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EVALUATION OF HELICOPTER INTERNAL NOISE BY ENHANCED STATISTICAL ENERGY ANALYSIS

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ABSTRACT

To estimate the helicopters internal noise, ECF has conducted a combined theoretical and experimental analysis on the Ecureuil. In order to achieve this goal, an analytical approach based on enhanced Statistical Energy Analysis (SEA) to solve noise problems in the aeronautic industry, has been used.

Four flights have been performed with ONERA in-flight measurement installation. For a complete noise knowledge in the medium frequency range, three types of excitation of very different spectral properties have been considered: mechanical, acoustic and aerodynamical ones. These recorded signals have represented the input data for the LASCAR software developed by AEROSPATIALE Les Mureaux, based on the "enhanced SEA" approach. It has been applied by ECF to determine the energy flows from the vibration or acoustic identified sources, through the physical parts of the fuselage structure. The coupling of the radiating panels with the connected cavities have allowed to compute the internal noise levels for each source. Finally, the comparison of the SEA calculated cabin noise spectrum with the experimental one gives the opportunity to improve the helicopter modelization.

Then the differents ways to extend the SEA application domain are examined. In conclusion, this approach appears to be quite adapted to the project or design step, for it allows a sensitivity study of the cabin vibro-acoustic response within a short time and low cost.

1 INTRODUCTION

The internal noise level of helicopters becomes a very important comfort criterion for a commercial point of view. However, the architecture of present helicopters is generally responsible for a high level of noise inside the cabine at the meshing discrete frequencies of the cinematic linkage. Besides the use of new lighter composite structures associated with the increase of forward speed and engines power are likely to increase the interior noise level for the next helicopters. So the extra sound-proofing treatment panels inside the cabin induced by stronger excitations would constitute an indesirable pay load penalty. Therefore, it is of high concern at the project and design stage, to consider the vibration levels of the fuselage in the medium frequency range and its acoustic coupling with the cabin cavity.

ECF has performed work to reduce the helicopter internal noise for many years. Up to now the noise reduction efforts were made after the in-flight measurements of the cabin noise levels for the delivered helicopters. Therefore only a "a posteriori" sound proofing treatment was likely to be designed in order to obtain the internal noise objectives (in terms of added weight and noise levels) for the commercial versions (military, offshore, VIP). This current methodology reveals to be time and weight consuming. Moreover it limits the efficiency of the acoustic treatment because of technological limitations of cabin noise reduction. So it appears that the best industrial solution consists to take into account this acoustic constraint at the design level of the structure, but also for the engines and associated equipments.

So ECF has initiated the modelization of the medium frequency vibration and acoustic response of its helicopters cabin in order to treat the internal noise problem at the manufacturing upstream level.

- The first step of this work is to calculate the energy transfers in the cabin structure with the data about the constitutive elements, available at the project or design stage.
- Then it is necessary to estimate the in-flight excitations from a data basis or to directly acquire them after the first prototype test, to obtain the absolute acoustic levels inside the cabin.
- From that, it becomes possible to perform a parametric study to evaluate the influence of a structural modification of the bare helicopter cabin and to quantify the overall internal noise improvement from the noise reduction of the sources separately taken into acount (gear box, engine group, air intakes...)

So this sensitivity study is potentially able to make impacts on the helicopter definition itself, just before the first prototype manufacturing and testing.

In order to validate its internal noise calculation based on the enhanced Statistical Energy Analysis (SEA), an experimental and computation work has been undertaken for an Ecureuil. The in-flight recorded excitation spectra constitute the input data for the vibration and acoustic response calculations. The measured cabin noise can then be compared to the calculated one and used for the optimization of treatment.

2 EXPERIMENTAL DATA BASIS ACQUISITION

2-1 Methodology

- flight test objectives

An in-flight vibration and internal noise measurement campaign has been conducted by ECF and ONERA on a single-engine Ecureuil equipped with a fenestron called AS350Z (see Figure 1). The global purpose was to generate an experimental data base which can be used in two ways:
- first in characterizing the real internal noise excitation sources with the associated vibration and acoustic helicopter cabin response and their evolution with the flight conditions: forward speed and main gear box (MGB) transmitted torque.
- secondly in validating a SEA helicopter model in order to make available a parametric tool for internal noise predictions of next ECF helicopters.

