ENVIRONMENTAL PROTECTION

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ACCURACY AND UNCERTAINTY OF AIRCRAFT NOISE MODELLING

Various models for predicting aircraft noise around airports are described. Improved acoustic models of aircraft are formed by summing models for the noise sources peculiar to each of the aircraft types. Their accuracy and uncertainty are assessed by means of comparison with flight trials measurements.

Описано різні моделі для прогнозу авіаційного шуму навколо аеропортів. Поліпшені акустичні моделі літаків створено за допомогою складання моделей для окремих джерел шуму, особливих для кожного з типів літаків. Їх точність і достовірність оцінено порівнянням з вимірюваннями, виконаними під час випробувальних польотів.

Introduction

The ability to assess and predict noise exposure accurately is an increasingly important factor in the design and implementation of any airport improvements [1]. Possible methods for modelling noise radiation, propagation and attenuation, include both analytical and semi-empirical results. The current tendency is towards less empirical and more analytical and numerical techniques. It should he noted that ICAO is carrying out analyses of existing models and methods for assessing the acoustical characteristics of the various sources associated with aircraft noise events and is making proposals for their use [2; 3].

Two approaches to analysis of aircraft noise phenomena have been defined and implemented in computer programs. The first approach is based on l/3-octave band spectra noise analysis of any type of aircraft in any mode of flight or during maintenance activities in the vicinity of an airport. It provides estimation of any type of aircraft noise criteria by means of set of noise spectra varied during the particular noise event or for any kind of noise exposure. The approach is implemented in a model and appropriate software **NoBel**. The second approach is based on the concept of "noise radius" and provides calculations of aircraft noise exposure units around the airports or at any noise monitoring point. The basic "noise radius"- relationships may be obtained from experimental data as well as by calculation (for example, by using the **NoBel** program). The task of deriving an acoustic model for each type of the aircraft under consideration has been proposed and solved in a manner that reconciles experimental data with calculation.

Thus, the aircraft noise models, used in BELTRA solutions, are of sufficient reliability and accuracy. The second modelling approach has been utilized in software **IsoBell'a.** Here, the basic acoustic models for aircraft of any type will be examined on its accuracy and uncertainty.

The acoustic model of an aircraft

An aircraft is represented by a set of noise matrices, each dependent on flight mode and consisting of sound pressure level *(SPL)* spectra (in a l/3-oclave band form) for a defined number of directions of sound propagation from the acoustic source. In some cases the noise matrices are obtained experimentally, in others they are obtained by means of calculations based on the models for the particular acoustic sources [4-10] of interest for the aircraft under consideration. It is impossible to define the characteristics of all phenomena by means of analytical and semiempirical models only. The most common phenomena determining or influencing the accuracy of noise matrices are the engine installation effects and noise abatement treatments. Both experiments and calculations have some disadvantages and the derivation has been formulated to overcome them [1].

The sound pressure level spectrum $\{SPL_{jk}\}$ of aircraft noise of any type in spectral bands N_j, j=1,N_j, and in some k-th direction of sound propagation, where k = 1, N_k , with reference to previous considerations, can be defined by:

$$SPL_{jk} = SPL_{jkp} + \Delta SPL_{jk}, \qquad (1)$$

where

SPL_{jkp} is the predicted value of SPL_{jk} resulting from a sum of particular models SPL_{jki} for characteristic (or dominant) noise sources, i = 1,..,N_s;

ΔSPLjk are spectral corrections for differences between the predicted SPL_{jkp} and measured values SPL_{jk}.
For each aircraft of interest, SPL_{jkp} is defined by:

$$SPL_{jkp} = \sum_{i=1}^{N_S} SPL_{jki} \quad (2)$$

Spectral corrections are defined as the spectral transfer functions for the total acoustic model of the aircraft as follows:

