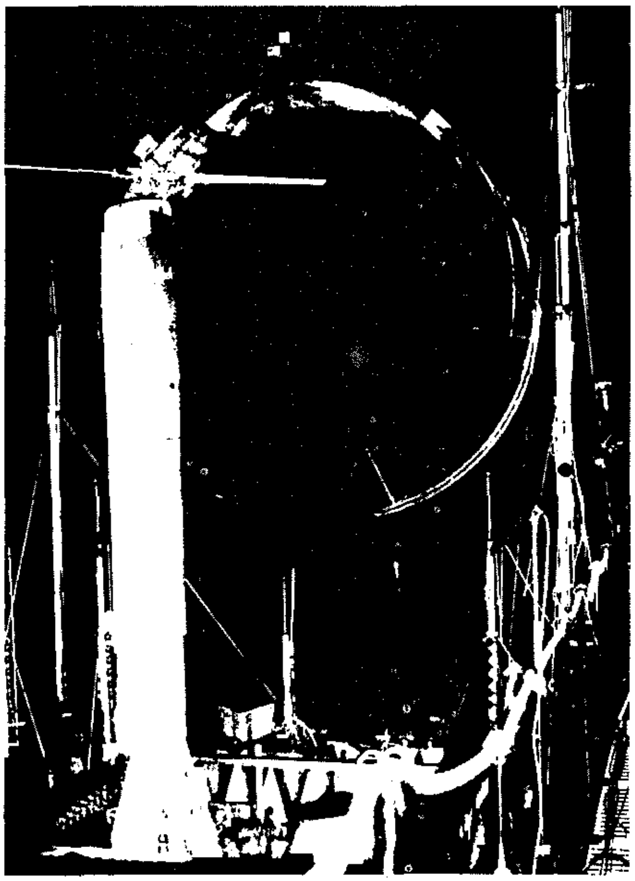
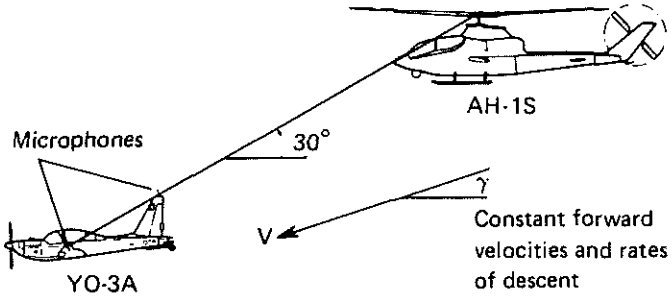


Fig. 4 – Test stand of the U.S. Army with 1/7 scale OLS model rotor, installed in CEPRA 19 anechoic wind tunnel.

The first objective of such a program is to know if the interaction phenomenon between blade and vortex can be correctly simulated on a wind tunnel model. To answer this question, the U.S. Army has available flight tests (Fig. 5) that they carried out with microphones installed on a silent aircraft followed by the helicopter [13, 14]. The second subject of interest is to know more precisely the characteristics of the blade-vortex interaction [15] and to predict the resulting noise [16]. To this end, one of the U.S. Army rotors is equipped with some fifty pressure transducers.

Fig. 5 – Full-scale blade-vortex interaction acoustic measurement technique.



Analysis of microphone signals makes it already possible to conclude as to the validity of wind tunnel simulation [17]. This first experiment with a helicopter rotor model in CEPRA 19 has also brought to light a number of problems raised by the use of this wind tunnel in these conditions. It seems easy to remedy them, and further studies are quite promising.

## 3. COMPARISON OF CALCULATED AND MEASURED THICKNESS NOISE

This last part is based on the experiment just described (section 2.3) as it actually makes it possible to study, more finely than by flyover recordings, the validity of the prediction program of tone noise (see section 1.2). As the exploitation of the signals of the blade-mounted pressure transducers has not yet been undertaken, we shall limit ourselves here to thickness noise.