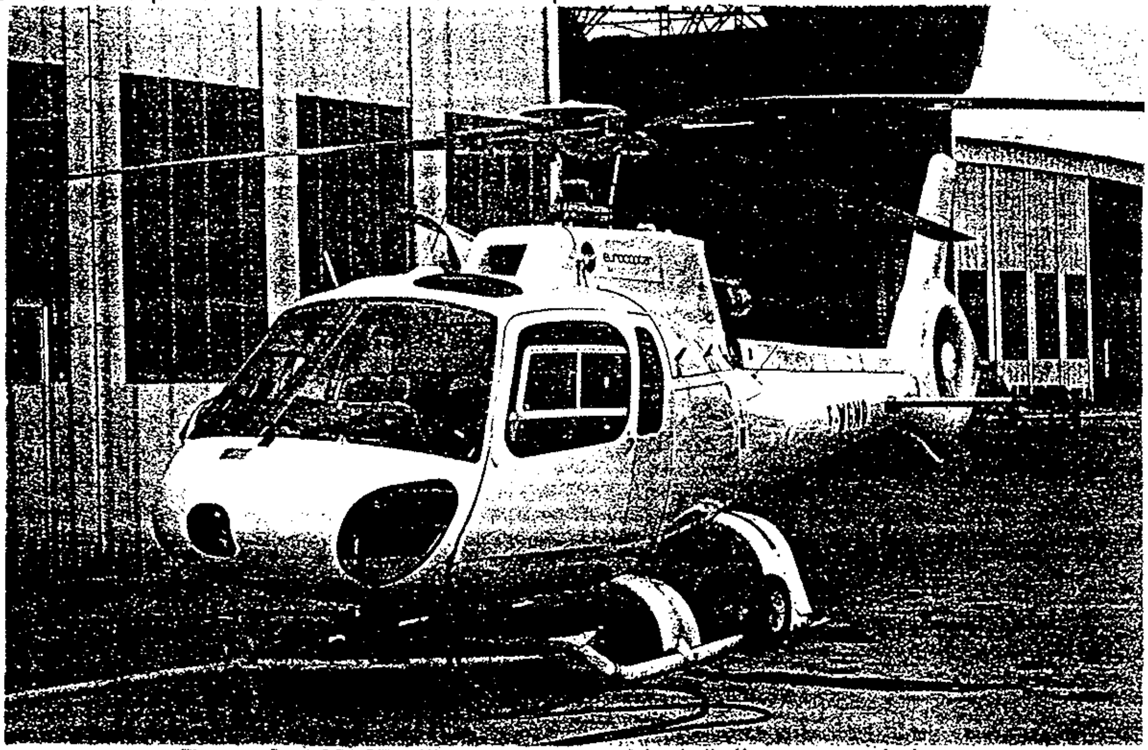


Figure 1: AS350Z with measurement installation general view

– test equipment

To achieve this goal, the AS350Z has performed four flights without sound-proofing treatment, at different forward speeds and transmitted torques:

- hover out of ground effect delivered torque = 65 %
- three forward flights - v = 82 kts delivered torque = 50 %
  - v = 105 kts delivered torque = 65 %
  - v = 130 kts delivered torque = 95 %

where % is the pourcentage in respect with the nominal torque delivered by the engine group.

The vibro-acoustic team of the ONERA Structures Department has instrumented the helicopter with 61 sensors: 46 accelerometers, 12 microphones and 3 boundary layer pressure sensors

The overall measurement equipment is divided into two sub-sets:

- an on board recording system including:
  - sensors supply and signal conditionning (electronic adaptators and amplifiers)
    - 4 X 32 channels signal switching system
    - 28 track FM analog tape recorders
- a ground installation consisting of the ONERA laboratory truck including:
  - digititalization system
  - two work stations for signals acquisition, processing and analysis

After each flight test, the analog recorded signals are sent to the ground truck for further processing.

2-2 excitations measurements

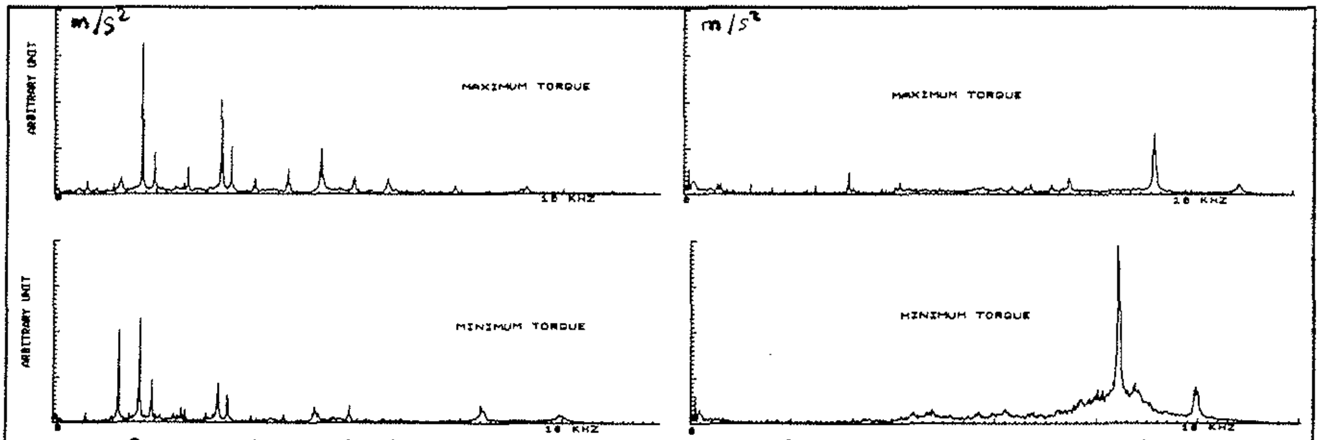
– mechanical inputs (engine, gear box)

The vibration excitations have been recorded by 8 accelerometers:

- one vertical accelerometer located on each strut attachment and two extra accelerometers located in horizontal directions on a MGB reference strut.
- one vertical accelerometer located on one engine suspension attachment.
- one vertical accelerometer located on the input rear transmission bearing.

The recorded acceleration spectra levels change in a complex manner with the delivered engine torque, which depends itself on the forward speed (see Figure 2a).