$$\Delta SPL_{jk} = SPL_{jko} - SPL_{jkp}, \quad (3)$$

where SPL_{jko} are the experimentally observed values of SPL_{jk}.
The observations must be carried out either during flight testing in accordance with noise certification requirements or during noise engine testing at the outdoor testing facility. In the latter ease, of course, various flight effects and airframe acoustic sources are excluded.
In general, SPL_{jko} and SPL_{jkp} are functions of many parameters, so the transfer functions ΔSPL_{jk} are functions of these parameters too. The main parameters are the flight mode (engine type and thrust) and the direction of noise propagation from source to receiver. If the results of engine noise testing are presented in the form of noise matrices, then it is possible to define the directional relationships for the transfer functions ΔSPL_{jk}. *SPL*-spectra for flight noise testing in the direction of maximum magnitude of instantaneous sound levels $L_A(t)$ or *PNL(t)* (or *PNLT(t)*) are the more accessible data in practice. The flight mode relationships can be defined for them and then generalized for any direction of noise propagation.
The method for identification of spectral transfer function ΔSPL_{jk} is based on the likelihood approach [11]. Equation (3) then acquires the following form:

$$\Delta SPL_{jk} = SPL_{jko} - SPL_{jkp} - E_j, \quad (4)$$

where E_j are the spectral errors, which cannot be included in the transfer function between the observed and the predicted noise data. If the errors E_j have a normal or Gaussian distribution, the likelihood principle can be applied in the form of the minimum value of the sum of least squares:

$$\sum_k E_{jk}^{\;2} = \sum_k \left(SPL_{jko} - SPL_{jkp} - \Delta SPL_{jk}\right)^2 = \min. \quad (5)$$

Therefore, in the general case, the sums of ($SPL_{jkp}+\Delta SPL_{jk}$) may be performed from the results of linear regression SPL_{jkr}, defined by means of the OLS method and ΔSPL_{jk} would be the systematic portions of differences between SPL_{jko} and SPL_{jkp}. Errors E_j would be the unsystematic portions of the differences ($SPL_{jko} - SPL_{jkr}$) - they can be interpreted as the measures of the precision of the defined solutions. In accordance with the likelihood principle, the following sum

$$M = \sum_k E_{jk}^2 / \sigma^2 \quad (6)$$

must be distributed in accordance with a χ^2-distribution for (N_k-1)-degrees of freedom, where σ is the dispersion of the error distribution, and N_k is the number of directions of sound propagation under consideration (N_k =16-19 for complete noise matrices, all directions are seperated uniformly by 10°).
This property can be used to assess the assumption about E_j.
Thus the acoustic model for an aircraft involves the following steps.
1. A preliminary acoustic model of the aircraft is obtained as a sum of particular models forcharacteristic noise sources [see formula (1)] for every case (or direction) *k* of the observed data SPL_{jko} and for each acoustic source considered. The computer program **NoBel** is used for this step.
2. Linear regressions are performed to define least squares estimates SPL_{jkr}
3. The transfer function and error function are defined by:

$$\Delta SPL_{jkp} = \sum_{jk} W_j \left[SPL_{jkr} - SPL_{jkp} \right] / \sum_j W_j . \quad (7)$$

$$E_{jk} = \sum_{jk} W_j \left[SPL_{jkr} - SPL_{jko} \right] / \sum_j W_j , \quad (8)$$

where
W is a spectral weighting function, every component of which in any band of the spectrum is either 1 or, for bands containing tonal components, greater than 1.
At this stage the following equations are useful:
the vector of total spectral differences *E* is defined by

$$E = \left\{ \sum_{jk} W_j \left[SPL_{jkr} - SPL_{jko} \right] / \sum_j W_j \right\}^{1/2}, \quad (9)$$

so that

$$E^2 = \Delta SPL_{jk} + E_{jk}^2$$

and the relative error index of agreement *d* is defined by

$$d_j = 1 - \frac{\sum_j \left\{ W_j \left[SPL_{jko} - SPL_{jkp} \right] \right\}^2}{\sum_j \left\{ W_j \left\{ \left[SPL_{jkp} - SPL_{jkor} \right] + \left[SPL_{jko} - SPL_{jkor} \right] \right\} \right\}^2} \quad (10)$$

where

SPL_{jkor} is an average estimate for the observed data:

$SPL_{jkor} = \Sigma\ (Wj\ SPL_{jko})\ /\ \Sigma Wj$.

The index of agreement d_j is nondimensional and varies between 0 and 1. If d_j = 1 the resulting prediction model is reliable and compliant to the observed data in the *j*-th band under consideration. Steps 2 and 3 are realized in a computer program named **TRANSFER**.

4. The possible solutions are compared through the sum of squares of residual errors and χ^2-statistics which are calculated in the computer program named **TRANSCHI**.