### 3.1 Experimental conditions analysed

The following study concerns only the standard U.S. Army two-bladed rotor (B = 2), with straight tip (see Fig. 4). It is the 1/7 scale model of the AH-1G/OLS rotor.

Its diameter is D = 1.916 m. Thickness noise calculations are performed with a blade cross section area estimated at 7 $cm^2$. As it is constant all along the span, the sound pressure is simply proportional to it.

Although the installation comprises a moving microphone allowing the acoustic field exploration up to a distance of 6 m from the source, we preferred to use fifteen fixed microphones installed at 3.26 m from the rotor centre. Thus, the relative distance (1.7 D) is the same as in the U.S. Army flight tests [14]. Most of the microphones are located within the zones where the rotor emits most of the noise, i.e. upstream and in the disc plane or underneath (Fig. 6).

The four fundamental parameters to be maintained in the acoustic simulation are the following :

- the rotor tip Mach number $M_H = \pi DN/a$, where a is the speed of sound and N the rotation velocity, in rotations per second ;

- the advance ratio $\Lambda = V/(a.M_H)$, where V is the velocity of the incident flow ;

- the reduced thrust coefficient $C_T/\sigma$, $\sigma$ being the rotor solidity ;

- the angle of inclination $\alpha$ of the blade tip plane relative to the flow axis, related to the rate of climb R/C or of descent R/D of the helicopter.

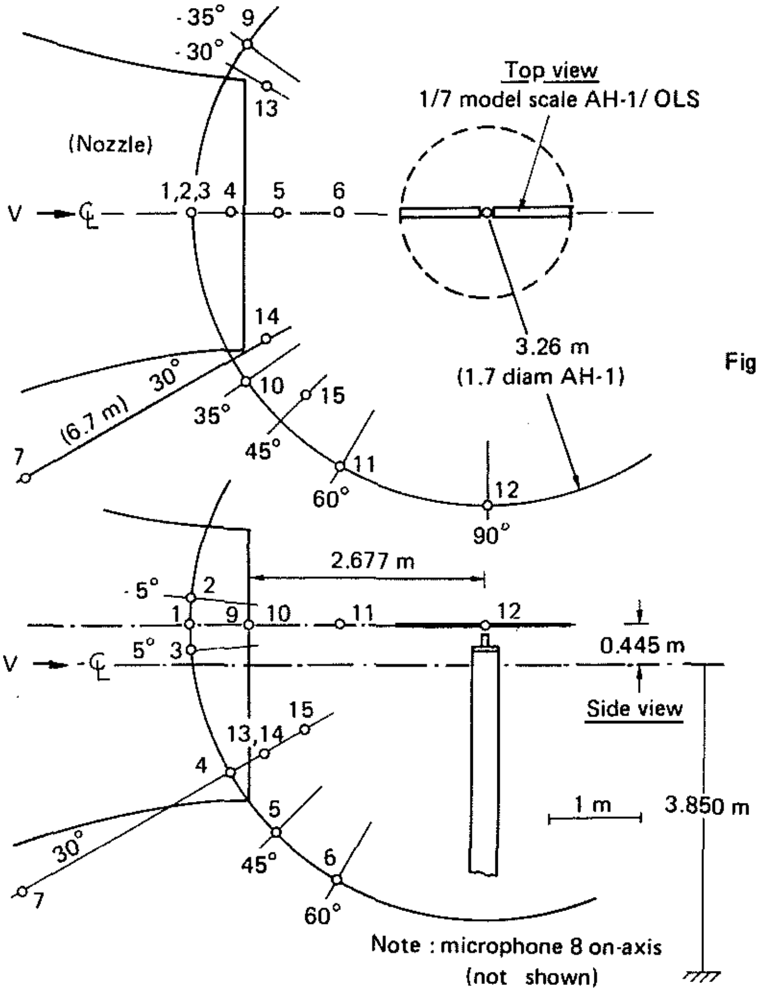


Fig. 6 — Location of rotor and microphones (initial configuration) in CEPRA 19 open jet wind tunnel.

