EXPERIMENTAL STUDY OF HIGH-SPEED IMPULSIVE ROTOR NOISE IN A WIND TUNNEL

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Abstract

This paper presents high-speed impulsive (HSI) noise measurements performed in ONERA S2Ch acoustically lined wind tunnel on two non-instrumented model rotors, the first one with rectangular blades, the other one with 30 deg. sweptback tips named F30. Typical results, parametric variations and comparisons between the two rotors are presented. F30 provides an important noise reduction in the direction of maximum HSI noise radiation by delaying delocalization towards higher tip speeds. Correlations with theoretical and past experimental aerodynamic results help interpreting this gain as a consequence of a decrease in transonic effects brought by the blade sweep.

In view of future acoustic optimization, emphasis is laid on the influence of geometrical parameters on noise. Previous studies have shown that the tip shape governs the appearance and intensity of delocalization, this is illustrated by the present results. A less known aspect of the problem is that the tip geometry may influence deeply noise radiation through modifications of the shock surface geometry. Some theoretical results which document the particular influence of varying the shock curvature are provided.

Notations

c :blade chord
M_{AT}:advancing tip Mach number
M_D :delocalization tip Mach number
M_H :hover tip Mach number
M_r :component of the Mach number of a moving source in the direction of the observer (Fig. 16)
R :rotor radius
N_g :overall sound pressure level
ΔM:increment for isomach mappings
Δt :time delay for noise reception (Fig. 18)
μ :advance ratio
ψ :azimuth angle (0 deg. corresponds to downstream direction).

Introduction

The extension of the flight domain of helicopters towards increasing advancing speeds comes up against an increase in main rotor noise as soon as shocks radiate from the vicinity of the blades to the far field, a phenomenon called delocalization. An intense research effort has been accomplished during the last decade to better understand acoustic phenomenons, and improve noise prediction in view of designing quieter rotors. Restricting our field of interest to high-speed impulsive (HSI) helicopter noise, we recall that the main rotor was recognized as the most important source of noise thanks to pioneer tests (Ref. 1). The dominant part played by quadrupole sources in the transonic regime was firstly demonstrated on propellers (Ref. 2), then on helicopter rotors, with the first theoretical noise predictions (Ref. 3). In this last study, the concept of delocalization was defined and a delocalization criterium based on the coalescence of the inner and outer supersonic regions of the fluid relatively to the moving blade was validated, at least for hover.

This work was followed by semi-empirical predictions (Ref. 4) and an early aerodynamic/acoustic optimization (Ref. 5), both based on an extension to forward flight of the aforementioned delocalization criterium. Theoretical efforts were pursued with HSI noise predictions in hover (Refs. 6, 7), investigations on the detailed structure of quadrupole source distribution (Ref. 8), studies of the effect of the shock geometry on noise radiation (Refs. 9, 10), and improvements of aerodynamic calculations to provide acoustic codes with more precise input data (Ref. 11).

In parallel with theoretical work, an intense experimental research effort was undertaken with extensive aerodynamic and acoustic wind tunnel tests (Refs. 12-17) in view of the validation of existing or future prediction codes.

This paper presents noise measurements that have been obtained in ONERA S2Ch wind-tunnel, fitted with acoustic lining, on two non-instrumented model rotors (extensively tested in the past in pressure-instrumented versions (Ref. 18)), one with rectangular tips, the other one with 30 deg. sweptback ones named F30.

The objectives of the test have been twofold:

- to provide a database for future prediction code validations (though the wind tunnel is not truly anechoic);

- to investigate the occurence of delocalization and verify if the criterium (Ref. 3) validated for hover can be extended to forward flight.

In the following sections, the experimental design is first described, then typical results, parametric variation of noise and comparisons between the two rotors are presented. Correlations between experiment and prediction of delocalization using a Transonic Small Disturbance (TSD) code are also shown.

A final discussion emphasizes the importance of geometrical parameters on noise. It is known that the blade tip shape influences the delocalization tip Mach number (above which delocalization occurs). A less known effect may be that it affects, in a certain extent, the external shock curvature in presence of delocalization: a few analytical results taken from Ref. 9 show the extreme dependence of noise on this parameter.

Experimental design

Wind tunnel

The tests have been performed in the ONERA S2Ch wind tunnel fitted with (removable) acoustic lining (Fig. 1). The diameter of the test section is 3 meters, the maximum wind speed that can be achieved is 110 m/s without lining and 95 m/s with the lining.

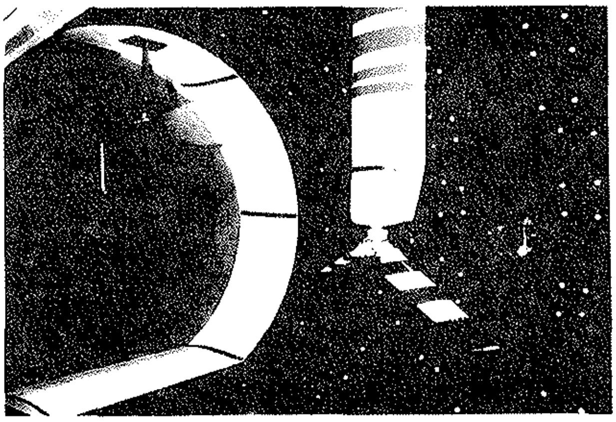


Fig.1 Acoustic tests in S2-Ch wind tunnel on a high-speed non-lifting rotor.

Model rotor

The rotor used is a two-bladed rotor of the Aerodynamic Department of ONERA on which extensive local pressure measurements were performed in the past (Ref. 18). The instrumentation has not been reconditioned for the present campaign.

The rotor is stiff, untwisted, with symmetrical NACA profiles and with removable tips. Two kinds of tips have been successively employed: straight and 30 deg. sweptback, named F30 (Fig. 2) with the same chord and absolute thickness at their extremity (note that the swept part of F30 represents, along the span, 1.3 tip chord length). The diameter of the rotor is 1.50 m when it is equipped with rectangular tips, 1.67 m when it is equipped with F30 tips. In order to compare transonic effects between the two kinds of blades, the rotors have been tested at similar tip Mach numbers.

