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EQUIVALENT CALCULATION METHOD OF FLYOVER NOISE LEVEL OF CUTBACK TAKE-OFF FOR CIVIL JET AIRPLANE AIRWORTHINESS CERTIFICATION

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Abstract

The airworthiness regulations permit the use of engine power cutback take-off procedure to demonstrate the compliance of flyover noise level for large civil subsonic jet airplane. In this paper, we propose a high-precision and widely applicable equivalent method for calculating the flyover noise of engine power cutback for large subsonic jet airplane type airworthiness certification. Firstly, based on the Noise-Power-Distance (N-P-D) database established by the equivalent flight test procedure, the tone-corrected perceived noise level adjusted for reference conditions（PNLT_r） versus power and distance database is constructed for the equivalent calculation of engine power cutback flyover noise. Secondly, the construction method of PNLT_r history and time interval corresponding to the reference flight track are derived. Then the equivalent calculation method of the flyover noise level is carried out based on the constructed PNLT_r history. Finally, the method is verified by using flight test results of civil subsonic jet airplane ARJ21-700, and the optimal control method of flyover noise level is analyzed. The results show that the proposed method meets the airworthiness regulations and can be used to obtain the equivalent flyover noise level for any engine power cutback condition based on the N-P-D database, and can be directly used for flyover noise optimization.

Keywords: flyover noise; airworthiness certification; engine power cutback; flight test; flyover noise optimization

1. General Introduction

Large civil subsonic jet airplane usually has a certain engine power reserve and engine power cutback take-off procedure can be used [1-3]. This procedure could reduce the length of time of engine heavy load operating condition, improve the reliability and operating efficiency, reduce the pollutant emission, and reduce maintenance cost. The engine power cutback optimization [2-3] also may lead to reduction of flyover effective perceived noise level (EPNL) to meet the increasingly stringent noise limit of airworthiness regulations [4-7] and reserve an even larger margin of noise limitation.

Researchers have conducted numerous studies about ground noise characteristics of engine power cutback take-off procedure. Grantham W D et al [8], FAA [9-10] and Antoine N E [11-12] found that the ground noise level of civil airplane can be reduced by engine power reduction and flight status optimization. The take-off and landing procedures for community noise abatement have been developed. Shankar [3] proposed a dynamic cutback optimization method for flyover noise reduction and analyzed the effect of power reduction initial altitude and spool down behaviors. The studies of Crichton D et al [13] explored the effects of engine thrust ratio, nozzle area, jet speed, fan speed and other characteristics on the flyover noise during take-off phase, and proposed a take-off profile to reduce the noise level. Some researchers [14-15] proposed an equivalent flyover noise calculation method based on noise time history construction and conducted a series of studies on engine power cutback optimization for civil jet airplane in airworthiness certification. Zhang et al [16] investigated the flyover noise optimization method for a given engine power cutback configuration and proposed a flyover noise minimization method by finding the optimal initial implementation point. Researchers from China [17-18] conducted the equivalent method recommended by ICAO [19-20] to calculate flyover EPNL of engine power cutback take-off procedure for civil jet airplane airworthiness certification. These studies focused on the impact of engine power cutback take-off procedure on ground noise and promoted the development of relevant provisions of airworthiness regulations.

The certification noise level not only determined by aircraft noise sources, but also relate to the flight status and test environment. According to the noise airworthiness regulations[4-7], the noise compliance flight test and noise level calculation method must meet the relevant provisions. The engine power cutback take-off procedure changes the aircraft noise source characteristics and take-off profile, resulting in the flyover noise level no longer be measured and evaluated easily in accordance with the reference procedures given in the airworthiness regulations. A reasonable equivalent compliance flight test and noise level calculation method need to be developed.

The ICAO Environmental Technical Manuals [19] and advisory circular of airworthiness regulations [20-22] allow to use equivalent flyover noise level evaluation method based on equivalent noise certification flight test data for engine power cutback take-off procedure. Some sketchy recommendations of flyover noise level calculation are given as follows: Flyover noise levels with power reduction may be established from the merging of tone-corrected perceived noise level adjusted for reference conditions versus time (i.e. PNLT_r history) measurements obtained during constant power operations. As long as PNLT_r history, the average engine spool-down power characteristics, and the flight track during this period, which includes the transition from full to reduced power, are known, the flyover noise level may be computed.