Whereas these four parameters intervene in the phenomenon of blade-vortex interaction, only the first two are determining thickness noise. From these is deduced the advancing-tip Mach number $M_A = (1 + \Lambda).M_H$. The value of $M_A$ remains here sufficiently subsonic for it being legitimate to admit that the air compressibility effect does not modify too much the thickness noise (more details in section 3.3).

### 3.2 Comparison between calculation, wind tunnel and flight tests

The accent has been made in Ref. [17] on the microphone located upstream of the rotor, at 30° beneath the axis (n° 4 of figure 6), as it is in this zone that the blade-vortex interaction is most manifest. Figure 7 presents an example of temporal signatures over a rotation period T. The signals obtained in flight by the U.S. Army and in the wind tunnel are similar : for each of the two blades, the narrow positive peaks due to interaction with the vortices are followed by a wider negative hump corresponding to thickness noise.

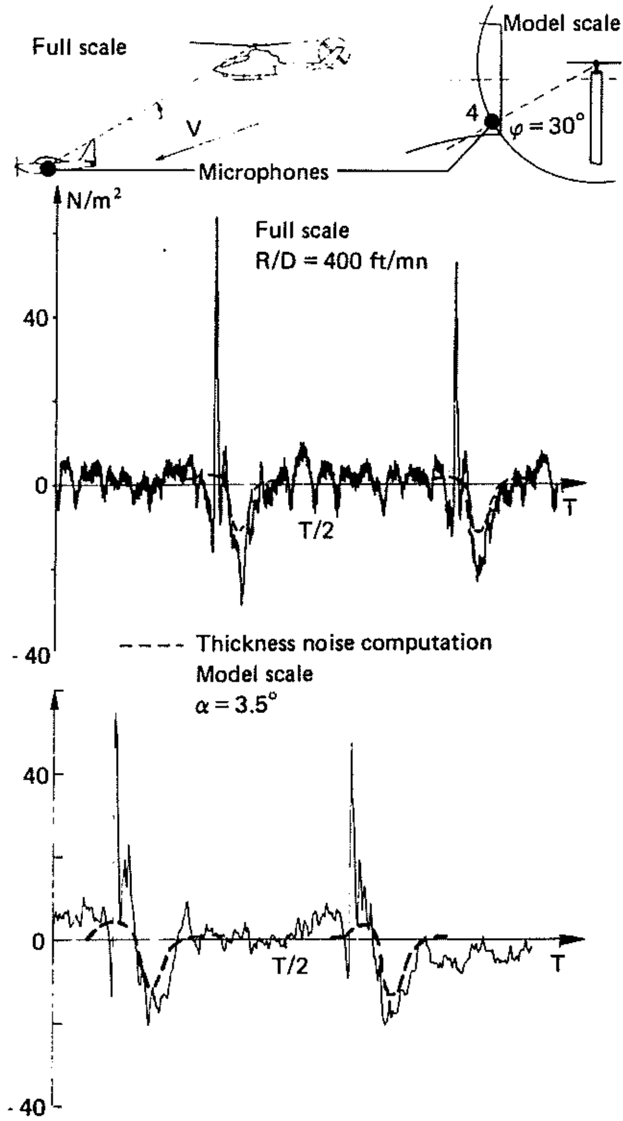


Fig. 7 — Comparison between full scale and model scale measurements (unveraged signals), and thickness noise computation : $M_H \simeq 0.664$ , $\Lambda \simeq 0.165$, $M_A \simeq 0.773$, ($C_T \simeq 0.0057$). Upstream microphone, 30° under the flow axis (N° 4 on figure 6).