Thus the basic acoustic model of an aircraft of any type is derived from the noise matrices and the value of each component of the matrices is defined by formula (1). The models are represented in terms of the parameters of aircraft flight (engine) modes and of the stale of ambient environment, so they can be used for any aspect of the aircraft noise problem. This method for deriving an acoustic model of an aircraft has been validated by means of flight testing data obtained from preliminary noise certification results for the Yakovlev-40 aircraft. Measurements are available for both take-off and approach stages, so the transfer functions are defined for two flight modes. Figure, *a*, *b* shows upper and lower limits of the spectral differences *E* between observations and initial predictions. In both cases the No 11 flights were excluded from the model improvement process because the corresponding data were anomalous. The spectra resulting from the model improvement process SPL_{jko} (1), SPL_{jkh} (2) and SPL_{jk} (3) are shown in figure *c*. In all cases (of course, without No 11 flights) the index of agreement d_j varies between 0,88 and 0,96 over the spectral bands. The averaged value of index d_j for No 11 flight = 0,62. For most of the spectrum bands, the probability *P* that the assessed χ^2-statistic is higher than the χ^2-distribution law is between 0,92 and 1,00, so the reliability of the resulting acoustic model is quite high. Small deviations from these good results are observed in a few low-frequency bands (for which d_j = 0.77). The ground effects here are substantial and higher accuracies in the overall spectrum have not been achieved despite application of a ground interference model in the prediction procedures, since accurate data about the type of rejecting surfaces and their characteristics were not available.

Spectral weighting function

A spectral weighting function *W* in equations (7-10) may be dependent of spectral correction implented for noise criteria, used in particular task of noise impact assessment. For example, for L_{Amax} definition correcting filter of type “A” must be used, with highly decreased low frequency and little bit decreased high frequency octave or third-octave spectral levels and increased spectral levels between 1 and 4 kHz. Thus spectral weighting function *W* may account on significance of the spectral component and its spectral elements must be differ from 1 as in linear case of noise level assessment:

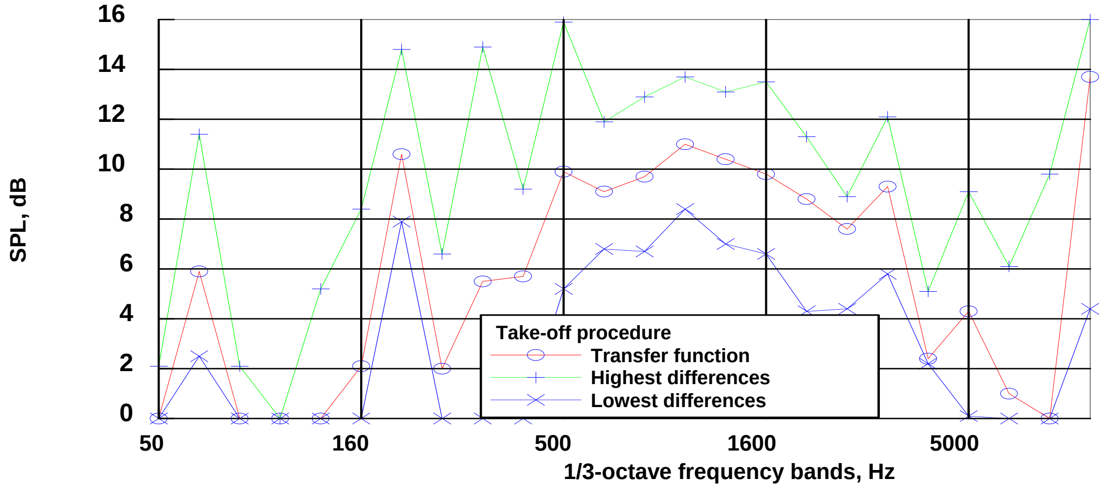
$$W_j = \frac{10^{0,1(SPLj + \Delta SPLjA)}}{10^{0,1SPLj}} \quad (11)$$

