Experimental Study of Turboshaft Engine Core Noise

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An experimental method is presented for locating the sources contributing to the low-frequency (0–5 kHz) broadband noise of a turboshaft engine. This method is based on a three-signal coherence technique using the signals of two internal probes in a section of the engine and of an external microphone placed in either the near or far field. The principle of the method is not new, but it seems never to have been applied before for turboshaft core noise source separation.

I. Introduction

THE development of noise standards for helicopters requires extensive study in order to characterize the different sources contributing to the noise radiation. For certain helicopter flight conditions, engine noise predominates over main and tail rotors. This noise comes from the compressor and turbine, core, and exhaust jet. Unlike turbojet engines, this last source of noise is not very important on turboshaft engines because the jet exit velocity is much lower. Since compressor and turbine pure tone noise is easy to identify, this paper deals only with core noise, which remains a relatively unknown source of noise, and is focused on the experimental method used at Turboméca for locating the source of core noise on a static test stand.

II. Core Noise Source Location Technique

Experimental Assessment

The broadband noise characterization in the frequency range 0–5 kHz is one of the major objectives of the present engine noise study.

This noise is indeed predominant, especially in the aft arc, as shown in Fig. 1. The figure presents examples of narrow-band spectra obtained in the far field 20 m from the engine center in the forward ($\Theta = 40$ deg) and aft ($\Theta = 130$ deg) arcs of a TM 333 turboshaft engine. Oscillations noticed in the low-frequency bands of the spectra are generated by ground reflection effects over the concrete area of the test stand; the far-field measurements are thus made with a 3 m high-pole microphone. The other noise sources are essentially caused by the axial and centrifugal compressors.

Broadband nose in the 0–5 kHz range issues mainly from the nozzle and is composed of core and jet noise. Jet noise should not make a large contribution to the far-field radiation since the exit velocity of the jet is very low (the exit Mach number never exceeds 0.2).

Core noise is generally said to be composed of combustion noise (direct combustion and/or entropy noise) and noise due to the interaction of the turbulent flow within the engine with fixed obstacles (struts and vanes, nozzle) and with the turbine. Combustion noise is a low-frequency random noise, the spectrum of which is centered in the 100–500 Hz range, while the interaction noise spectrum covers a range of 1000–5000 Hz.[1,2]

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Data Processing

Ordinary Coherent Output Spectrum

The scope of the data processing method presented in this paper is to find the contribution of each core noise source to the engine radiation. The process is somewhat similar to what has been done elsewhere.[3-6] It consists of measuring simultaneously the fluctuating pressures inside the engine and the external acoustic field. The contribution of each core noise source to the engine sound field is provided, in an ideal case, by the ordinary coherent output spectrum between the signals of an internal probe S located near the source and of an external microphone M.

This coherent spectrum is classically defined by

$$S_{S/M}(f) = \gamma^2_{SM}(f) S_M(f)$$

where $\gamma^2_{SM}(f)$ is the coherence function between the two signals and $S_M(f)$ the external microphone spectrum.

The coherent output spectrum $S_{S/M}(f)$ provides the actual contribution of the source (or of the set of sources) seen by the internal probe S only if: 1) the signal of S does not contain any extraneous noise; and 2) there is no nonlinear distortion of the signal of S as the sound field propagates from S to M.

Actually, the first condition is not fulfilled since there is a strong hydrodynamic pressure field inside the engine caused by the turbulent flow as well as a nonpropagating sound field (stationary waves and decay field associated with sound reflections and cutoff properties of the engine duct). Consequently, the ordinary coherent output spectrum underestimates the contribution of the source to the external sound field spectrum. This will be clearly shown by some results presented in the next section. In order to estimate the actual contribution of the source, a three-signal data processing technique using two internal pressure signals and the external microphone signal is necessary.