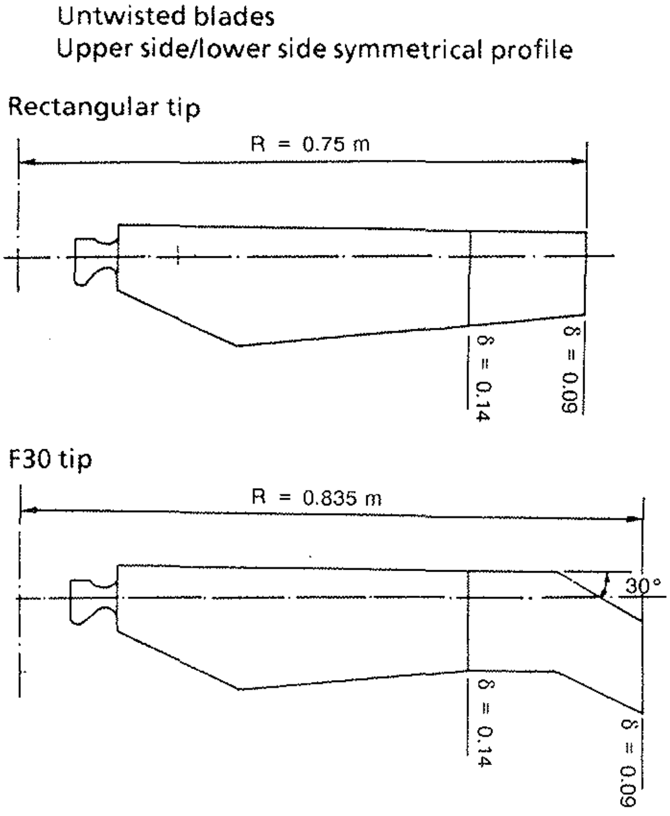


Fig.2 Blade planforms of the two-bladed non-lifting rotor.

High-speed impulsive noise is maximum upstream of the rotor, near the rotation plane. It is essentially composed of a quadrupole term (related to the shock created on the advancing blade tip) and a thickness one. A weaker component is due to the loading. In order to minimize this term and also to simplify aerodynamic calculations, the tests have been performed at zero lift, the rotor axis is then kept vertical.

Parameters M_{AT}, M_H, μ covered the following ranges:
M_{AT} :0.78 to 0.91
M_H :0.55 to 0.65
μ :0.35 to 0.45.

Acoustic instrumentation

The experimental set-up is shown in Fig. 3. It consists of 1/2 inch (1.27 cm) Bruël and Kjaer microphones. Two microphones (Nos 5 and 6) are fitted with nose cones and mounted on struts facing the wind, upstream of the rotor, to detect delocalized shocks. The other microphones are mounted flush with the acoustic lining.

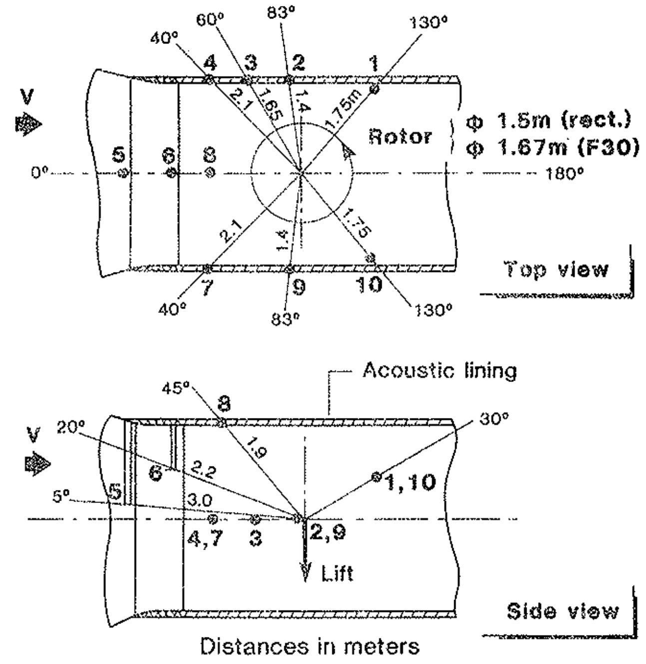


Fig.3 Experimental set-up for high-speed rotor tests in S2-Ch wind tunnel: microphones are flush-mounted except 5 and 6, mounted on struts.

Signal processing

In order to assess discrete frequencies which essentially compose the high-speed impulsive noise spectrum, microphone signals are processed in synchronization with the rotation of the rotor shaft. A sampling frequency of 512 per rev. (about 20 kHz) is selected for on-line processing. The sampling rate is increased up to 1024 per rev. for the most impulsive cases.

The processing is the following. First, an ensemble average is taken of 100 elementary signatures. Next, the spectrum of the averaged signal (coherent spectrum) and overall sound pressure levels (OASPL) are calculated in dB and dBA. dBA levels are scaled to a full-scale, 12 meters in diameter, rotor.

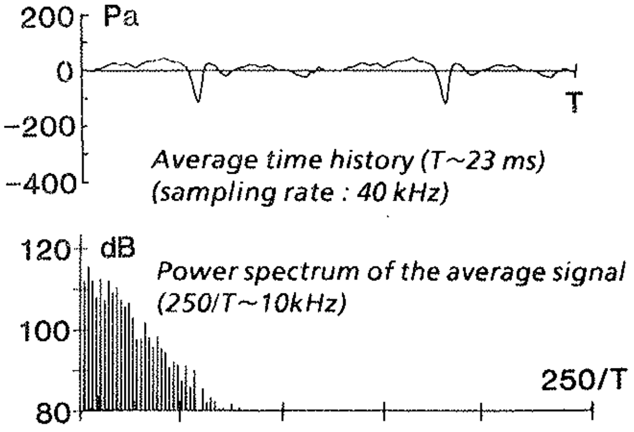
Experimental results

Detection of delocalized shocks

On a transonic rotor, a supersonic fluid pocket develops on the advancing tip, starting from a certain azimuth. A shock appears which moves towards the leading edge as the azimuth increases, then moves back and finally disappears on the retreating blade. As long as the shock remains attached to the blade (localized), the radiated noise (which increases with M_{AT} and with the thickness of the blade outer sections) is essentially thickness noise. It is known that the noise changes in nature at the delocalization tip Mach number M_D (function of μ and of the blade geometry), above which shocks radiate from the vicinity of the blade tip towards the upstream direction causing intense impulsive noise.