- the meshing frequencies and their related harmonics appear clearly in the spectra corresponding to the MGB accelerometers. The general shape is common for the 4 MGB vertical acceleration spectra and their order of magnitude is comparable. However, the evolution of the acceleration level at a given frequency versus the engine transmitted torque, is different from one accelerometer to another.
- two broader bands centered on the passage frequency of the compressor rotating blades dominate in the higher frequency domain for the accelerometer located on the engine attachment (see Figure 2b).



2a: accelerometer located on a MGB strut attachement

2b: accelerometer located on the engine attachement

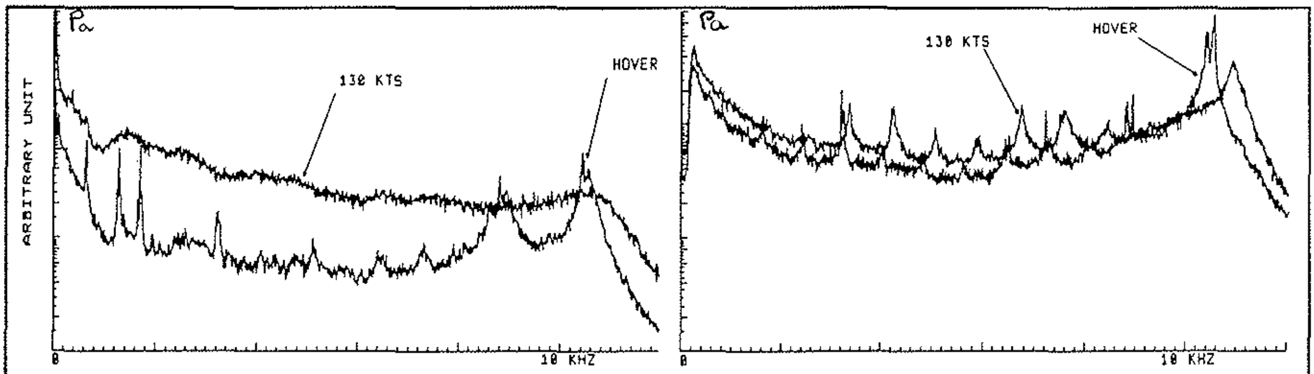
Figures 2: Iso-scale vertical acceleration spectra for two transmitted torques

- acoustic inputs (rotors, air intakes and engine exhaust)

Two types of acoustic excitations are considered (the most representative spectra are presented in Figures 3):

- outside the fuselage (the microphones are protected from the aerodynamical flow):
  - two microphones located in front of the MGB air intakes below the main rotor
  - one microphone put above the engine air intake grid
  - one microphone mounted on the horizontal stabilizer
- inside the fuselage:
  - two microphones located in the MGB cavity

The spectra given by the two microphones are quite identical in the MGB air intake case and in the MGB cavity case. So only a spatially averaged spectrum can be considered for each of these both excitations.



3a: microphone located under the main rotor before the MGB air intake

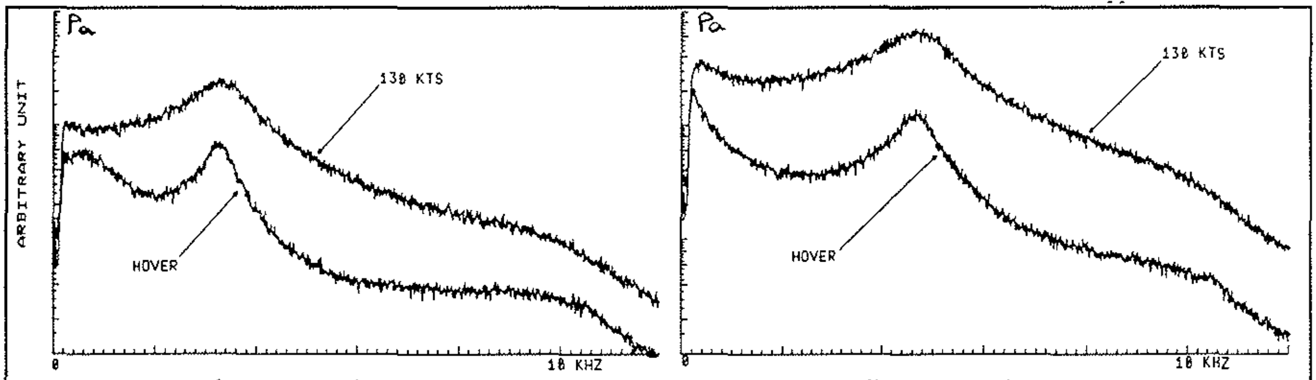
3b: microphone located above the engine air intake

Figures 3: Iso-scale external acoustic pressure spectra

- aerodynamical inputs (boundary layer noise)

Three boundary layer flush mounted sensors have been fixed on the cabin windows in order to acquire the order of magnitude of the aerodynamical excitation and its related spectral characteristics (see Figures 4):

- one boundary layer sensor located on the windscreen
- two on the cabin windows of the cokpit door



4a: sensor located on the windscreen left part

4b: sensor located on the left door

Figures 4: Iso-scale boundary layer spectra

The unsteady pressure maximum shifts to the higher frequencies as the sensor distance to the cabin nose increases. In parallel, the averaged excitation level increases with the forward speed while the spectral shape is altered. This spectral evolution with the forward flight is comparable for the three sensors.