Three-Signal Coherent Spectrum

The method utilized here is similar to that described by Chung[7] and used by Krejsa[8] and Shivashankara[9] for aircraft engine noise source location, especially for separating fan, jet, and core noise. It seems to the authors that it has never before been applied for identifying turboshaft noise sources. It is assumed that each signal of the internal probes S1 and S2 is made up of the acoustic source pressure signal and of an extraneous noise not correlated with the source signal. If the noise-free signals of S1 and S2 are linked by a linear relationship (both probes hear the same source or set of sources) and if the extraneous noise signals are uncorrelated and do not correlate with the external microphone signal, then it can be shown that the actual contribution of the source perceived by the probes to the external sound spectrum is given by the three-signal coherent output spectrum defined by

$$S_{S1\text{-}S2/M}(f)=\frac{\gamma_{S1M}\cdot\gamma_{S2M}}{\gamma_{S1S2}}S_M(f)$$

where γ_{S1M}, γ_{S2M}, and γ_{S1S2} are the square roots of the coherence functions.

This method was tested with the engine not running. A white noise signal filtered within the 2–4 kHz frequency range was emitted by an electroacoustic source (JBL 2420) inside the combustion chamber of the engine. The three-signal coherent output spectrum obtained for any probe pair matched the external microphone spectrum. This result shows the validity of the method in the case of hydrodynamic noise-free signals.

Let us go back to the two assumptions made for applying this technique. First, extraneous noises on both probes should be uncorrelated. This implies that the probes must not be too close to each other in order to keep the hydrodynamic pressure field from becoming coherent on the distance between the probes.

On the other hand, this distance should not be too large in order that the probes detect the same source. If one of these probes also picks up another source, the three-signal coherent spectrum does not provide the actual contribution of the source perceived by both probes.

In this latter case, another three-signal coherence technique presented by Bendat and Piersol,[10] using partial and multiple coherence functions, would apply if the signals were not contaminated by extraneous noise, which is a wrong assumption in the present case. For several probe pairs, we have experimentally compared the three-signal coherent spectra previously defined with the spectra obtained from

$$S'(f)=\gamma^2_{M:S}(f)\,S_M(f)$$

where $\gamma^2_{M:S}(f)$ is the multiple coherence function defined in Ref. 10.

$S'(f)$ provides the linear contribution of the two sources (one of them is picked up by both probes) to the far-field spectrum. The comparison shows that $S'(f)$ is always lower than $S_{S1\text{-}S2/M}(f)$ except when signals S1 and S2 are not noisy, which happens, for instance, if S1 and S2 are near-field microphones instead of internal probes. In this case, $S'(f)$ and $S_{S1\text{-}S2/M}(f)$ match.

Therefore, the three-signal technique proposed in Ref. 10 and utilized in applications similar to the present one by Karchmer[11] and Muthukrishnan et al.[12] does not seem to be valid for core noise source location because of the contamination of the internal signals by extraneous noise.

To apply the three-signal coherence technique, a compromise has to be found for the probe location. The probes must be placed neither too close to each other nor too far apart. In order to characterize the core noise sources in each section of the engine, the two probes are placed in the same section at different azimuthal angles.

III. Experiment

Engine and Instrumentation

Engine

The experiment has been conducted on a TM 333 turboshaft engine. The engine is set on a platform in such a way that its axis is 3 m above the concrete area. In order to characterize the actual engine noise, the shaft power is absorbed by a hydraulic brake used as a load. This allows coverage of the whole power range corresponding to the different flight conditions.

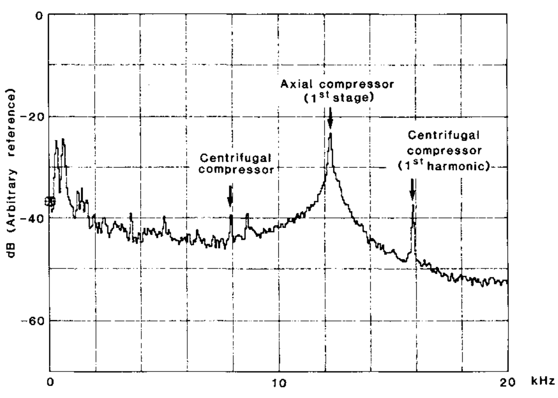
Internal Pressure Measurements

Fluctuating pressure measurements in the engine are made with probes of the "semi-infinite" waveguide type similar to those used by other authors (see, for instance, Ref. 6). The transducer is either a ¼ in. condenser microphone whenever possible or a piezoelectric transducer when the mean static pressure in the engine is much higher than the ambient pressure. Figure 2 shows a scheme of a probe. The cut-on frequency of the first higher-order mode in the tube is 33 kHz and the "semi-infinite" tube is designed for suppressing the stationary waves in the duct.