Typical results of Fig. 4, relative to microphone 5, located upstream of the rotor, illustrate this phenomenon. In delocalization conditions (Fig. 4b), a steep recompression peak can be seen in the signature, associated with an enrichment of the spectrum in higher harmonics as compared with the non-delocalized case (Fig. 4a). A comparison with Fig. 5, relative to microphone 4, lateral and flush-mounted, shows the extreme directivity of shock radiation: delocalization is indeed easily detected by microphone 5 and not by microphone 4.

a) no delocalization : $M_{AT} = 0.872$, $\mu = 0.364$



b) delocalization : $M_{AT} = 0.911$, $\mu = 0.396$

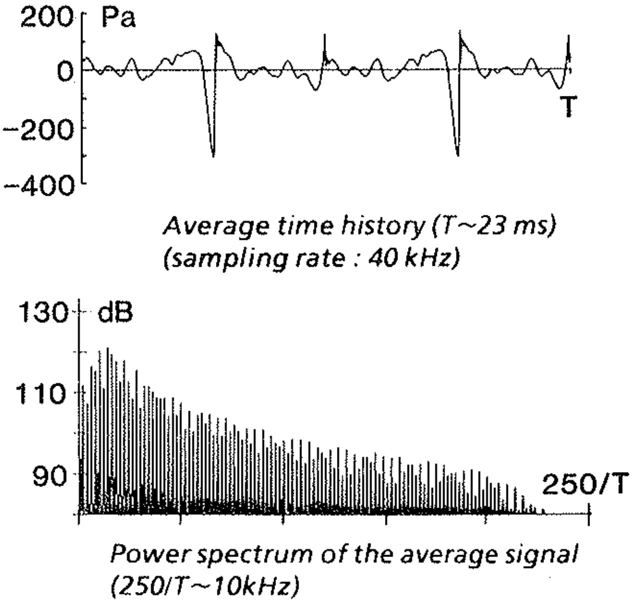
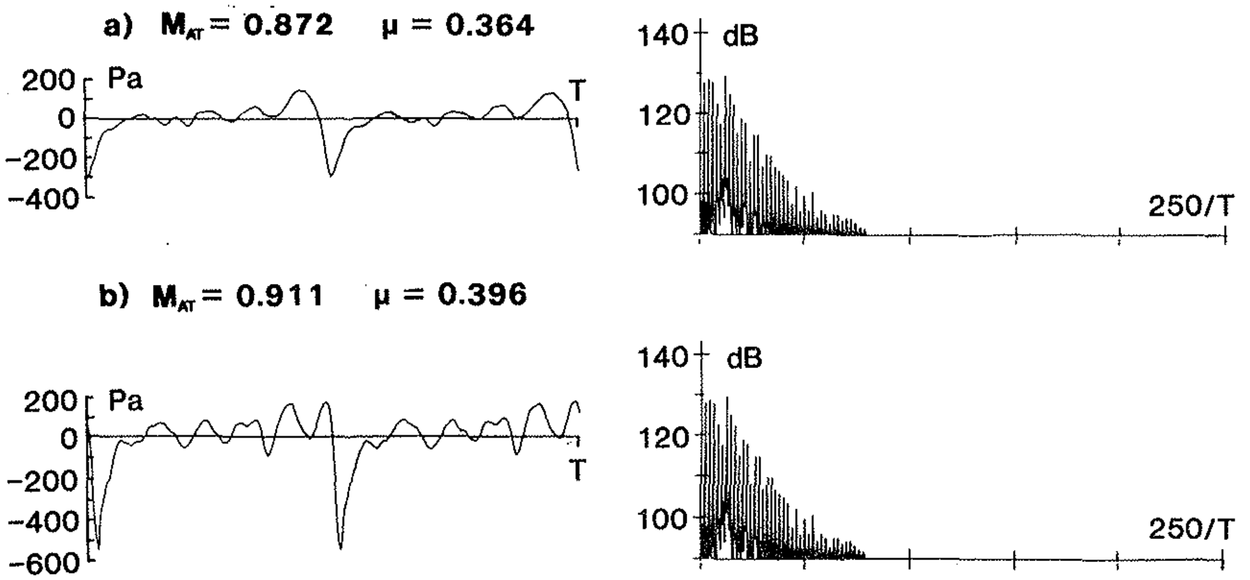


Fig.4 Typical results: F30 tips, microphone # 5.



Averaged time history (T~23ms) (sampling rate 20kHz)

Power spectrum of the averaged signal (250/T~10kHz)

Fig.5 Typical results: F30 tips, microphone # 4.

<u>Noise level comparison between the two rotors and parametric variations</u>

A comparison in dBA noise level between straight and F30 blades is presented in Fig. 6 (microphone 5) and Fig. 7 (microphone 4). Levels from Fig. 7 should be reduced by approximately 3 dB to correspond to the same distance from the center of rotation as microphone 5 (3 meters). This comparison clearly shows the advantage of F30 tip (though not of an optimized advanced design) over the straight one, in the forward direction where lies the maximum of directivity of high-speed impulsive noise. A noise reduction of 6 dBA is obtained in this direction at the highest Mach number values, when shocks are radiated. At the lowest values of M_{AT}, the observed gain mainly corresponds to thickness noise; no gain can be noted in the lateral direction (Fig. 7) due to directivity effects.

<u>Study of the beginning of delocalization</u>

A comparison of the start of delocalization between the two types of blades can be made from Figs. 8 and 9 which show, respectively for the straight and F30 tips, the instantaneous time signatures and coherent spectra for increasing values of M_{AT} and for an advance ratio of 0.4.

The increase in negative peak amplitude, the appearance of a positive recompression peak and the enrichment of the power density spectrum in high frequencies noticed in Fig. 8c show that, for M_{AT} = 0.890, delocalization is established on the rectangular blades while it is just beginning on the swept ones (Fig. 9c).

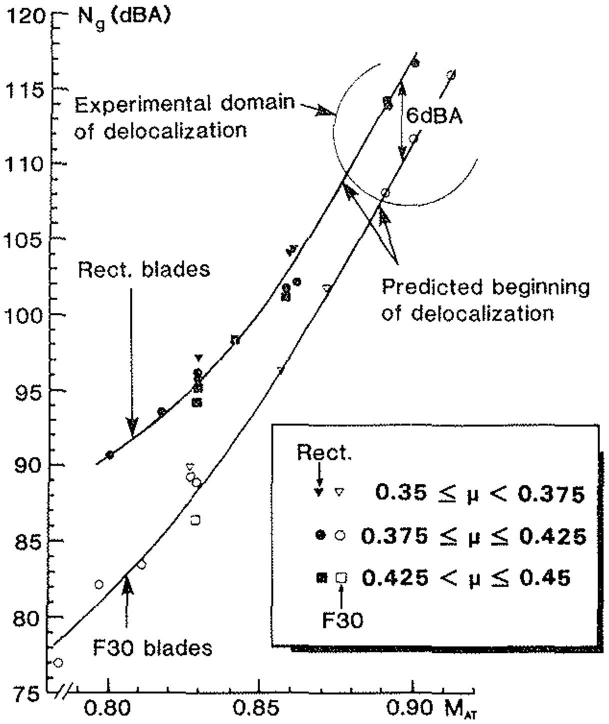


Fig.6 High-speed impulsive noise level (scaled to a full-scale rotor) versus advancing tip Mach number: S2-Ch, microphone # 5.