But for some cases, the constructed PNLT_r history between 10 dB-down of maximum tone-corrected perceived noise level adjusted for reference conditions ($\mathrm{PNLT}_r\mathrm{M}-10$ dB-down) may contain noise time history portions of normal engine power climb, reduced engine power climb and engine spool-down, which makes the flyover EPNL evaluation more complicatedly. Firstly, the equivalent compliance flight test should choose a wide range of engine power settings reasonably to ensure that enough test data are gathered. Secondly, when the $\mathrm{PNLT}_r\mathrm{M}-10$ dB-down contains two or more phases of engine power condition, the specific equivalent calculation method for flyover EPNL need to be developed. Especially for the engine spool down phase, the PNLT_r history construction method should be proposed to improve accuracy. Finally, how to achieve a minimum flyover EPNL by optimizing the engine power cutback procedure needs to be investigated. The existing airworthiness regulations and related materials do not give enough specific practical technical recommendations.

Pursuant to the relevant provisions of ICAO ANNEX 16 Vol. I [4] and CAAC CCAR-36 [5], this paper proposes a high-precision and widely applicable equivalent method for calculating the flyover noise level of engine power cutback take-off based on N-P-D database for subsonic jet airplane airworthiness certification. The flyover noise EPNL_r of engine power cutback are calculated by constructed PNLT_r history. The PNLT_r history of different flight phase separated by engine power setting is constructed respectively to improve precision and universality. For the normal take-off engine power climb phase and reduced engine power climb phase, the conventional PNLT_r history construction method is adopted. But for the engine spool down phase, a different construction approach is presented. Then the flyover noise level equivalent calculation method is validated by noise certification flight test data of a regional civil jet airplane ARJ21-700 [17-18, 23]. Finally, a general process for flyover noise optimization based on the proposed flyover noise equivalent calculation method is developed to determine the optimal engine power reduction initial height for any pre-specified engine power. The application analysis of this optimization process is carried out to find optimal flyover EPNL of ARJ21-700.

2. Calculation method of EPNL Based on N-P-D

According to ICAO ANNEX 16 and CCAR-36, noise certification flight tests of flyover noise of subsonic jet airplane can be performed using basic procedure or equivalent procedure [4-5, 19-20]. A typical take-off profiles are illustrated in Figure 1. For the approved normal power take-off profile of basic flight test procedure, the airplane begins the take-off roll from point A' with maximum take-off weight, lifts off at point B' and begins its climb at a constant angle and stable flight status at point C'. After that it passes point D located above the reference flyover noise measuring point K' and ends climb at point F. The noise measured at reference measuring point corresponding to the C-E section of the flight track should contains the $\mathrm{PNLT}_r\mathrm{M}-10$ dB-down. Then the airplane must land to refuel for next test run. Where engine power cutback procedure is used, it is started at point P and completed at point Q. From here, the airplane begins a second climb at a constant angle up to point F', the end of the flight track of this test run. The airworthiness regulations allow the use of equivalent flight test procedure to establish N-P-D database (the equivalent procedure referred to as the N-P-D procedure hereafter), and the certification noise levels can be derived based on it. The N-P-D procedure adopts flight path intercept process. Noise certification flight test runs can be conducted continuously with intercepting the target flight track without performing an actual landing and take-off for each test run. As shown in Figure 1, after the airplane passes point F, a test run is completed, the airplane adjusts flight path and fly to point A, reaches the approved flight status and configurations at point B, intercepts the target flight track at point C'. After that it climbs at a constant angle and stable flight status to passes point C, D, E, end up to point F. Then this test run completed and next test run still can be conducted by adopting the above process.