The thickness noise calculation results are traced on the experimental curves, after adjustment of abscissa. The modulus of the peak value is slightly lower than in both measurements ; it should however be remembered that an error on the estimation of the blade cross section area is expressed by the same relative uncertainty on the theoretical sound pressure, which may account for small discrepancies. The shape of the signal is very informative : calculation represents well the flight measurement, while the wind tunnel one is wider. This comforts the presumption advanced in Ref. [17] : as the microphone considered had to be placed not in the anechoic chamber but in the nozzle, the signal is perturbed by reflections on the walls and by structural resonances. That is why acoustic treatment of the tunnel convergent should then be considered for future tests on helicopter rotors.

As thickness noise is maximum along the axis ahead of the rotor, it is interesting to examine also the corresponding microphone (n° 1 of figure 6). Figure 8 concerns the same conditions as before : we actually observe that this transducer records higher negative peaks, while interaction peaks are neatly smaller. Comparison between flight and model tests remains good, although the level measured in the wind tunnel are higher. This difference may be attributed to the fact that, during bench experiments, the hygrometric factor of the air was rather high ; there resulted some modifications in the sensitivity of the microphones located within the flow.

The calculation of thickness noise is again superposed to the negative peaks. The level found is slightly higher than in flight and somewhat lower than that obtained on model. This tends to confirm an overevaluation in the latter case. As for the signal shape, its width in particular, it is actually the same on the three curves. This results is important, as this parameter determines the abundance in the spectrum of high order harmonics, and thus have a direct impact on the nuisance produced.