2-3 sub-systems responses measurements

– medium frequency cabin vibration

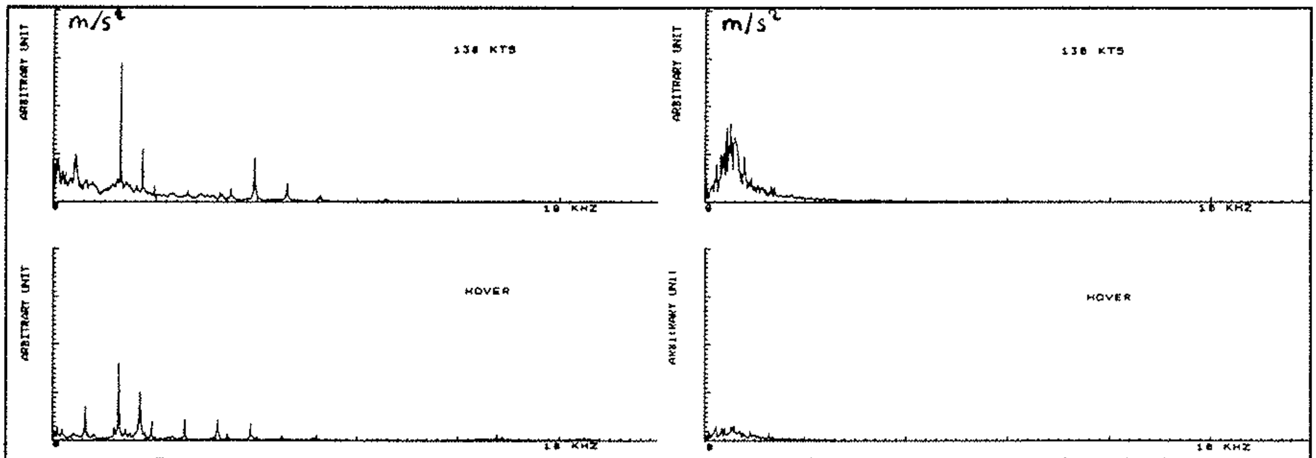
The accelerometers measuring the responses have been distributed on the internal fuselage to measure the acceleration levels of 7 selected sub-systems. Each identified sub-system has been equipped with 5 accelerometers to record its bending vibration field. These sub-systems were "a priori" selected among those which were likely to be the most significant in respect with the vibration energy flows towards the cabin:

- transmission deck
- rear cabin wall divided into its upper part and its lower part
- cabin roof
- left door
- left sub-door
- windscreen

The spectra can be divided into two groups (see Figures 5):

- determinist spectra corresponding to the metallic sub-systems
- broad band spectra corresponding to the flexible elements.

We have checked that the dispersion between the 5 acceleration spectra for a given sub-system is weak in the frequency bands considered.



5a: accelerometer located on the rear wall upper part

5b: accelerometer located on the left door

Figures 5: Iso-scale cabin vibration spectra

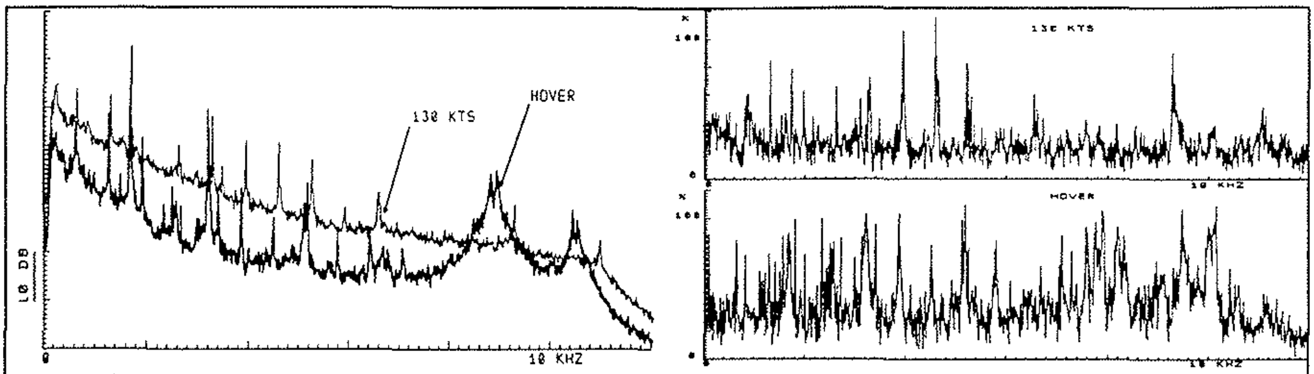
– internal noise

The acoustic cabin field is investigated by 5 microphones to acquire the mean value and the associated standard deviation which represents a SEA accuracy indicator. An extra microphone has been placed in the rear fuselage part as a validation sensor for the vibration and acoustic transfers towards the tail boom.

The internal noise spectra are composed of the superposition of a broad band noise and a determinist noise (see Figure 6a). The noise levels spatial dispersion is weak: less than two dB. The spatial energetic dispersion of the acoustic pressure field inside the cabin is defined by:

$$\varepsilon_p(f)\ (\%) = 100\,\frac{\sqrt{\langle p^4\rangle}}{\langle p^2\rangle}$$

Its average value on the frequency domain decreases when the forward speed increases (see figures 6b). Except for the meshing frequencies, the dispersion is weak. So in a first approximation, we can consider that the acoustic cabin field is diffuse, specially for the 130 kts forward flight.