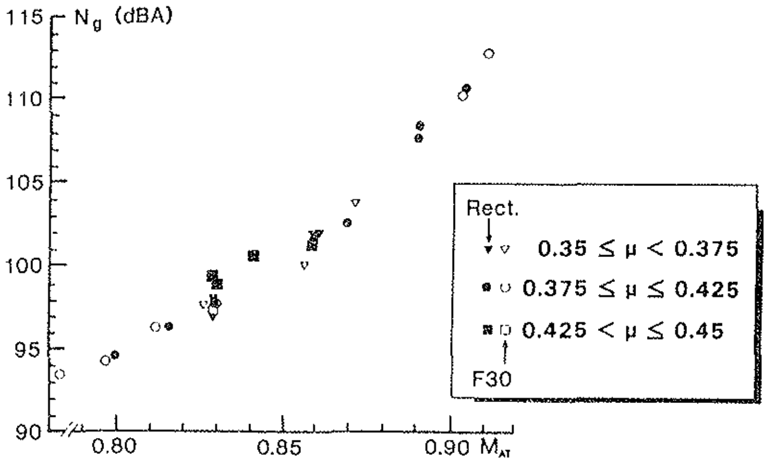


Fig.7 High-speed impulsive noise level (scaled to a full-scale rotor) versus advancing tip Mach number: S2-Ch, microphone # 4.

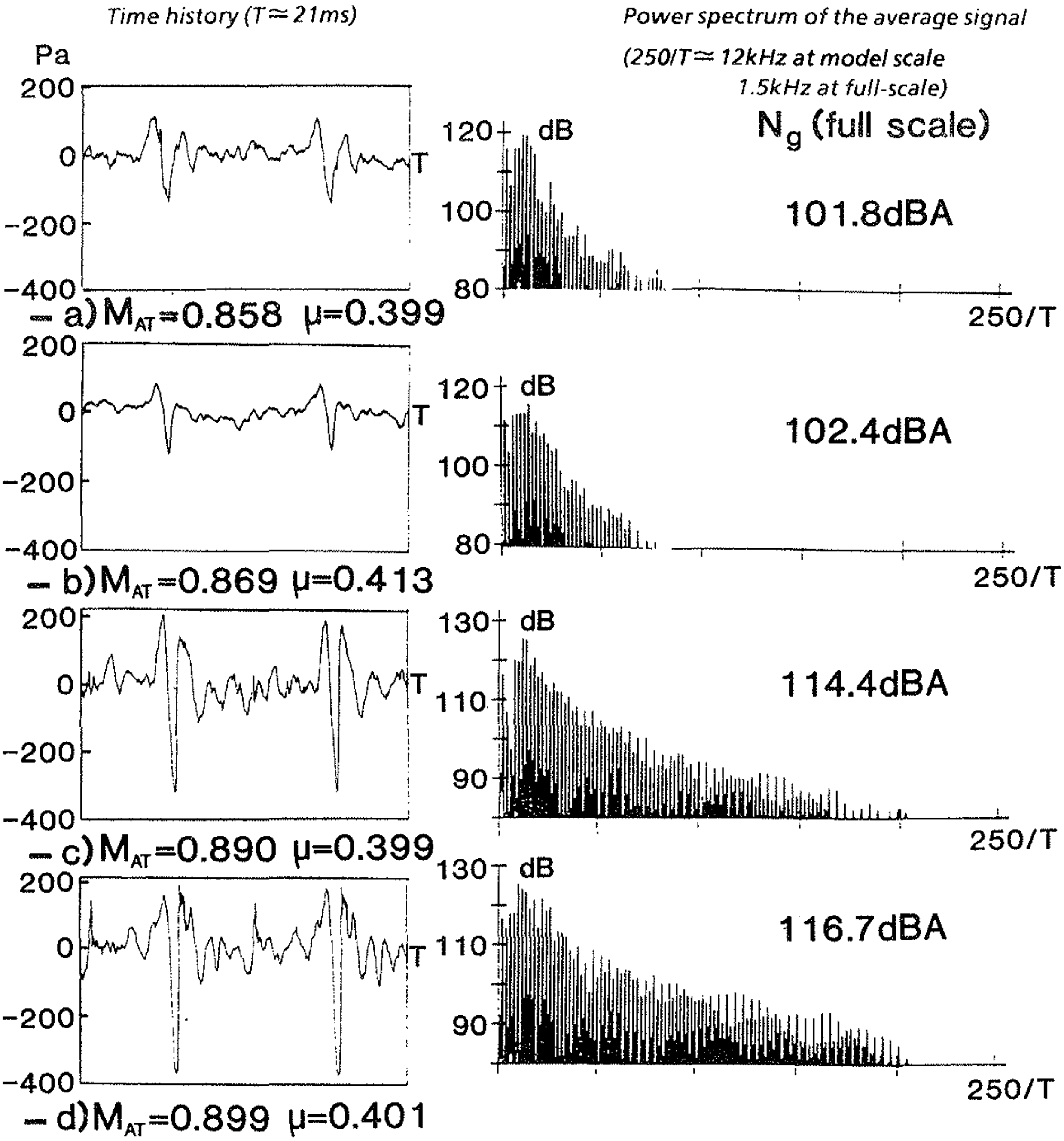


Fig.8 Evolution of experimental results for increasing advancing tip Mach numbers, showing occurence of delocalization (microphone # 5, straight blades).