where

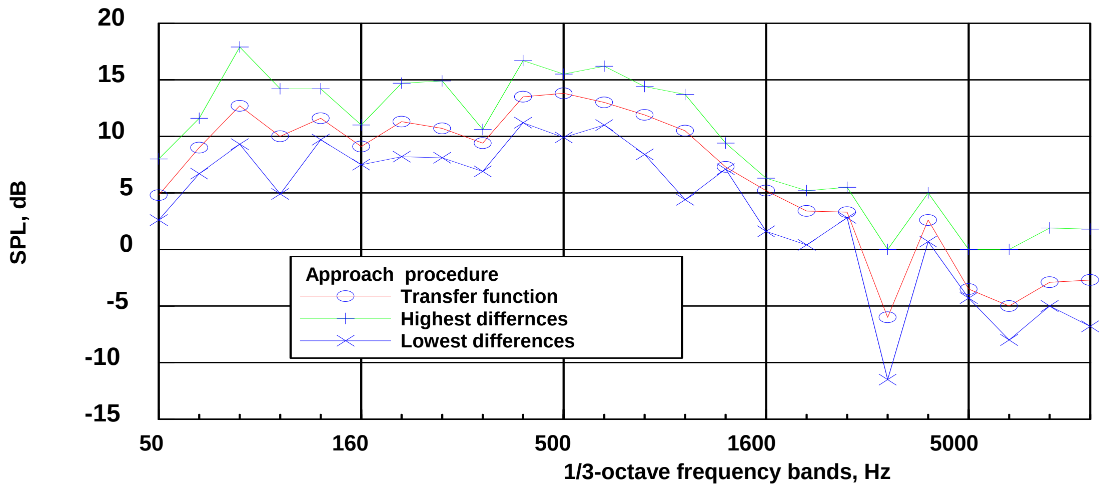
ΔSPL_{jA} is spectral correction for filter of type “A”.

For perceived noise level *PNL* assessment the spectral weighting function *W* may be used in same way as in equations (11), but with spectral correction ΔSPL_{jD} for filter of type “D”, which is used sometimes to model the noisiness scale of the PNL or directly by assessing the noisiness of the spectrum under consideration in relation to the pink noise spectrum of the same *OASPL*.

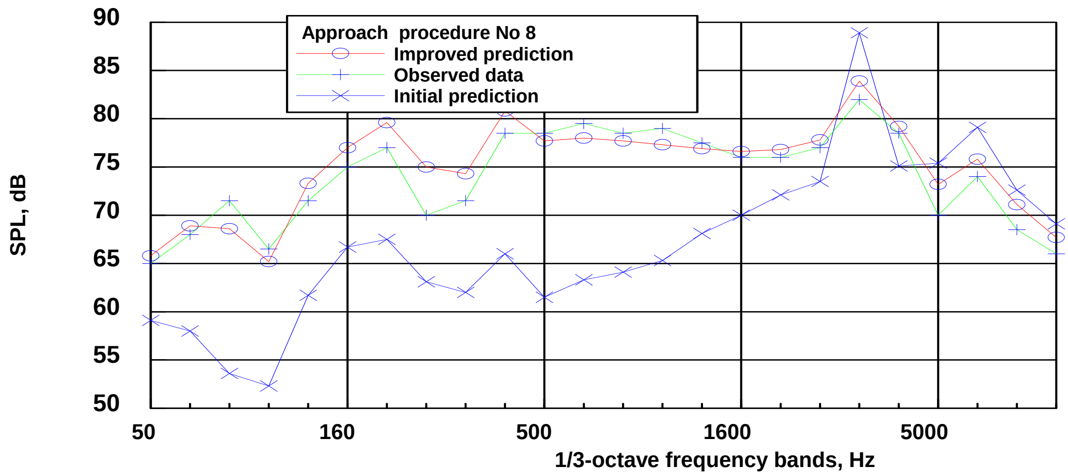
For noise event assessment the, where distance to noise source and directivity angle of noise radiation are changed a huge influence on results of the noise directivity patterns of separate acoustic sources exists, so as of the sound propagation effects. It means that index of agreement *d* during noise event assessment may change considerably due to inaccuracy of noise directivity patterns modelling or due to inaccuracy sound propagation effects modelling. In other words spectral transfer function ΔSPL_{jk} of the Basic Acoustic Model of the aircraft for noise event is a results of identification task solving including the influence of the directivity of sound radiation (sound matrix) and sound propagation effects.



a



b



c

The results of identification task for Yakovlev-40 airplane:
a – take-off procedure;
b – approach procedure;
c – approach procedure No 8