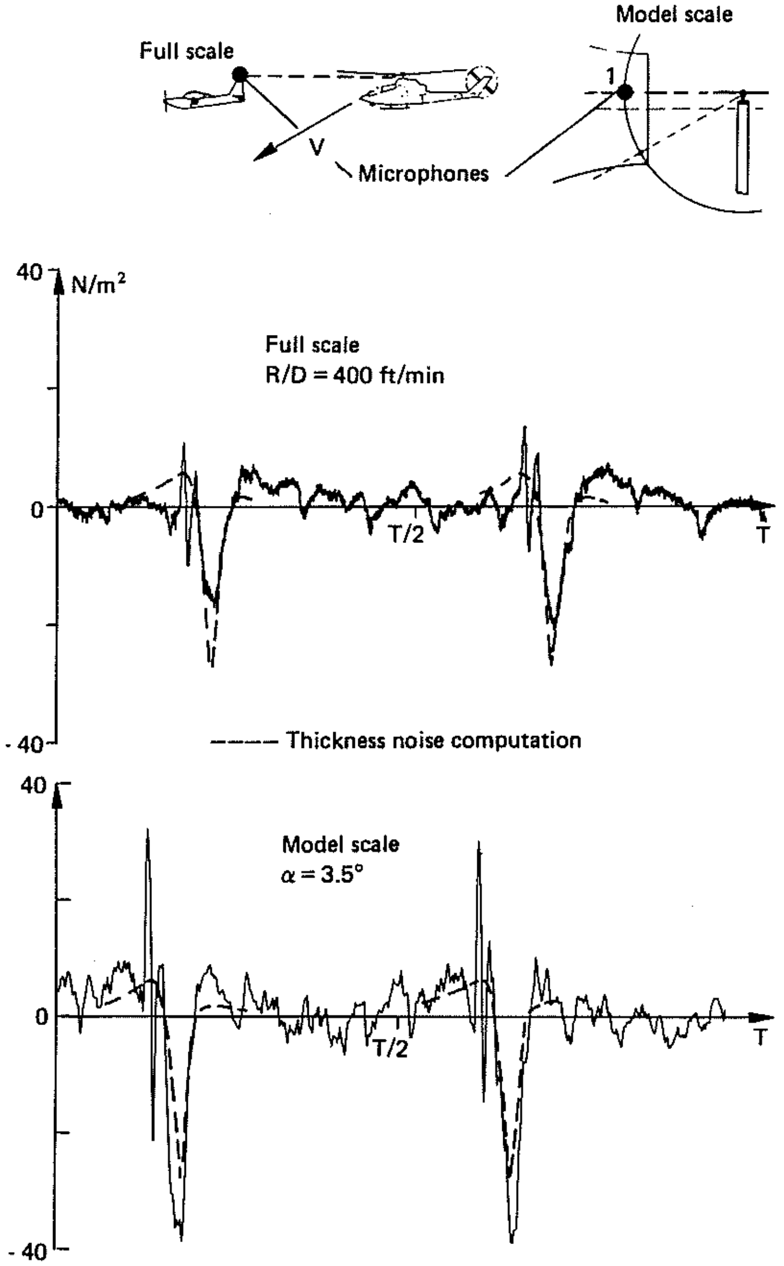


Fig. 8 – Comparison between full scale and model scale measurements (unveraged signals), and thickness noise computation : $M_H \simeq 0.664$, $\Lambda \simeq 0.165$, $M_A \simeq 0.773$, ($C_T \simeq 0.0057$). Upstream on-axis microphone (N° 1 on figure 6).

### 3.3 Evolution of thickness noise

The thickness noise directivity varies relatively little within a horizontal plane ahead of the rotor axis, as proved by both calculation and wind tunnel experiments. In the vertical plane containing the flow axis, it has already been mentioned that the maximum of emission is ahead of the rotor. Figure 9 presents the results on model, still for the same advance ratio ($\Lambda = 0.163$) but with a higher rotation speed ($M_H = 0.725$). Comparison with prediction shows again the effects already mentioned on microphones n° 1 and 4. At lower locations, measurement and calculation both show a neat reduction of thickness noise.