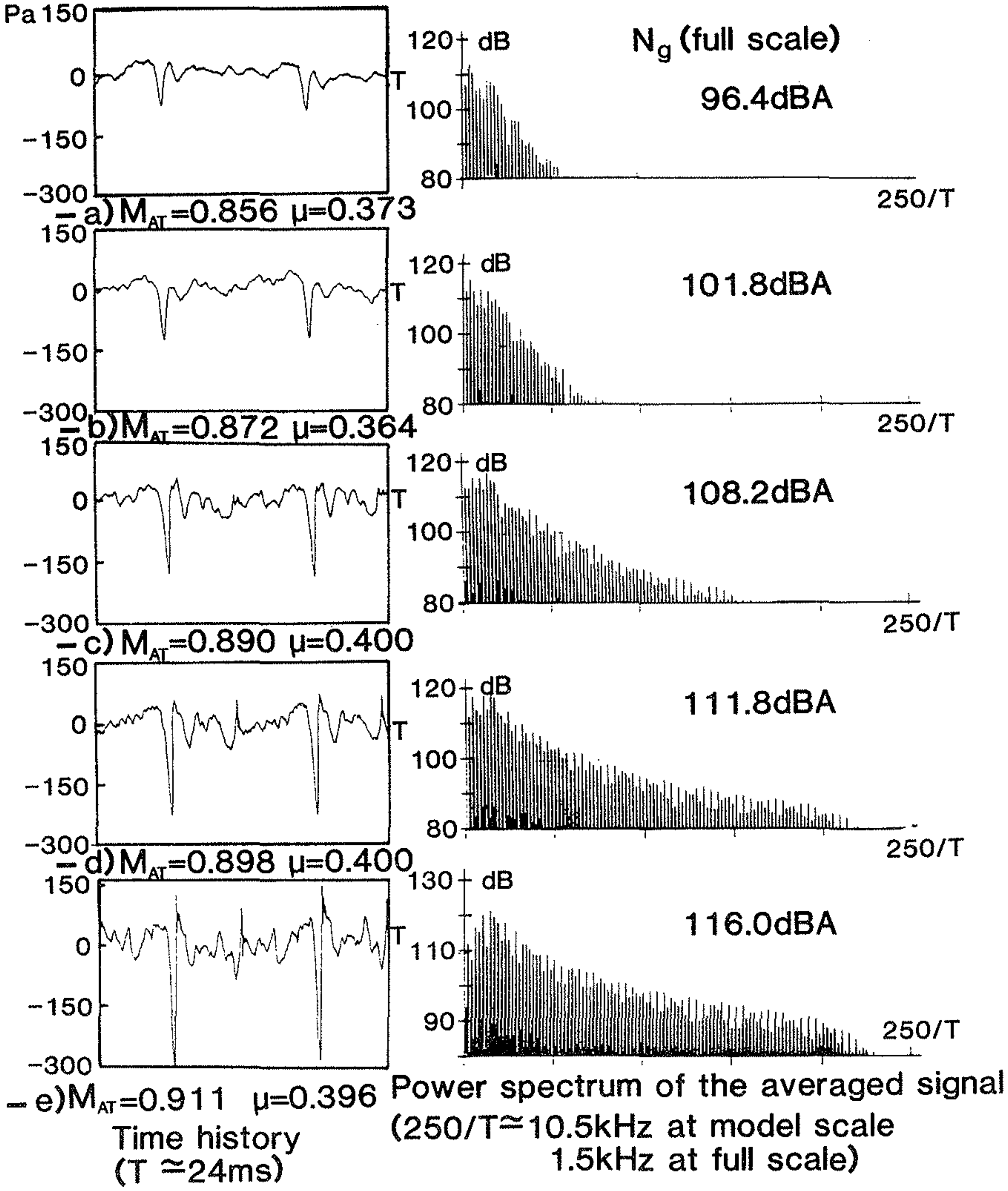


Fig.9 Evolution of experimental results for increasing advancing tip Mach numbers, showing occurence of delocalization (microphone # 5, F30 blades).

Correlation with theory and discussion

Study of the beginning of delocalization

Keeping in mind the delocalization criterium for hover (Ref. 3), we study the respective extensions of the inner and outer (relatively to the blade) supersonic fluid regions. Figs. 10 to 15 show, for different azimuth angles, isomach mappings obtained, in the blade frame of reference, by running the 3D unsteady TSD code of the Aerodynamics Department of ONERA.

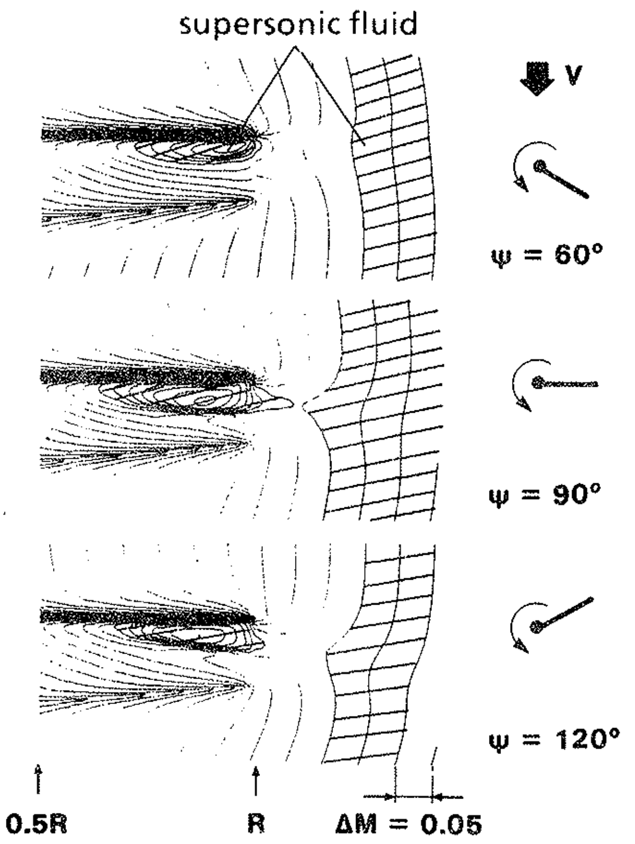


Fig.10 TSD predicted isomach-lines: straight blades, $M_{AT} = 0.875$, $\mu = 0.4$.

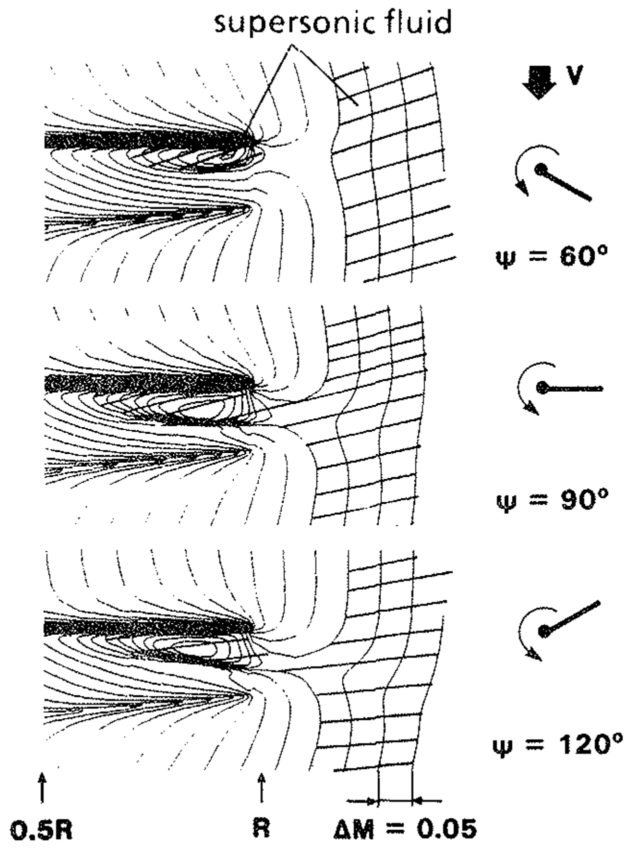


Fig.12 TSD predicted isomach-lines: straight blades, $M_{AT} = 0.890$, $\mu = 0.4$.