Basic aircraft noise trajectory model

The trajectory model is intended for research and assessment of noise levels (either as time varied sound spectra or in scales of perceived noise or of “A"-frequency weighting) under the flight path, at one or more reception points of interest. It is useful for assessing the efficiancy of low-noise treatments, low-noise flight procedures and takes actual flight rules and circumstances into account in the vicinity of a specified airport. The model is sufficiently sophisticated fur specialist investigations office aircraft noise problem. In principle the model consists of three main parts:

– an aerodynamic model for flight path parameters assessment;

– an acoustic model including sound propagation and attenuation effects defined in overall *SPL* form, so that the appropriate models for their assessment can be used;

– an acoustic model based on the noise radius approach, in which sound attenuation and propagation effects are included in the form of relationships between the relevant noise criteria and basic parameters of such effects.

The peculiarities of aircraft aerodynamic models are not considered here. However two remarks must be made. Such models have been derived as a system of differential equations, but it has been shown that a simplified system of algebraic equations is sufficient for aircraft noise assessment needs.

The flight trajectory may be represented by means of a set of linear and of arc segments, in which flight parameters are defined as approximately constant.

Accurate and reliable acoustic models have been achieved for all current types of aircraft and engines (tab. 1).

The trajectory models have been used for the analysis of the influence of various operational factors on aircraft noise levels under the flight paths during take-off and landing. Corresponding numerical predictions have been validated against experimental data (tab. 2).

The advantage of modelling methods is that they enable more thorough analysis of the influence of various factors (both separately and in combination) on aircraft noise levels. The effective perceived noise levels *EPNL* at noise monitoring points under the flight trajectory (No 2 for take-off and No 3 for landing, both are defined in accordance with ICAO requirements) and the area of the 90 EPNdB noise contour *S* were used as the noise impact criteria in the analysis.

The influence of such factors as speed and direction of wind (in the current investigation only the influence of wind on trajectory parameters has been considered because a reliable model for its acoustic effect was not available), condition and inclination of runway surface, usage of rolling start procedure on runway at take-off, are found to be insignificant.

Table 1

Spectrum-averaged indices of agreement *d* for various types of aircraft and engines (*m* - by-pass ratio)

Flight stage or operation mode	Turbojets and low-by-pass turbofans (1≤ *m* ≤2.3)	High-by-pass turbofans (2.4≤ *m* ≤5.6)
Take-off	0.88	0.93
Climbing	0.86-0.93	0.84-0.92
Climbing with throttle-back of engines	0.83-0.97	0.85-0.95
Landing	0.89-0.97	0.84-0.94

Table 2

Comparison of predicted and measured noise levels *EPNL* for aircraft in operation

Type of	Take-off, monitoring point No 2		Landing, monitoring point No 3	
	predicted	measured	predicted	observed
Tupolev-154	99.2	100.1±1.2	105.8	106.0±0.9
Tupolev-154M	98.3	98.4±0.9	100.7	102.1±0.5
Tupolev-204	97.0	96.0±2.6	102.2	99.9±2.7
Yakovlev-40	91.2	90.3±3.9	98.7	97.2±3.8
Yakovlev-42	93.8	93.4 ±0.7	103.7	102.4±1.6
Il’ushin-62M	100.2	102.9±2.5	100	103.5±3.8
Il’ushin-86	107.6	107.41±0.6	105.7	105.1±03

The important factors that influence the noise levels are predicted to be the take-off (or landing) mass of the aircraft and the ambient atmosphere temperature. The main conclusion of this section is the necessity of accounting for the influence of certain operational factors when calculating noise levels around airport. Moreover, if these calculations are connected with noise zoning and land use planning, the worst possible operational conditions must be considered. These will correspond to the highest intensity of aircraft movement, the highest in-flight masses, and the highest ambient temperatures i.e. the warmest season of the year. The ISA conditions are also interesting and must be used when comparing the calculation results for different airports and for other operational circumstances.

Conclusion

Acoustic models and appropriate methods for aircraft noise predictions around airports have been designed. The basic principles of the methodology are in good accordance with current national and international requirements for aircraft noise assessment methods. Their accuracy and uncertainty are in accordance with the requirements of procedures used for noise control purposes – administrative and economic.

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