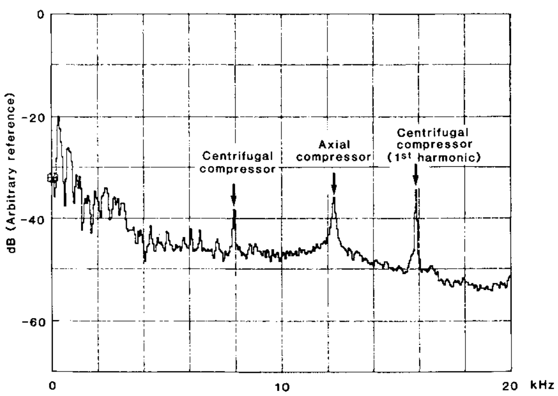
Fourteen internal probes are mounted on the engine duct in seven different sections from the air intake to the nozzle exit (Fig. 3). Two probes are set in each section with an angular distance of 90 deg or more between the probes (the length scale of the turbulent flow is assumed to be small on the circumference).

Near- and Far-Field Measurements

A microphone, called M1, is placed in the engine near field close to the nozzle at a distance of 0.55 m from the engine axis in the nozzle exit plane.



a) Θ = 40 deg.



b) Θ = 130 deg.

Fig. 1 Far-field microphone spectra on a TM 333 turboshaft engine (P = 465 kW). Observation angle Θ is defined with respect to the engine axis with Θ = 0 deg corresponding to the air inlet. The dB reference is arbitrary, but it is the same for both spectra.

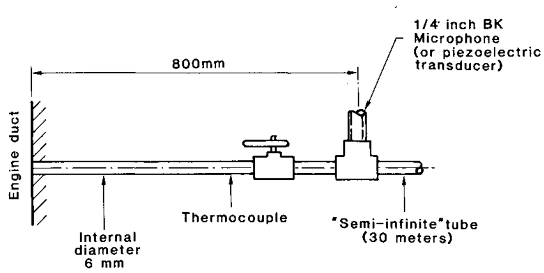


Fig. 2 Waveguide probe design.

The far-field microphone, called M2, is a ground level microphone located 20 deg from the engine center at $\Theta = 130$ deg (Θ is defined in Fig. 1) where the low-frequency broadband noise level is maximum. Results with other locations of the near and far-field microphones were also obtained during these tests, but they are outside the scope of this paper.

Results and Discussion

Comparison of Two- and Three-Signal Coherent Spectra

Before presenting results of comparisons between near- or far-field spectra and three-signal coherent spectra, it is useful to show the improvement gained by the use of the three-signal coherent spectrum instead of the two-signal coherent spectrum. For an engine power of 465 kW, Figs. 4a and 4b compare the two-signal coherent spectra $S_{7/M1}(f)$ and $S_{70/M1}(f)$ with the spectrum of the near-field microphone M1 (probes 7 and 70 are in the nozzle as shown in Fig. 3). The levels of the two-signal coherent spectra are much lower than that of M1 spectrum, except within a narrow frequency range around 300 Hz and on the compressor tones. On the other hand, the three-signal coherent spectrum $S_{7\text{-}70/M1}(f)$ is close to the external spectrum, even if it is fairly noisy (Fig. 4c). This "noise" is partly due to the somewhat insufficient number of ensemble averages made during the signal analysis (200 averages).

The results of Fig. 4 confirm the remarks made in Sec. II. The ordinary coherent output spectrum underestimates the contributing of the source when the signal of the internal probe is noisy, whereas the three-signal coherent spectrum gives the actual contribution of the source to the external sound field.

Results obtained with the three-signal technique in the near and far fields are now presented for an engine rating of 568 kW (maximum continuous power); the results obtained with other engine ratings are similar.