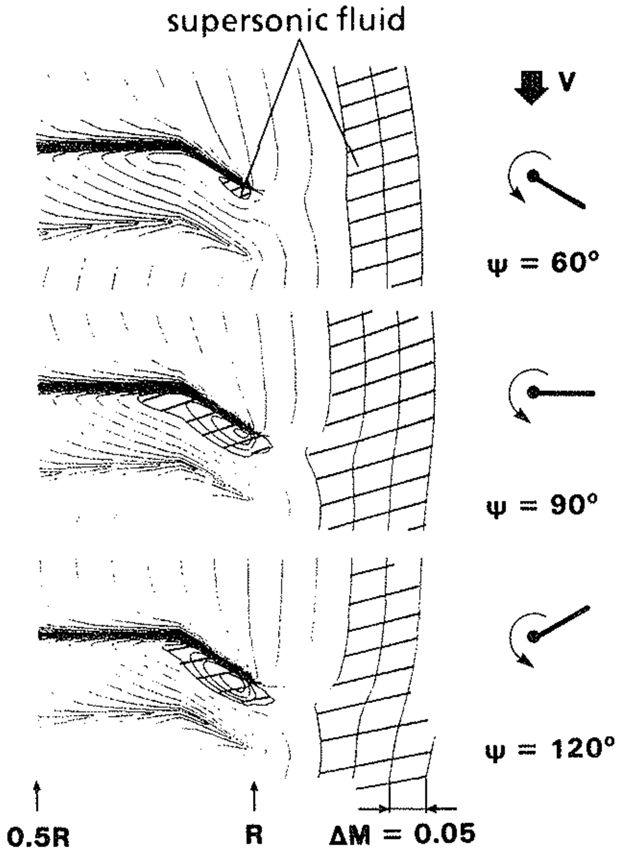


Fig.11 TSD predicted isomach-lines: swept blades (F30), $M_{AT} = 0.885$, $\mu = 0.4$.

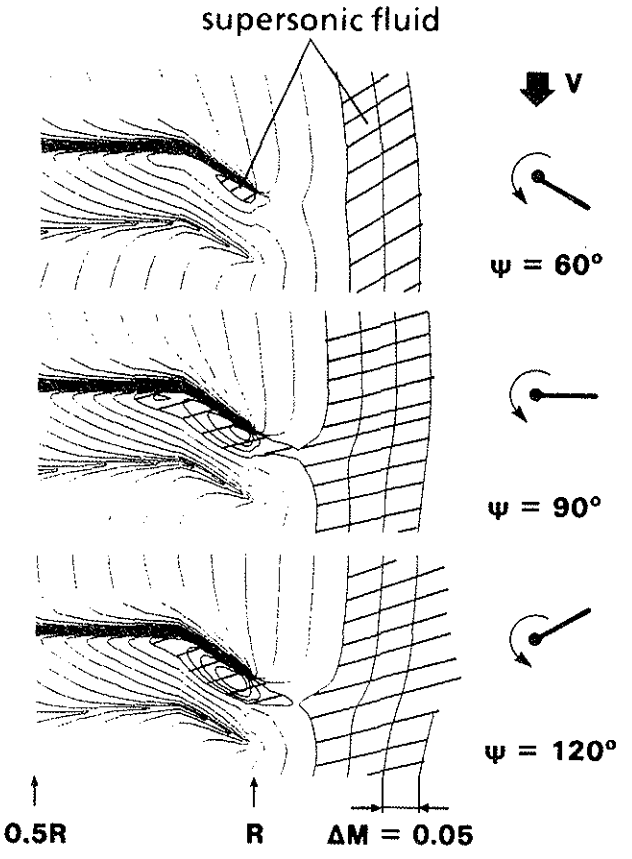


Fig.13 TSD predicted isomach-lines: swept blades (F30), $M_{AT} = 0.890$, $\mu = 0.4$.

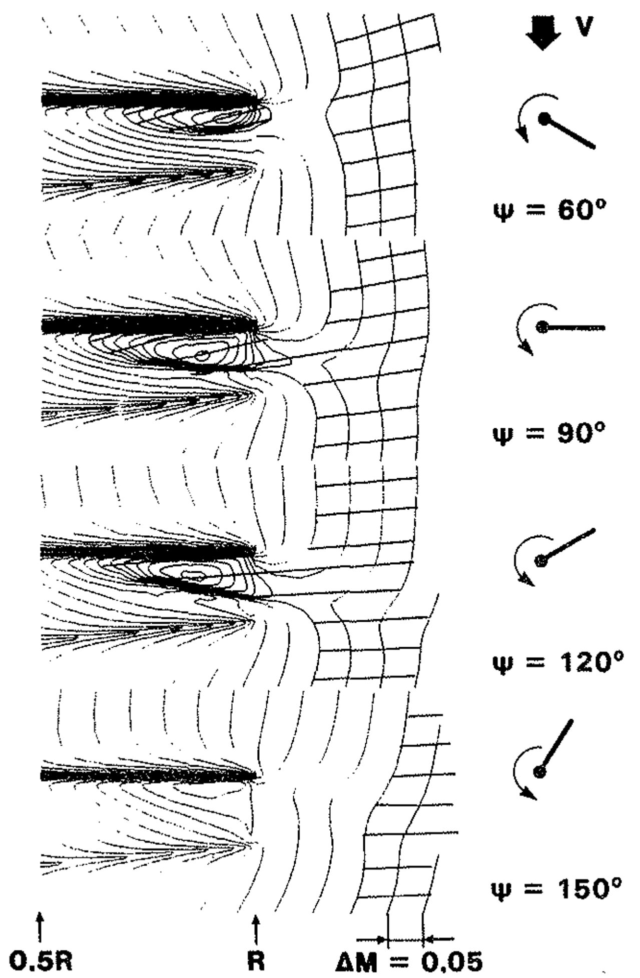


Fig.14 TSD predicted isomach-lines: straight blades, $M_{AT} = 0.898$, $\mu = 0.4$.