6a: microphone located between pilot and copilot heads

6b: spatial dispersion for the 5 recorded acoustic pressures

Figures 6: Internal noise spectral characteristics

- *reverberation time measurement*

A ground test evaluation of the acoustic reverberation properties of the cabin walls has been conducted. One loud-speaker located in one corner has been used to generate a white noise in each third octave frequency band noted fc. Then the transitory signal Lp(t,f) of the acoustic pressure versus the time t following the excitation switch off, has been measured in the 5 microphones positions. This experiment has been repeated for another location of the loud-speaker in the cabin.

This procedure allows to determine the spatially averaged reverberation time $T_r(fc)$ of the cabin defined by:

$$\langle Lp(t,f)\rangle = \langle Lp(f)_{(t=0)}\rangle - 60\ t \ /\ Tr(fc)$$

where <Lp(t,f)> , t and Tr are given respectively in dB and seconds.

So it is possible to calculate the equivalent absorption coefficient $\langle\alpha\rangle$ of the cabin walls as a function of the frequency by the Sabine formulation:

$$\langle\alpha\rangle\ (f) = 1 - \exp\left(\frac{-0.161\ V}{T_r(fc)\ S}\right) \qquad \text{with} \qquad S = \Sigma_j\ S_j$$

where V is the cavity volume (given in m^3) and Sj the surface (given in m^2) of each j panel which constitute the cabin. This acoustic parameter will be used in the SEA approach to calculate the acoustic pressure in the cabin from the radiated power by the surrounding panels.

2-4 Signal processing

Two signal processing methods were implemented:

- *narrow band signals processing*

First, a Fast Fourier Transform (with a 12.5 Hz frequency resolution) has been performed for all the acceleration and pressure levels (from 200Hz to 10 kHz) to obtain the direct and cross-spectra for the 61 signals (the phasis reference is given by the vertical accelerometer on one MGB strut).

Secondly, the coherence and transfer functions between the reference signal and the vibration or pressure signals have been computed. For instance, it appears that the coherence function between the cabin acoustic pressure and the MGB acceleration reference is high for the meshing frequencies and low for the remaining part of the investigated frequency domain.

- *statistical physical values elaboration*

First a frequency domain integration has been performed in order to obtain the band by band excitation and response spectra for SEA utilization: 100 Hz wide bands, third octave bands and octave bands.

Secondly, a spatially quadratic averaged spectrum is obtained from the 5 sensors for each SEA sub-system response.

3. ENHANCED SEA MODELIZATION

3-1 Study framework

- *principle*

The helicopter fuselage is modelized by a partition of physical sub-systems as panels, beams, shells and cavities. The calculated mechanical or acoustic coupling between these elements and their intrinsic damping are represented by a square matrix with frequency dependant coefficients.

The power balance equation between each connected element gives a linear equations system where the unknown is the modal energy vector. This linear approach (in respect with the energy) allows to calculate the modal energy of each physical sub-system for a given power excitation vector. This system resolution is repeated for each frequency band including more than 5 modes. Therefore the spatially averaged acceleration level for each mechanical element and the spatially averaged acoustic pressure for each cavity are determined for all concerned frequency bands and specially in the dBSIL4 frequency domain. (the dBSIL4 unit is the arithmetic mean value of the dBlevels for the 0.5, 1, 2 and 4 kHz octave bands).

- *specific assumptions*

- the possible spectral correlation between the above mentionned excitations are ignored.
- the structure behavior is supposed to be linear in all the frequency bands and for the range of excitation magnitude, considered in this study.
- the possible damping at the mechanical element connections is not taken into acount.

Whatever the sophistication of the model, the accuracy of the acoustic levels SEA prediction is limited by the average dispersion of the levels inside the cabin, due to the assumption of diffuse fields. Therefore the AS350Z is well adapted to this first validation study, for its relative structural simplicity compared to larger helicopters (as Dauphin or Super-Puma) and also for its low acoustic levels dispersion inside the cabin.

- *enhanced SEA*

In the frequency bands with a sufficient modal density, Statistical Energy Analysis (SEA) is available. However, in its standard form, SEA cannot be used to solve internal noise problems in helicopters industry. So SEA has been improved by Space and Defence Division of AEROSPATIALE. As examples, the supplied improvements are (see references 1 and 2):

- the calculation of the vibroacoustic response of structures submitted to:
    - acoustic excitations other than diffuse fields (boundary layer noise, plane waves,...)
    - mechanical excitations as gear box or engine attachment vibrations. (the power supplied by these mechanical excitations are estimated using the mobility concept).
- the determination of high frequency response of sandwich structures.

Except damping, all SEA parameters (modal density, coupling loss factors) are calculated. So the software LASCAR developed by AEROSPATIALE can be used as a predictive tool and does require no extra test results other than the excitation sources determination.