Near-Field Results

Figure 5 compares the spectrum of the M1 microphone (close to the nozzle exit) with each of the three-signal coherent spectra obtained with different probe pairs. Once again, the coherent spectra look fairly noisy, although the signal analysis was performed on 600 ensemble averages. This is due to the low signal-to-noise ratio of the internal pressure signals. A good superimposition is observed between $S_{7\text{-}70/M1}$ and S_{M1}, which means that the noise on microphone M1 is almost entirely perceived in section 7 of the nozzle. The superimposition is not as good for the probes located further upstream in the engine, since they hear fewer sources radiating outside through the nozzle exit. This process allows us to deduce the axial positions of the different core noise sources: additional phase measurements of the cross-spectral densities between internal probe and external microphone signals show that the sound field in the engine propagates mainly downward. The level of the coherent spectrum $S_{5\text{-}50/M1}$ is slightly lower than that of $S_{7\text{-}70/M1}$, except in the narrow band centered at 300 Hz where $S_{5\text{-}50/M1}$ matches S_{M1}. The difference in levels between these two coherent specta can be attributed to a noise source located in the nozzle between sections 5 and 6 (the results obtained with probes 6 and 60, not shown in Fig. 5, are very similar to those obtained with the probes at section 7). This source is possibly due to the interaction of the flow with the struts and/or the walls in the nozzle (see Fig. 3).

With the internal probes situated upstream of section 5, a large difference is observed between the levels of the coherent spectra and of the M1 spectrum.

Probes 4 and 40, as well as probes 3 and 30 ($S_{3\text{-}30/M1}$ is very similar to $S_{4\text{-}40/M1}$) are located on the outer wall of the combustion chamber and thus should perceive the noise caused by the combustion. The hump centered about 300 Hz, which can

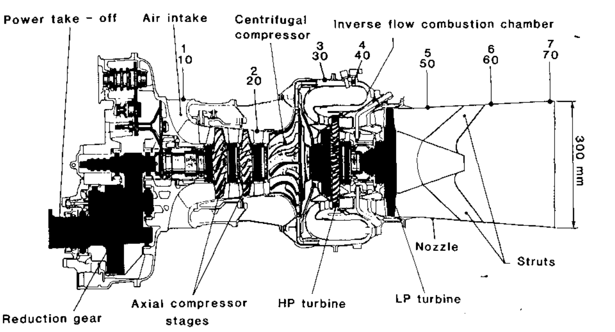
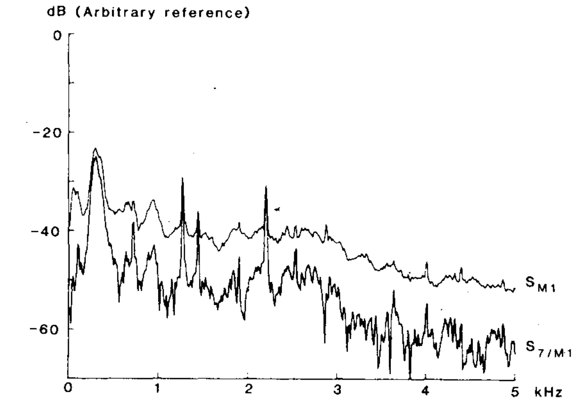
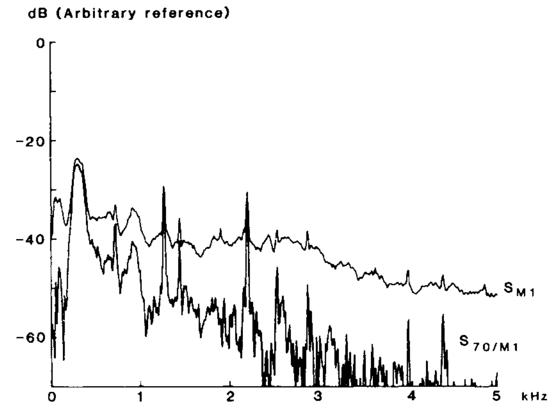


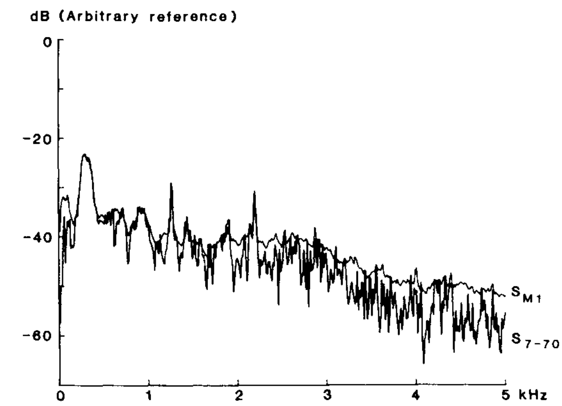
Fig. 3 TM 333 engine cross section with axial locations of the internal pressure probes. Probes 1 and 10 are in the same section, but circumferentially separated and so on.



a) Two-signal coherent spectrum $S_{7/M1}$.



b) Two-signal coherent spectrum $S_{70/M1}$.



c) Three-signal coherent spectrum $S_{7\text{-}70/M1}$.