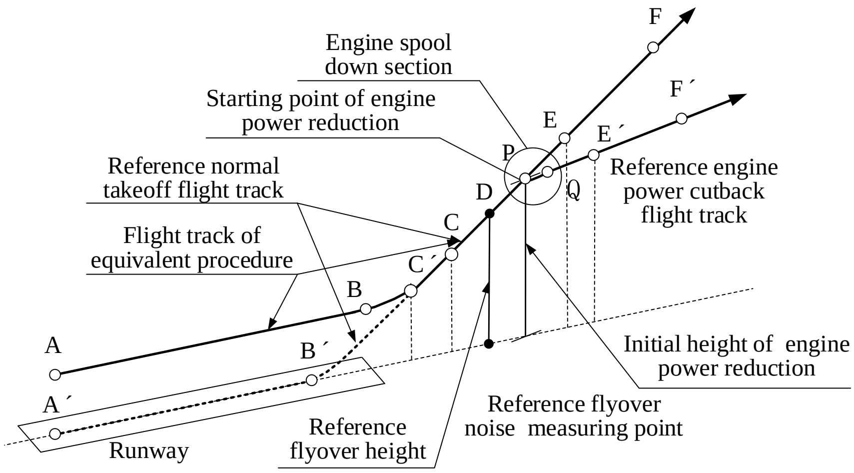


Figure 1 - Typical take-off profiles of flyover noise measurement

The N-P-D procedure usually sets a number of flight test runs to measure the flyover noise levels by flying over target altitude above the noise measuring point with a series of engine power settings. Due to the N-P-D procedure adopts flight path intercept process, several test runs can be completed in one flight to improves the test efficiency. The noise measuring points can be arranged flexibly which reduces the difficulty of test site preparation and improves the validity of the test data. N-P-D database contains a wealth of information of aircraft noise characteristics, which can be derived to obtain the certification noise level of derived airplane versions and acoustic change. It also contains the dataset for engine power cutback take-off flyover noise level evaluation by an equivalent method.

According to ICAO ANNEX 16 and CCAR-36, the criteria of the flyover noise level evaluation of civil jet airplane noise certification is EPNL [4-5]. Usually, the flight tracks and meteorological conditions of the N-P-D procedure are usually different from the references. So the flyover noise levels need to be adjusted to the reference flight track under reference meteorological conditions. Figure 2 shows schematic of flight track adjustment of flyover noise measurement, where K is the actual flyover noise measuring point, C-D-E is the actual flight track, K' is the reference flyover noise measuring point, C'-D'-E' is the reference flight track. Taking integrated method of adjustment [4-5] method as an example, the effective perceived noise level in the reference conditions (EPNL_r) can be calculated according to the following expression

$$\mathrm{EPNL}_r = 10\log_{10}\left[0.1\sum_{k=1}^{n}\Delta t_r(k)\,10^{0.1\mathrm{PNLT}_r(k)}\right] \quad (1)$$

where $\Delta t_r(k)$ is the length of time increment in the reference conditions. $\mathrm{PNLT}_r(k)$ is the tone-corrected perceived noise level in the reference conditions, which is derived by $\mathrm{SPL}_r(i,k)$. $\mathrm{SPL}_r(i,k)$ is obtained by adjusting $\mathrm{SPL}(i,k)$ to the reference conditions as follows

$$\mathrm{SPL}_r(i,k) = \mathrm{SPL}(i,k) + 0.01\left[\alpha(i) - \alpha_0(i)\right]r(k) + 0.01\alpha_0(i)\left[r'(k) - r(k)\right] + 20\log_{10}\left[\frac{r'(k)}{r(k)}\right] \quad (2)$$

where $\alpha(i)$ and $\alpha_0(i)$ are the sound attenuation coefficients for the flight test and reference atmospheric conditions in the frequency band i respectively. $r(k)$ and $r'(k)$ are the sound propagation paths length for the flight test track and reference track respectively.

The corresponding reference flight track C'-D'-E' of $\mathrm{PNLT}_r\mathrm{M}$-10 dB-down can be determined by keeping the sound emission angle of each flight track segment equal, i.e. $\theta_k = \theta_k'$. Then $\Delta t_r(k)$ and n can be calculated. After that $\mathrm{PNLT}_r(k)$ can be obtained by $\mathrm{SPL}_r(i,k)$ computed by Eq. (2). At last use Eq. (1) to calculate the EPNL_r.