3.2 AS350Z structure modelization

- *elements definition*

The AS350Z modelization and energetic transfers calculations have been performed with the LASCAR software. The model contains 84 structural elements and 5 cavities. It is an assembly of beams, stiffened panels, stiffened shells and 3D cavities. The materials involved are:

- AU4G and ASGM for the metallic parts
- Nida Nomex for the honeycomb structure
- altuglass for the transparent parts
- polycarbonate for the cabin
- elastomeres for the mechanical suspensions

- damping properties

For this first study, the damping for each type of material has been choosen independant on the frequency. Concerning the orthotropic structures, the damping of the stiffeners is choosen identical with the panel structure one. The typical values are:

10^{-2} for the honeycomb core and windows

10^{-4} for the metallic parts

10^{-2} to 1 for the elastomeric parts

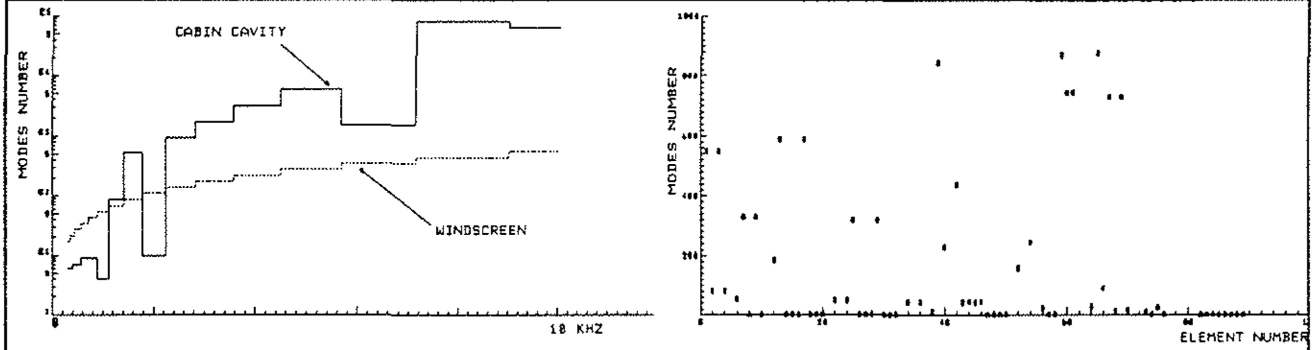
Whatever the panels surrounding the helicopter internal cavities, the absorption coefficient of the walls is assumed to be identical to the cabin one, as it is practically impossible to obtain the reverberation time for the cavities others than the cabin.

3.3 Calculation results

The calculations of the vibration and acoustic responses have been performed for the 16 third octave bands between 300 Hz and 10 kHz defined by their normalized central frequency: 315, 400, 500, 630, 800, 1000, 1250, 1600, 2000, 2500, 3150, 4000, 5000, 6300,8000 and 10000 Hz.

- estimated modal characteristics

The modal density of an acoustic or mechanical sub-system (see figure 7a) are roughly increasing with the third octave band central frequency as expected; for a given frequency band, it depends strongly on the considered mechanical element (see figure 7b).



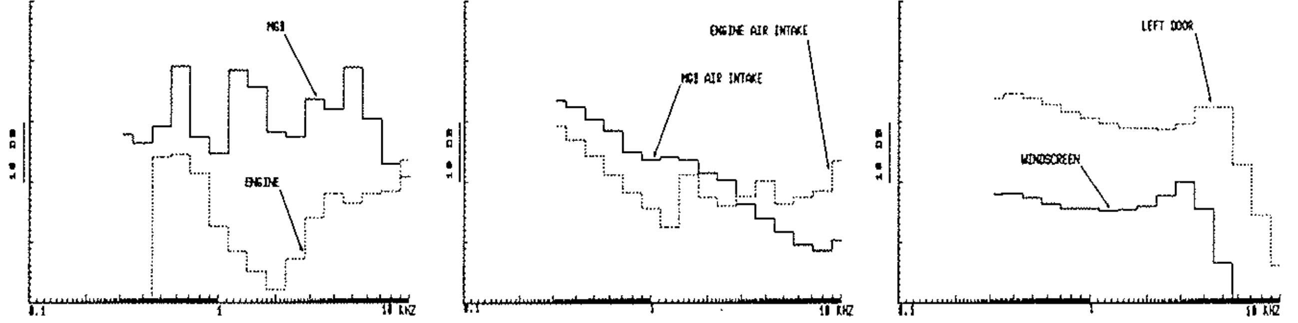
7a: modes number versus frequency for one structural element and the cabin

7b: modes number in the higher frequency band for all the structural elements

Figures 7: modes number calculated for the different sub-systems

- estimated partial internal noise

Using the LASCAR software, the calculations have been run for each of the identified source. The calculated noise spectra are shown for the most representative excitations in the figures 8 in the 130 kts forward speed flight case.