Fig. 4 Comparison of the two- and three-signal coherent spectra with the M1 spectrum ($P = 465$ kW).

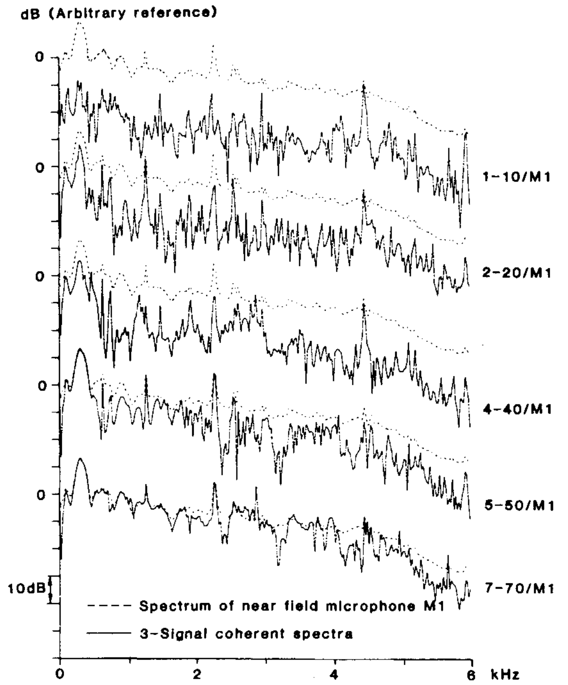


Fig. 5 Comparison of the three-signal coherent spectra with the near-field spectrum ($P=568$ kW).

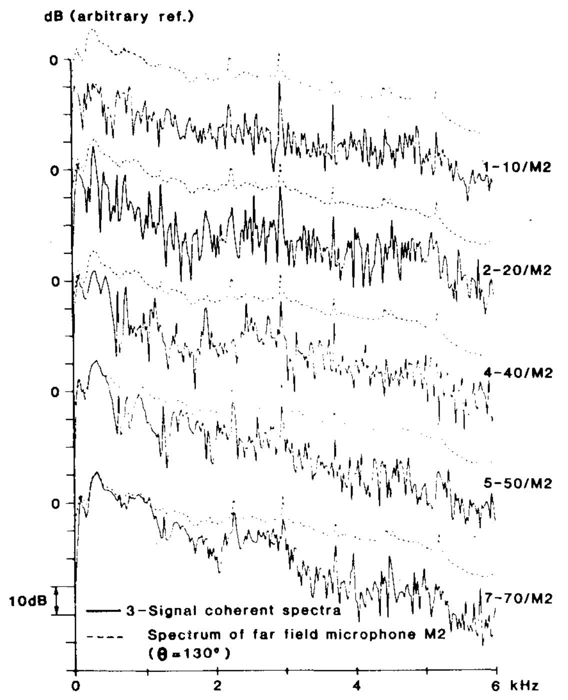


Fig. 6 Comparison of the three-signal coherent spectra with the far-field spectrum ($\Theta=130$ deg, $P=568$ kW).

be precisely ascribed to the combustion noise, is clearly seen on $S_{4\text{-}40/\mathrm{M1}}$, but its amplitude is 7 dB below that of S_{M1}. This difference may be explained by one of the following reasons:

1) Probes 4 and 40 are not suitably placed to clearly perceive the direct combustion noise or this source does not provide an important contribution to the external sound field.

2) There is a strong extraneous noise (hydrodynamic or nonpropagating sound field) in the combustion chamber, coherent over the distance between the two probes.