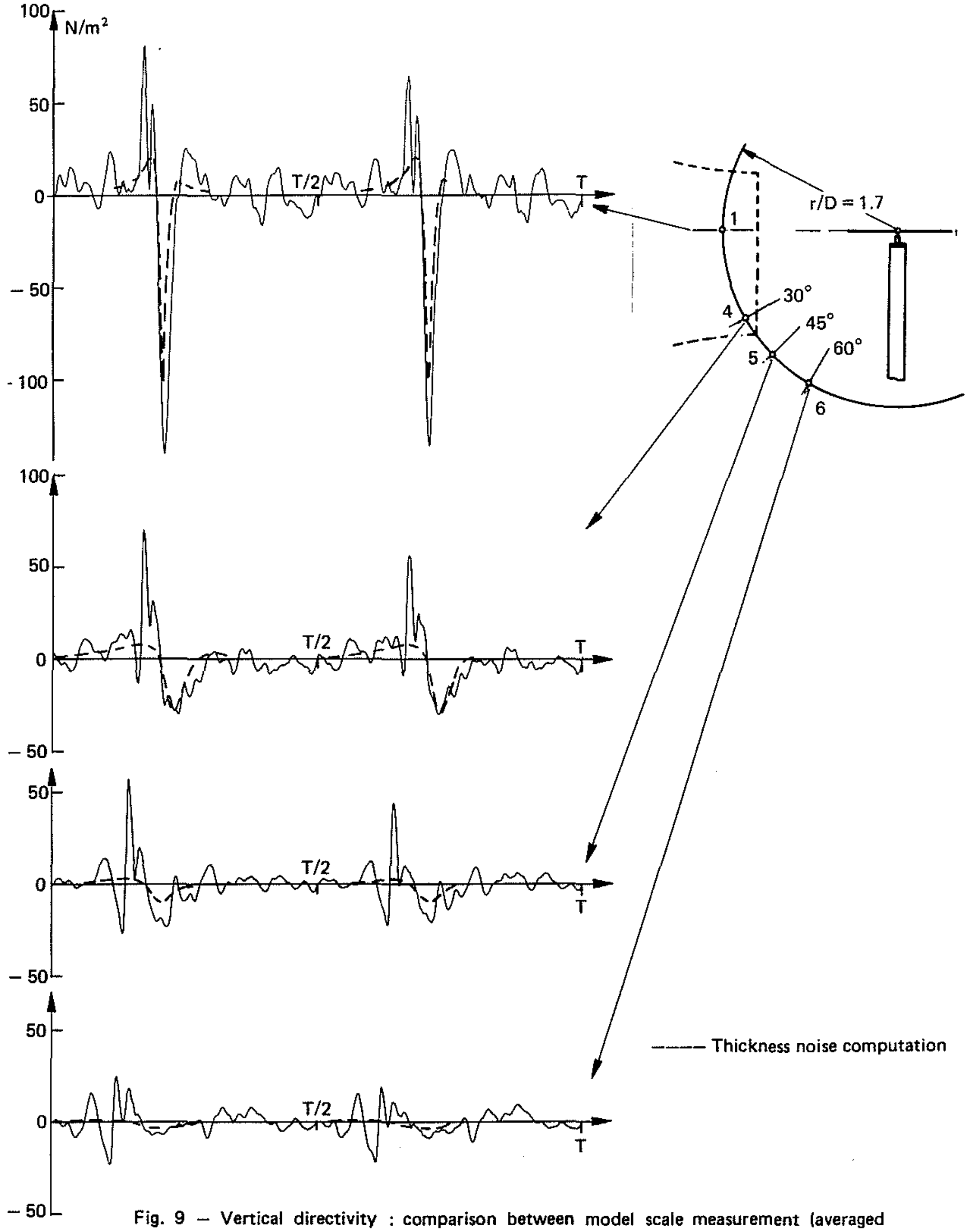


Fig. 9 – Vertical directivity : comparison between model scale measurement (averaged signals) and thickness noise computation; $M_H = 0.725$, $\Lambda = 0.163$, $M_A = 0.843$, ($C_T = 0.0056$, $\alpha = 3.5°$).

Furthermore, figure 10 sums up various conditions of rotation speed ($M_H \simeq 0.620$, $0.664$ and $0.725$) and of advance ratio ($\Lambda \simeq 0.130$, $0.164$ and $0.195$). The results concern the emission ahead of the rotor (location of microphone n° 1 on figure 6). The values found, for the maximum level of the negative impulse as well as for the width of the base of this peak), make up a single curve as a function of advancing blade tip Mach number $M_A = (1 + \Lambda).M_H$, which thus appears as the fundamental parameter of thickness noise.

The peak value increases with $M_A$ (Fig. 10 a). Calculation gives a correct estimate of the U.S. Army flight experiments, with a slight overevaluation, increasing with $M_A$ : this discrepancy may be attributed to the effect of air compressibility. We find again, as on the example of figure 8, a noticeably higher level on microphone n° 1 of the wind tunnel. However, the measurements of microphones n° 2 and 3, located only 5° above and beneath the former one (see Fig. 6), are closer to calculation. As for the peak duration (Fig. 10 b), it decreases when $M_A$ increases, which means that the sound emission presents a more and more impulsive character. Prediction is very close to measurement (see Fig. 8), with however a tendency to provide a longer duration.