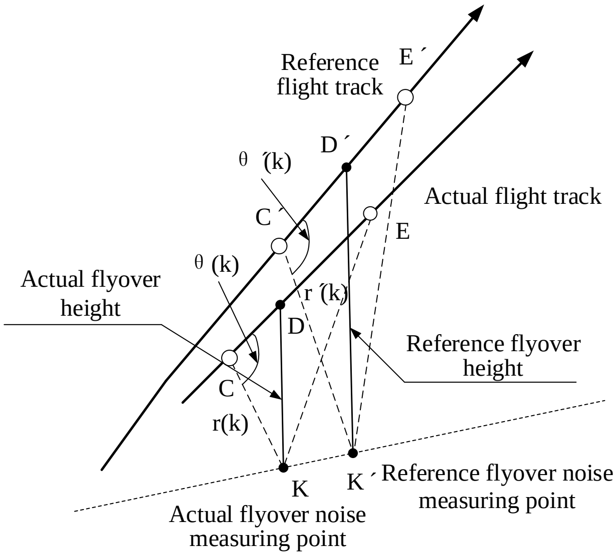


Figure 2 - Schematic of flight track adjustment of measured flyover noise

For the N-P-D procedure, the flyover noise levels at each engine power setting can be adjusted to the reference conditions by above process. Then the N-P-D database are established for flyover noise. EPNL_r for any pre-specified engine power setting can be calculated by the following equation

$$\mathrm{EPNL}_r(p) = A + Bp + Cp^2 \quad (3)$$

where A, B and C are coefficients of the quadratic polynomial. p is characteristic indicator parameter of engine power. For the airworthiness approved normal take-off engine power, the flyover noise level EPNL_r can be calculated by Eq. (3).

3. Equivalent Flyover EPNL calculation method of engine power cutback

As shown in Figure 1, for engine power cutback take-off procedure, the airplane climbs at approved normal take-off engine power to a predetermined engine power reduction altitude (point P), then reduces the engine power to a predetermined value quickly, begins a second climb until it reaches the test run end point F. Due to the engine power reduction, the flight track corresponding to

$\mathrm{PNLT}_r\mathrm{M}-10$ dB-down changed from C-D-P-E to C-D-P-Q-E', the measured flyover noise changes accordingly. In this situation, the EPNL_r calculation method based on conventional $\mathrm{N\text{-}P\text{-}D}$ database, stated from Eq. (1) to Eq. (3), no longer can be applied directly any more. Consequently, based on the $\mathrm{N\text{-}P\text{-}D}$ database established by equivalent flight test procedure, an equivalent calculation method for engine power cutback flyover noise level is proposed as follows.

3.1 Calculate flyover noise level based on PNLT_r history

According to airworthiness regulations [4-7], average normal take-off engine power must be used from the start of take-off to the point where at least a certain height above runway level is reached. These provisions only limit the starting height for engine power reduction and minimum engine power can be reduced to. It means that the engine power cutback manner, such as the engine power reduction initial height and the engine power reduction value, can be chosen according to the actual situation. So there are three common cases for engine power cutback flyover noise evaluation, which are:

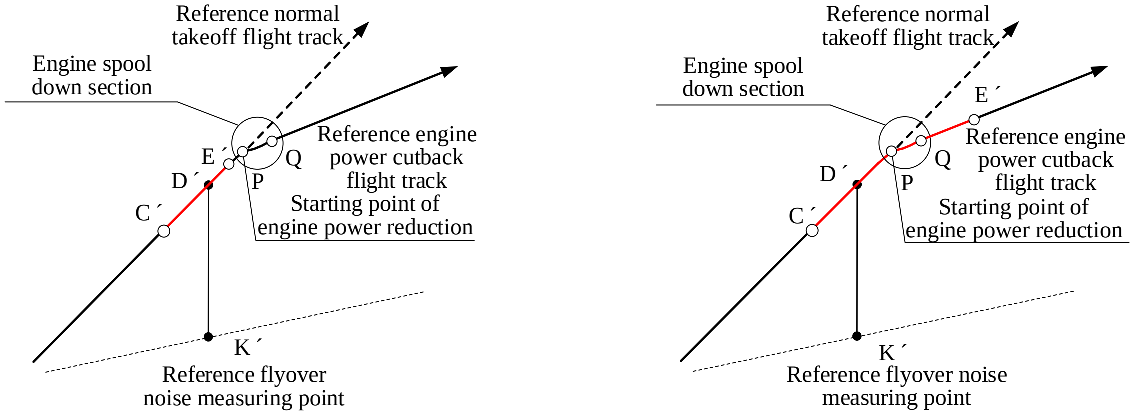
Case 1: The reference flight track section $\mathrm{C'\text{-}D'\text{-}E'}$ corresponding to $\mathrm{PNLT}_r\mathrm{M}-10$ dB-down lies entirely before the engine power reduction point P, as shown in Figure 3 (a).