8a: calculated noise due to vibration excitation (MGB)

8b: calculated noise due to acoustic excitations (air intakes)

8c: calculated noise due to boundary layer pressure (door's window)

Figures 8: 130 kts enhanced SEA estimations
Iso-scale calculated internal noise third octave spectra examples

Finally, it is possible to link the quadratic spatially averaged cabin pressure $\langle p^2 \rangle$ and the surrounding panels vibration levels $\langle \gamma_j{}^2 \rangle$, to the quadratic accelerations and pressures representing the excitation by (keeping in mind that the excitations are assumed decorrelated):

$$\langle p^2 \rangle = \Sigma_k \; a_{p,k} \; \langle \gamma_k{}^2 \rangle + \Sigma_l \; b_{p,l} \; \langle p_l{}^2 \rangle$$

$$\langle \gamma_j{}^2 \rangle = \Sigma_k \; a_{\gamma,k} \; \langle \gamma_k{}^2 \rangle + \Sigma_l \; b_{\gamma,l} \; \langle p_l{}^2 \rangle$$

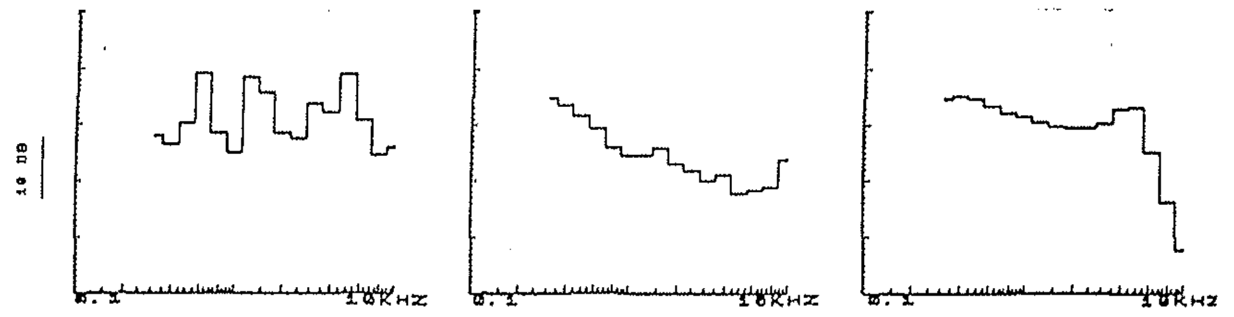
where the coefficients $a_{p,k}$, $b_{p,l}$, $a_{\gamma,k}$ and $b_{\gamma,l}$, depending on the frequency, are deduced from the SEA calculations performed for each isolated excitation.

$a_{p,k} \; \langle \gamma_k{}^2 \rangle$ represents the structure borne noise: vibration excitation

$b_{p,l} \; \langle p_l{}^2 \rangle$ represents the airborne noise: acoustic and boundary layer excitation

From these SEA results, we can already see that it is possible to evaluate the influence of a given excitation on the noise spectrum in each frequency band. For instance, in the 130 kts forward flight case, it is found that (see figures 9):

- the acoustic excitation prevails in the low frequency range and in the 10 kHz octave band (due to the compressor frequency emergence).
- the boundary layer excitation appears also in the low frequency range and in the 5kHz band.
- the vibration excitation (MGB) is predominant only in the medium frequency range where the meshing pure tones are high. The engine attachment vibration is significant in the 10 kHz band.



9a: SEA vibration noise (MGB + engine)

9b SEA acoustic noise (air intakes + engine exhaust)

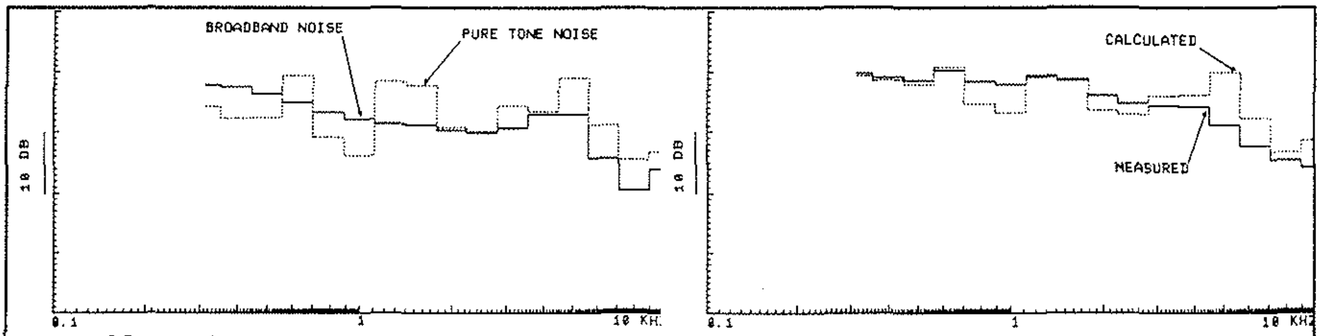
9c: SEA boundary layer noise (windscreen + door)

Figures 9: 130 kts enhanced SEA estimations
iso-scale calculated partial noises for the three excitation types

- *global internal noise calculation*

It is then possible to separate the noise coming from the sources presenting a pure tone (vibration excitation) spectrum from the noise coming from sources presenting a broad band spectrum (aero-acoustic excitations), as it is shown in figure 10a.

Finally, the total SEA calculated internal noise spectrum obtained from the summation of the ten partial quadratic partial cabin pressures is compared to the measured one in Figure 10b.



10a: calculated broad band and calculated pure tone noise

10b: calculated global noise and measured internal noise

Figures 10: 130 kts enhanced SEA estimations without adjustment
iso-scale internal noise spectra

The SEA noise calculation is quite satisfactory for the frequencies where the acoustic or aerodynamical excitation dominate. Nevertheless, the SEA vibration noise is overestimated, in the frequency range above 5 kHz. This feature which appears for every flight case, is analysed hereafter.