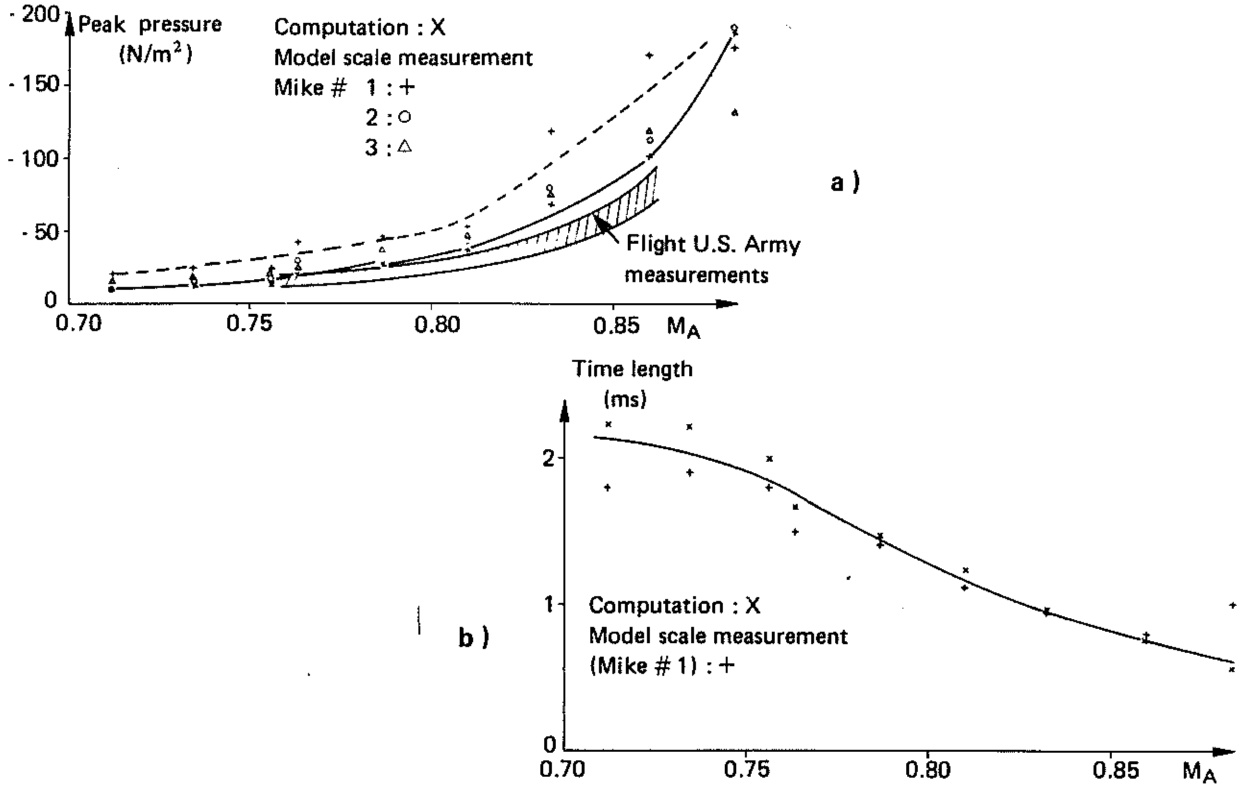


Fig. 10 — Comparison between thickness noise computation and measurement, as a function of the advancing-tip Mach number : $M_H \simeq 0.620$, $0.664$ and $0.725$ ; $\Lambda \simeq 0.130$, $0.164$ and $0.195$. a) Peak pressure of the negative pulses ; b) Time length of the negative pulses.

This temporal evolution has a direct impact on the spectra shape. Figure 11 concerns the medium advance ratio $\Lambda \simeq 0.164$, with three different rotation Mach numbers : this choice results from the fact that $M_A = (1 + \Lambda).M_H$ is proportional to $M_H$ and varies more slowly with $\Lambda$. The abscissa is graded in reduced frequency f/N and the acoustic tones are harmonics of the blade passage frequency B.N = 2N. The calculation of the envelope of thickness noise spectra clearly shows that the maximum is displaced towards the harmonics of higher order, and that the decrease becomes slower and slower when the rotation frequency N, hence $M_H$, increases. The wind tunnel measurement by microphone n° 2 (see Fig. 6) confirms very well this tendency. The spectrum part at a higher frequency may be essentially attributed to the very narrow impulses due to blade vortex interaction.