Case 2: The reference flight track section $\mathrm{C'\text{-}D'\text{-}P\text{-}Q\text{-}E'}$ corresponding to $\mathrm{PNLT}_r\mathrm{M}-10$ dB-down contains two or three sections as follow: the normal take-off engine power climb phase section $\mathrm{C'\text{-}P}$, the engine spool down phase section $\mathrm{P\text{-}Q}$ and the reduced engine power climb phase section $\mathrm{Q\text{-}E'}$. The most complicated case is shown in Figure 3 (b).

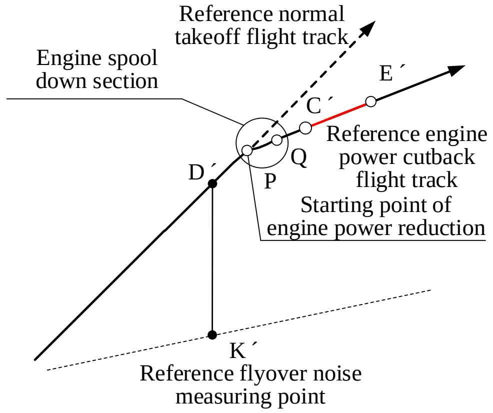
Case 3: The reference flight track section $\mathrm{C'\text{-}E'}$ corresponding to $\mathrm{PNLT}_r\mathrm{M}-10$ dB-down lies entirely after the engine spool down phase end point Q, as shown in Figure 3 (c).

Most complicated case is case 2 as shown in Figure 3 (b). This kind of case usually means that the moderate engine power reduction initial height and power reduction value are chosen. The reference flight track section corresponding to $\mathrm{PNLT}_r\mathrm{M}-10$ dB-down contains three reference flight track sections. In view of this situation, the flyover noise optimization can be achieved by finding the optimal engine power reduction initial height for any pre-specified engine power reduction. Usually for case 2 and case 3, the noise level of $\mathrm{PNLT}_r\mathrm{M}-10$ dB-down is lower than the normal take-off engine power case, as shown in Figure 4.

For the abovementioned three cases, according to the technical manual of airworthiness regulations [19-20], there are two ways for flyover EPNL_r calculation. The first one is a relatively easy way based on the $\mathrm{N\text{-}P\text{-}D}$ database, using Eq. (3) directly, which is applicable to case 1 and case 3. This is the basic application scenario of the $\mathrm{N\text{-}P\text{-}D}$ database. The second way is based on the PNLT_r history constructed by $\mathrm{N\text{-}P\text{-}D}$ database, to calculate the flyover noise level equivalently by Eq.(1). The second way can be applicable to the complicated case 2, as well as to the case 1 and case 3. Obviously, the second one is a widely applicable equivalent method. Based on this, a new integrated equivalent method for calculating the flyover EPNL_r is proposed as bellow.