3) The sound field is decorrelated on the path from the combustion chamber to the nozzle inlet because of the turbulent flow. This mechanism should nevertheless be frequency dependent and especially noticeable at high-frequencies, but nonlinear effects cannot be excluded.

4) Indirect combustion noise (or entropy noise) caused by convection of temperature inhomogeneities through a pressure gradient (for instance, a turbine stage) could prevail over direct combustion noise. In this case, pressure measurements in a section between the high- and low-pressure turbines could give further information. Unfortunately, it was not possible to set probes in such a section in this experiment, but results obtained on another installation (a Makila turboshaft engine) clearly indicate that a source of noise is radiating outside up to at least 1 kHz in this part of the engine.[13] This source of noise may be due to combustion and/or flow/turbine interaction.

Finally, the levels of the coherent spectra with probes in Secs. 1 and 2 are also much lower than that of the M1 spectrum, especially $S_{1\text{-}10/\mathrm{M1}}$. No source upstream of the combustion chamber contributes to the core noise radiated from the nozzle.

Far-Field Results

Figure 6 shows results obtained with the far-field microphone M2 at 130 deg. The probe signals have been time delayed before the analysis in order to compensate the wave propagation delay from the engine to the far field.

As for the near-field results, a large difference in levels is observed between the far-field spectrum and the coherent spectra obtained with the probes in or upstream of the combustion chamber. This result confirms that the upstream part of the engine does not contribute to the far-field noise in that direction.

But contrary to the near-field case, the levels of the coherent spectra $S_{5\text{-}50/\mathrm{M2}}$ and $S_{7\text{-}70/\mathrm{M2}}$ (with the probes in the nozzle) are much lower than that of M2 spectrum above 3 kHz and the difference is still rather important between 1.2 and 3 kHz with probes 7 and 70 and a fortiori with probes 5 and 50.

This gap cannot be explained only by a loss of coherence of the sound field along the path between the engine and the far-field micophone, due to turbulence. The tests are indeed carried out in low-speed wind conditions. Furthermore, the loss of coherence due to the turbulent atmosphere should be nearly the same in any direction: the divergence between the far-field spectrum and the coherent spectra is, in fact, somewhat less important in the forward arc ($\Theta=40$ deg.)

A more likely reason that could explain the difference between the near- and far-field results is related to the space structure of the sound field close to the engine.

If the source could be considered as a monopole, which to some extent is true at low frequencies, a high level of coherence should exist between the near and far fields. Otherwise, in the case of an extended volume source, the far-field radiation depends directly on the axial wave numbers of the pressure field close to the engine. In the present case, jet noise (which is, of course, an axially extended source) appears insignificant in the near field at M1 (see Fig. 5), but may yield some contribution to the far field at M2 even if the jet velocity is very low. To elucidate this point, extensive pressure measurements in the near field will soon be carried out on this engine and a near/far-field extrapolation technique[14] will be applied, which could help to characterize the sources contributing to the far-field engine radiation.

IV. Conclusions

The objective of this paper was to present a data processing technique for source separation of turboshaft engine core noise. This method is not new, but it seems that it has never before been applied to turboshaft engines. Furthermore, it is used up to 5 kHz in the present study, whereas other results are obtained at lower frequencies (up to about 1 kHz).

With some hypotheses, the three-signal coherent technique allows us to deduce the actual contribution of each source to the external sound field and thus presents a major improvement over the ordinary two-signal coherent technique.

Even if complete and definitive results cannot still be given (internal probes were missing in some sections of the engine, in particular between the high- and low-pressure turbines). This technique seems to be promising when supplemented by phase measurements. Most of the core noise radiated from the nozzle originates from the part of the engine between the combustion chamber and the free turbine, but pressure measurements at the outer wall of the combustor itself indicate that the sound field in the combustor (which is generally called direct combustion noise) does not seem to contribute significantly to the external sound field. This result has to be confirmed in further experiments. Unlike the near field, the far-field coherent spectra with the probes close to the nozzle exit match the microphone spectrum only within the low-frequency range (up to 1.2 kHz). This result indicates that other noise sources (i.e., jet noise) may contribute to the far-field spectrum, but their contributions are masked in the near field by a sound field that does not radiate to the far field. This point needs to be clarified with the help of a near/far-field extrapolation technique.

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