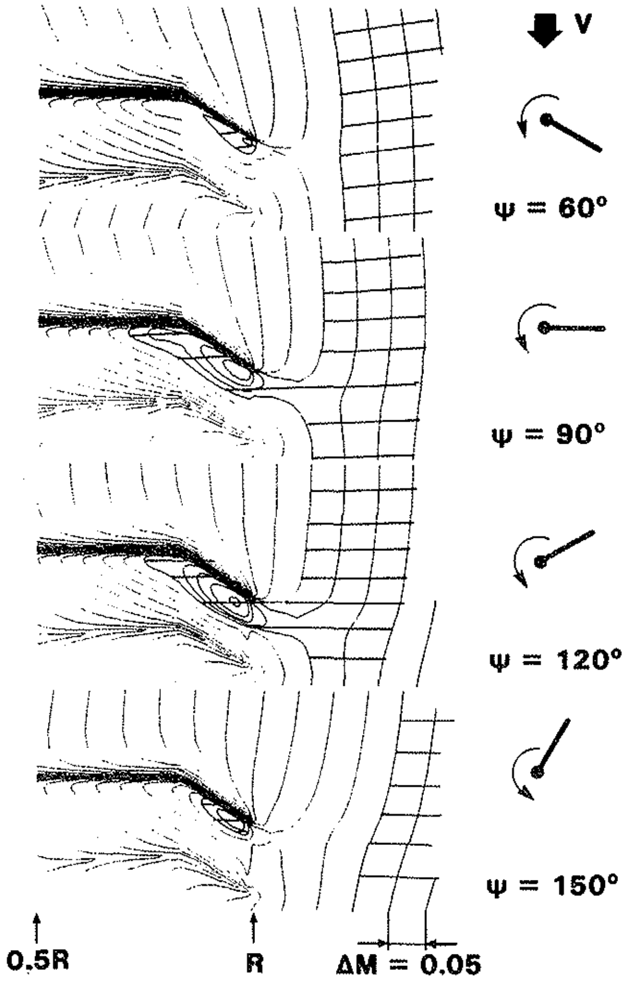


Fig.15 TSD predicted isomach-lines: swept blades (F30), $M_{AT} = 0.898$, $\mu = 0.4$.

On the straight tip, delocalization nearly begins at $M_{AT} = 0.875$ (Fig. 10) and is already installed at $M_{AT} = 0.890$ (Fig. 12) while, on F30, it has not yet happened at 0.885 (Fig. 11) and seems just beginning at 0.890 (Fig. 13). These predictions agree fairly well with the experimental results presented in Section "Study of the beginning of delocalization".

Qualitative correlation between noise experimental results and predicted transonic aerodynamics

Figs. 12 to 15 show that, once delocalization has appeared, local transonic Mach numbers and the extent of the coalescence zone of inner and outer supersonic fluid regions relatively to the blades are lower on F30 than on the straight blades (compare Fig. 12 and Fig. 13, Fig. 14 and Fig. 15). The higher velocity gradients and stronger shocks predicted on the rectangular blades agree with aerodynamic experimental results obtained in the past on pressure-instrumented versions of these two types of blades (Ref. 18).

Due to higher velocity gradients on the straight blades, higher noise levels can be expected. This qualitatively agrees with our experiments. The ONERA quadrupolar prediction code (Ref. 6) being presently restricted to hover does not allow to perform HSI noise predictions in the advancing case in order to compare with experiment: this will be the next step of the study.

Influence of geometrical parameters on HSI noise

The aforementioned results show how the blade tip geometry influences the intensity of transonic effects which consequently affects HSI noise. This result is not new (Refs. 4-6, and 14 for instance). Another effect, not suspected up to now, might be that the tip shape affect the shock geometry and then more or less influence noise radiation. In the non-delocalization case, the shock remains confined to the blade tip. In the delocalization case, the shock extends beyond the tip. Then, the region comprised between the blade tip and the vicinity of the sonic surface plays an important part in noise radiation: every modification of the external shock geometry is expected to deeply influence HSI noise.

Two recent independent studies at NASA Langley (Ref. 10), in the non-delocalization case, and at ONERA (Ref. 9), in the delocalization case, show the dependence of HSI noise on the curvature of the shock. Some results and figures (Figs. 16 to 18), taken from Ref. 9, are presented to illustrate this effect.

Only the effect of a modification of the shock curvature in the rotation plane is studied: the word "curvature" here means "curvature in the rotation plane".

Let us consider a shock C in the rotation frame of a transonic hovering rotor and an in-plane observer O (Fig. 16a). The maximum quadrupole contribution to the noise signature arises when point S_I has a relative Mach number equal to 1 in the observer direction. Then, Figures 16b and 16c suggest that elementary noise radiations from different sources arrive nearly in phase in the case of a straight shock (Fig. 16b) whereas they are delayed in time in the case of a curved shock (Fig. 16c).

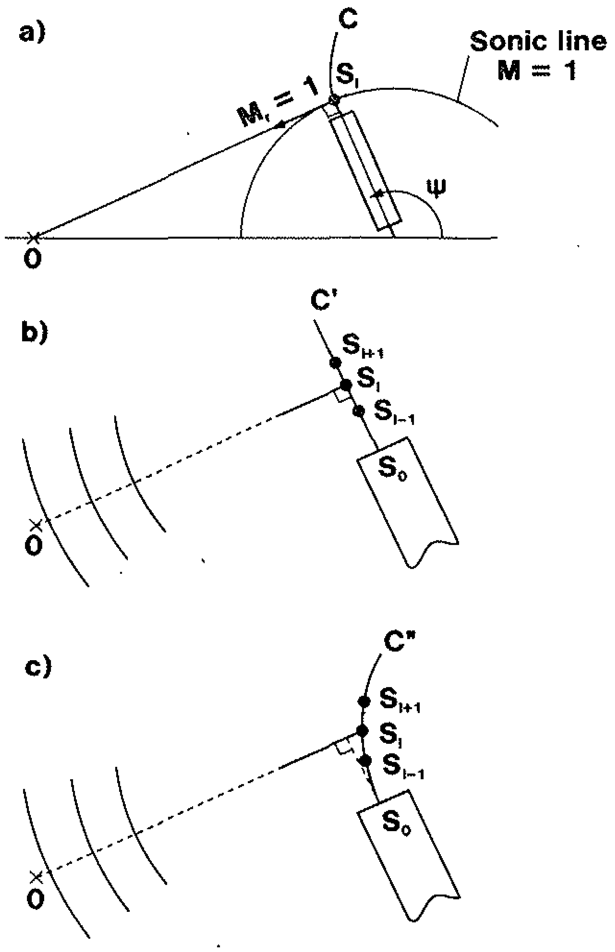


Fig.16 Shock geometry and acoustic radiation.