(a) Case 1 (b) Case 2



(c) Case 3

Figure 3 - Three typical cases of flyover noise evaluation for engine power cutback take-off

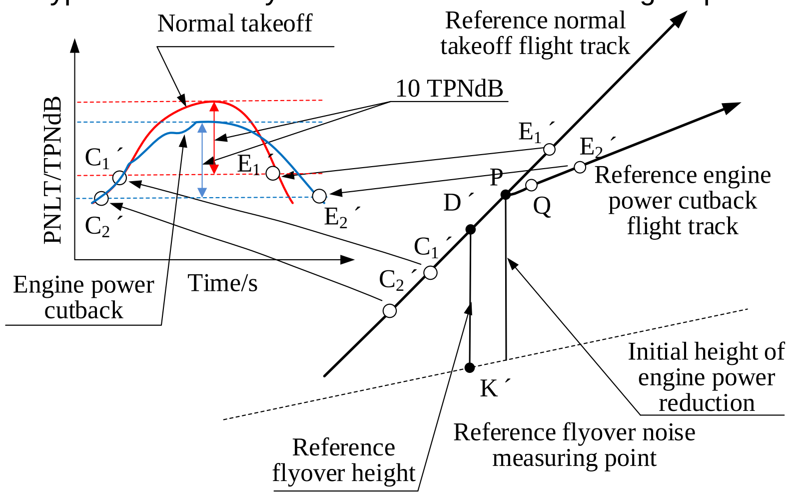


Figure 4 - The flyover noise $PNLT_r M-10$ dB-down and the corresponding reference flight track

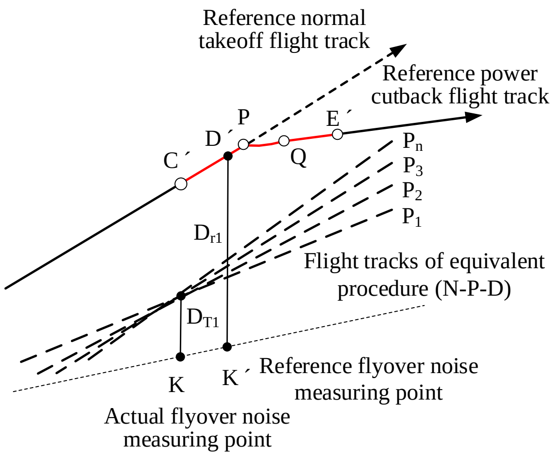
The flight profile based on equivalent N-P-D method is illustrated in Figure 5 (a). An example of the $PNLT_r$ history construction process are given below. The flyover noise data is extracted from a flight test project of a civil jet airplane ARJ21-700 [17-18, 23]. The following sections of this paper provide more information about the aircraft and the flight test project. As shown in Figure 5 (b), the $EPNL_r$-P-D database can be established by summarizing the data from 7 valid test runs (the key parameters are $EPNL_r$, flyover height and engine power value). We obtain $PNLT_r$-P-D database which is needed for normal engine power take-off flyover $EPNL_r$ calculation, as Figure 5 (c) shows. That is, the expression of $PNLT_r$ is as follow

$$PNLT_r = f\ \theta, p, H_r \tag{4}$$

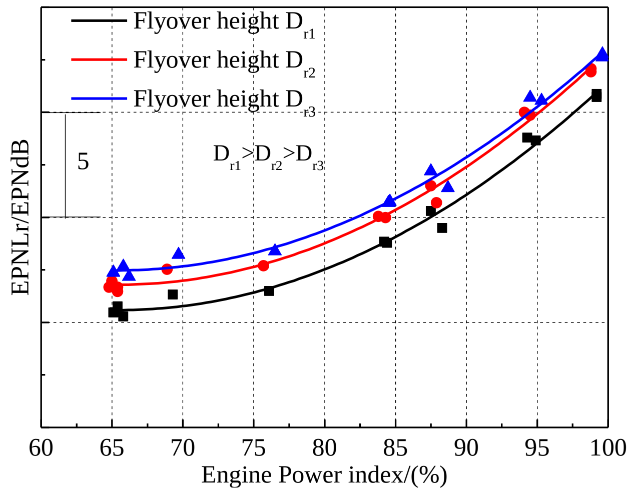
where p is characteristic indicator parameter of engine power, H_r is the reference flyover height, θ is noise emission angle defined as shown in Figure 2.

Based on $PNLT_r$-P-D database, $PNLT_r$ under any emission angle, flyover height and engine power value can be obtained by interpolation. So, according to the reference engine power cutback flight track C'-D'-P-Q-E' as shown in Figure 5(a), $PNLT_r$ versus noise emission angle can be synthesized. Then the $EPNL_r$ can be calculated by Eq. (1). Figure 5 (d) plots an example of $PNLT_r$ history constructed by $PNLT_r$-P-D database as shown in Figure 5 (c). It is shown that the $PNLT_r$ history construction process does not need actual flight tests. The flyover noise level of engine power cutback take-off procedure is calculated by the synthesized $PNLT_r$ history. It yields essentially the same noise level to the real flight tests. So this method is a so-called equivalent method.