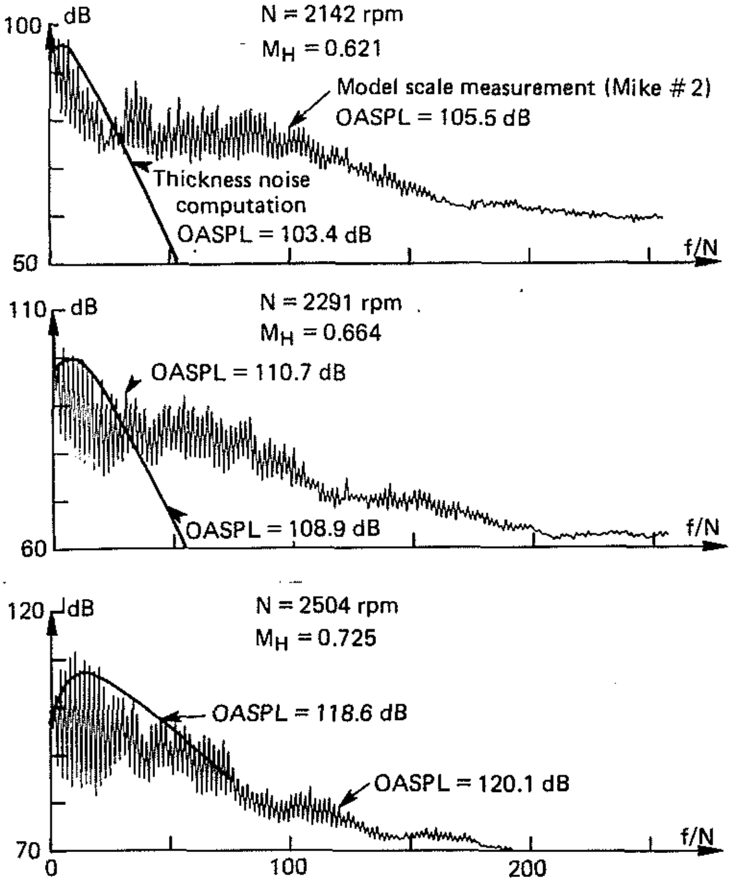


Fig. 11 – Spectral shape of the acoustic signal for $\Lambda \simeq 0.164$ and different rotor tip Mach numbers $M_H$.

Consequently, the increase of $M_H$, or more generally of $M_A$, entails, as regards thickness noise, on the one hand a level increase and on the other hand an increased role of high frequencies (so much so as the frequency of a harmonic of a given order is proportional to N or $M_H$). This latter effect adds up to the former one to provoke a still more important acoustic nuisance (in dBA for instance).

## CONCLUSION

In this paper we attempted to describe the present state of theoretical and experimental studies concerning helicopter rotor noise, as carried out at ONERA. It appears that the acoustic phenomena related to transonic velocities on the advancing blade tip are not yet modelled in a satisfactory manner.

For the subsonic domain, we have at our disposal an important campaign performed in 1981 in the CEPRA 19 anechoic wind tunnel. Recordings taken with the U.S. Army rotor model equipped with pressure transducers make it possible to better characterize the blade-vortex interaction, to verify the validity or to improve the precision of present-day calculations for predicting loading noise.

Analyses performed up to now already showed that the effects observed in flight can be correctly simulated on model. We particularly insisted here on comparing thickness noise calculations with U.S. Army flight measurements and anechoic wind tunnel tests. There results that this term is well predicted, as regards both absolute levels and shapes of the impulses, hence their spectrum : these are the two pieces of information essential for characterizing acoustic nuisance.

Moreover, this work confirmed some lack of precision in the measurements performed in the wind tunnel, inherent to the fact that it was the first time that CEPRA 19 was used for studies of helicopter rotor noise. Thanks to the remedies suggested we may expect that this test facitlity, equipped with the rotor bench under construction at the Aérospatiale Company, will be a very fruitful tool for further research.

## ACKNOWLEDGEMENTS

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