3.4 Discussion

- damping properties

It appears that damping is the most difficult property to acquire for the different elements.
The sensitivity on the internal noise levels with the damping properties depends on the type of excitation. It is found from these SEA results that for the aerodynamic or acoustic excitation, it is quite independant on the damping of strutural elements, but for the vibration excitation the choosen damping value for the excitated element is quite critical.
So, at this state of the art, only laboratory experiments performed on isolated panels or beams and also on connected elements can provide the intrinsic damping and assembly damping. This work has to be done essentially for the panels subjected to mechanical sollicitations. Then it can be extended to panels which are identified as strongly contributing to the internal noise . For instance, we represent in figure 11, an evaluation of the SEA internal noise after adjusting the vibration response of the transmission desk.

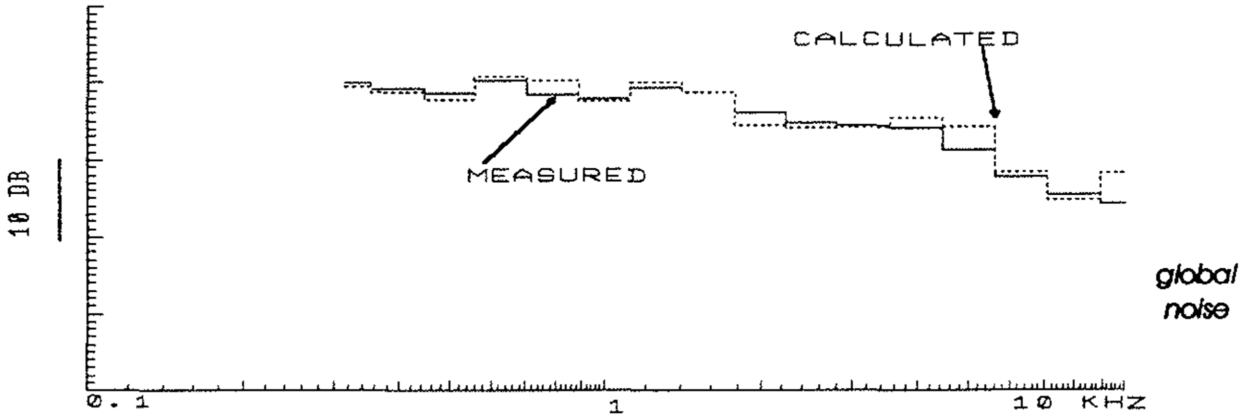


figure 11: internal noise SEA calculation with transmission desk adjusted response

- excitations representation accuracy

The signals considered as sources have to be analyzed carefully before a direct use for SEA modelization. In a first approach we can consider that the boundary layer pressures are not mutually dependant. For the MGB and engine air intakes, this assumption can reasonnably be made, but for the vibration excitations it is necessary to define an equivalent acceleration spectrum taking into account the correlations between the four struts levels.

We can also notice that the signals considered as input data for the software are not really pure excitations but in fact a linear combination of the physical external excitation and the response, at this sensor location, to the others excitations via all the transfers through the fuselage or the cinematic transmission. This feedback loop phenomenon is doubtless non neglectable for the acceleration levels measured on the MGB four strut attachments. A complete calculation of the uncoupled excitations and the induced vibration and acoustic responses which would take into account these mechanical couplings (representing a close loop analysis) would certainly furthermore improve the SEA accuracy.

This study indicates that the fluctuating external pressure recording represents a new and useful measurement for noise generation identification. At the time of this study, the correlation functions of the boundary layer noise were not known. Therefore, the incident noise has been considered diffuse. This approach is pessimistic for it overestimates the cabin noise related to this excitation. So, besides the classical helicopter gear noise problem, it is necessary to know also the aero-acoustic excitations for the lower frequency range or the high speed domain.

– software developments

Some works must be done to strengthen the SEA application field:

- to concentrate the efforts of modelization on the vibration excitation representation. For the AS350Z case, this difficulty is essentially seen at low forward speed.
- to extend this approach to the low frequency domain by combining it with the individual modes determination. A mixed finite element and SEA method could then cover the entire frequency range of interest.
- to refine the sandwich panels and composite beams modelization for future helicopter composite structure as NH90 helicopter.
- to take into account the in plane vibratory excitations of the transmission desk.
- to perform the SEA calculations for the frequency band with constant width, to point out the pure tones noise.

4 CONCLUSION

A combined measurement-analysis methodology in order to validate the prediction of helicopters internal noise by means of the SEA approach has been established.
The global objective of this work was to perform a complete evaluation of the possibilities and limits given by the enhanced SEA approach for an helicopter. The complexity comes from the number and variety of elements which are considered. The other difficulty is to introduce the different excitations with the same level of accuracy. This exercise has been done on the AS350Z for it was likely to give a large set of excitation sources such as aerodynamical, acoustic and mechanical ones. This study can be called as a global approach. The main tendencies are well estimated by these enhanced SEA results in a very large frequency band extending from 300 Hz up to 10 kHz. The derivatives are already sufficiently correct to allow a parametric study. This tool gives us the possibility to check the dependance of the internal noise levels with the excitation variations, and also with a structural modification. It allows now to do a complete characterization of the internal noise sources and of the coupling of the structure with the cabin.

A further application of this method is the design of optimized sound proofing panels.

5 ACKNOWLEDGEMENTS

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