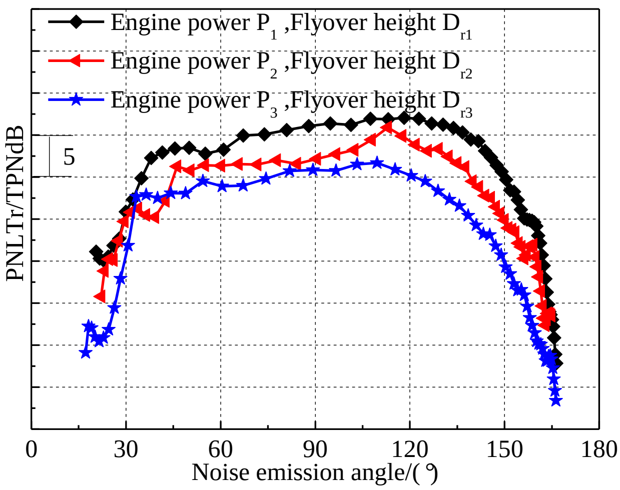
The $PNLT_r$ history of engine power cutback is constructed by interpolation of $PNLT_r$-P-D database which is actually calculated by data measured from test runs. There are some additional considerations for the design of flight test runs of the equivalent N-P-D method. Firstly, the engine power value of flight tests should cover the range from pre-determined cutback power to maximum take-off power. Ensure that there is no engine power extrapolation as far as possible. Secondly, a much longer noise measurement should be conducted for each test run effectively. It means that more PNLT_r data should be calculated than $\mathrm{PNLT}_r\mathrm{M}-10$ dB-down contained for each test run than ever. Ensure that there is no noise emission angle extrapolation as far as possible.



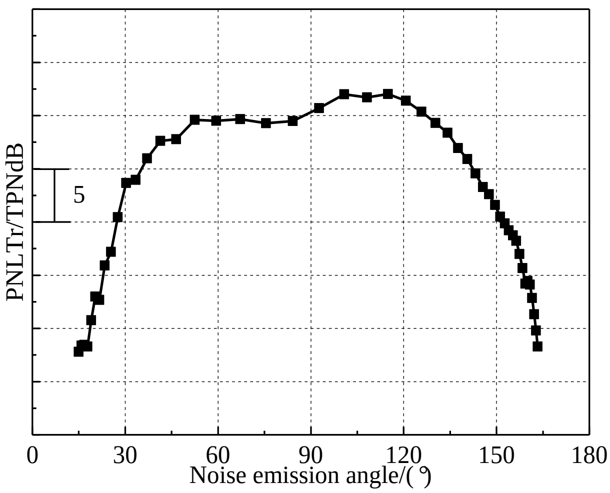
(a) The flight track



(b) Flyover Noise N-P-D Database



(c) PNLT-P-D database



(d) Constructed PNLT_r history

Figure 5 - Equivalent calculation process of flyover noise level of engine power cutback take-off

So far, the equivalent calculation process of engine power cutback take-off flyover noise level has been presented briefly. The following two subsections introduce the method of PNLT_r history construction and the method of time increment $\Delta t_r\ k$ calculation respectively.

3.2 The method of PNLT_r history construction

As shown in Figure 5(a), the actual flight tracks of N-P-D test runs are differ from the reference flight track. According to the relevant provisions of airworthiness regulations [4-7], the 1/3 octave band sound pressure levels $\mathrm{SPL}(i,k)$ of each time increment of the test runs need to be adjusted to $\mathrm{SPL}_r(i,k)$ in the reference conditions through Eq. (2). The PNLT_r of each time increment corresponding to reference flight track segment can be calculated by $\mathrm{SPL}_r(i,k)$. Then the PNLT_r-P-D database is obtained. The PNLT_r history of engine power cutback versus noise emission angle could be constructed by interpolation of PNLT_r-P-D database.