One can predict more impulsivity when the radius of curvature of the shock increases (from Fig. 16c to Fig. 16b). Furthermore, the occurence of the extremum of the negative pressure peak will be advanced in time from case 16c to 16b. The shape of the in-plane high-speed noise signature (resulting essentially from the addition of the thickness and quadrupole terms) will be deeply affected by this time delay.

The ONERA quadrupole noise prediction code for hover (Ref. 6) has been applied to the UH-1H rotor of the US Army (Ref. 7) hovering at a tip Mach number of 0.9, with TSD predicted quadrupole intensities as input data: the theoretical shock then obtained, named shock 1, is reproduced in Fig. 17.

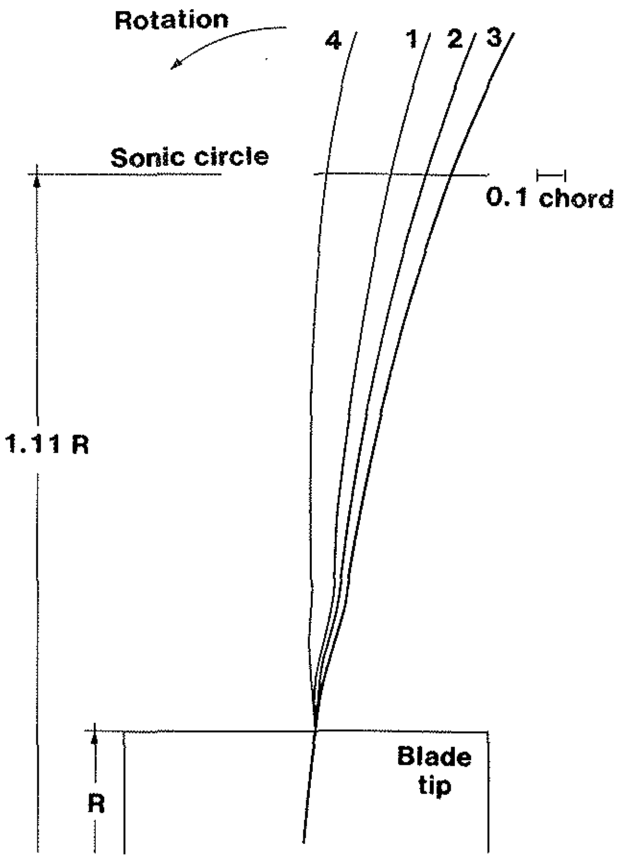


Fig.17 Different external shock curvatures simulated for the acoustic study ($M_H = 0.9$).

In order to quantify the sensitivity of quadrupole noise predictions to the curvature of the shock, different shock geometries have been simulated numerically starting from shock 1. The fictitious shocks are generated by translating in the chordwise direction, at every outer spanwise location, the input source data, of a quantity proportional to the span coordinate measured from the blade tip.

The different shock geometries named 1, 2, 3 and 4 are presented in Fig. 17. Shocks 2 and 3 are deduced from shock 1 by a downstream deformation, corresponding, on the sonic circle, to a displacement of 0.1 c and 0.175 c from shock 1 location. Shock 4 corresponds to an upstream deformation of shock 1 by 0.175 c on the sonic circle.

Fig. 18 compares the different quadrupolar time signatures. When one compares predictions from shock 3 to predictions from shock 4, the amplitude of the negative pressure peak of the signatures due to quadrupoles increases from about 290 Pa (which is of the same order as the negative peak pressure amplitude, 280 Pa, predicted for thickness noise (Ref. 6)) to 900 Pa, while the extremum is advanced in time by 0.1 ms (which means 1/200 of the period of rotation). Such a delay will dramatically influence the shape of the predicted signature as it was pointed out previously.

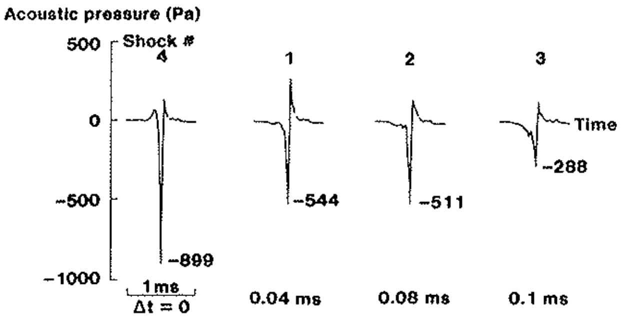


Fig.18 Different quadrupole time signatures calculated for different shock geometries: rotor UH-1H, $M_H = 0.9$, in-plane observer, distance = 3.09 R.

The computed tendency agrees with qualitative considerations on the influence of shock curvature on noise deduced from Fig. 16. Quadrupole noise, which constitutes the dominant part of the HSI noise in presence of delocalization, thus appears to be very sensitive to this geometrical parameter.

Conclusion

Acoustic tests performed in acoustically lined ONERA S2Ch wind tunnel demonstrate the ability of this facility (though not truly anechoic) to perform high-speed noise studies, particularly to compare different blade geometries in view of an acoustic rotor optimization.

The major findings are as follows:

1) The validity of the delocalization criterium (Ref. 3) has been checked successfully on two model rotors in the forward-flight case.

2) A good qualitative correlation between experimental noise results and predicted transonic aerodynamics has been observed.

3) Within the range of variation of the test parameters, a 6 dBA (scaled to full-scale) noise reduction has been obtained with F30 near the rotation plane, upstream of the rotor, which is the direction of the maximum directivity of HSI noise. This result is encouraging for future blade design since F30, of ancient design, is far from being an optimized blade tip.

4) Analysis through TSD computations shows that this gain is related to a lowering of transonic aerodynamic effects which delays delocalization towards higher tip Mach numbers and reduces velocity gradients once delocalization has appeared. This is a consequence of the sweep geometry, already known from previous studies.

5) Recent works show that modification of the shock geometry through appropriate blade tip design should also be considered in view of acoustic optimization of high-speed rotors. More precisely, increasing the bending of the shock surface rearwards (or diminishing the bending forwards) is expected to reduce HSI noise radiation, a conclusion which may be somewhat altered by non-linear propagation effects.

Future effort will be focused on investigating the influence of the blade and shock geometry (and how they are related to each other) on HSI noise by performing forward-flight aerodynamic and noise predictions.

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