Take the most complicated case shown in Figure 3(b) for example. As shown in Figure 6, the reference flight track corresponding to $\mathrm{PNLT}_r\mathrm{M}-10$ dB-down contains three sections as follow: the normal take-off engine power climb phase $\mathrm{C}'\text{-}\mathrm{P}$, the engine spool down phase $\mathrm{P}\text{-}\mathrm{Q}$ and the reduced engine power climb phase $\mathrm{Q}\text{-}\mathrm{E}'$. For each section, the PNLT_r history is constructed respectively. Then the PNLT_r history of $\mathrm{PNLT}_r\mathrm{M}-10$ dB-down is merged by these sections.

For the sections of normal take-off engine power climb phase and reduced engine power climb phase, the engine power is set at predetermined value respectively. According to the relevant provisions of airworthiness regulations [4-7], the measured flyover noise should be analyzed at each time increment(usually $\Delta t\ k$ is 0.5s). So the actual flight test tracks are segmented by time increment $\Delta t\ k$ .The corresponding reference flight track $\mathrm{C}'\text{-}\mathrm{P}$ and $\mathrm{Q}\text{-}\mathrm{E}'$ shown in Figure 6 can be determined by keeping the sound emission angle of each flight track segment equal, i.e. $\theta_k = \theta'_k$. The reference flight track $\mathrm{C}'\text{-}\mathrm{P}$ contains segments from Q'_1 to Q'_{L-1} and the reference flight track $\mathrm{Q}\text{-}\mathrm{E}'$ contains segments from Q'_{m+1} to Q'_{n_r}. Assume that the airplane complete an entire test run only with the normal take-off power and reduced engine power respectively. For each flight test engine power value and reference flyover height ($\mathrm{K}'\mathrm{D}'$ for normal take-off power and $\mathrm{K}'\mathrm{D}''$ for reduced engine power), establish the PNLT_r-P-D database. The corresponding noise emission angel can be calculated by the position of flight track segment and flyover noise measuring point. Based on the PNLT_r-P-D database, PNLT_r can be obtained by liner interpolation. Due to the reference flyover height is a constant, the PNLT_r can be interpolated by engine power value and sound emission angle in turn. Figure 7 gives an example, the constructed PNLT_r history of normal take-off engine power climb phase is illustrated by black curve marked by triangle symbol, and the constructed PNLT_r history of reduced engine power climb phase is illustrated by blue curve marked by circle symbol.

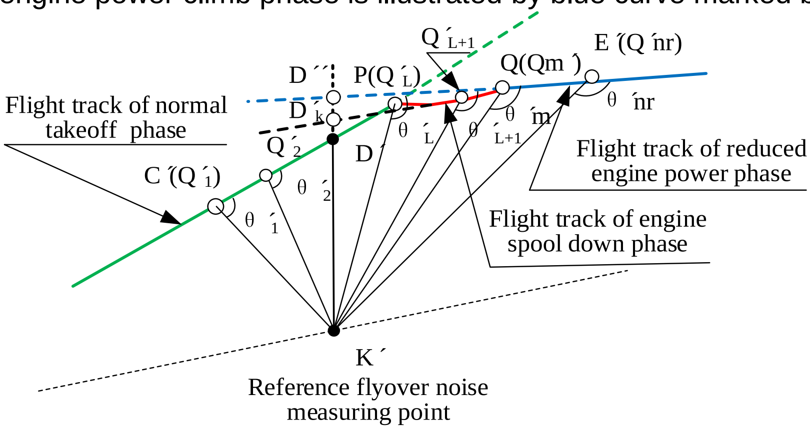


Figure 6 - The segment method of the reference flight track corresponding to $\mathrm{PNLT}_r\mathrm{M}-10$ dB-down

For the section of engine spool down phase, because of the engine power and climb angle are vary with time, the construction process of the PNLT_r history is more complicated than others. As shown in Figure 4(a), the engine spool down period of engine sometimes too short to be segmented like the sections of normal take-off engine power climb phase and reduced engine power climb phase. The engine spool down flight track maybe contains too few segments to lead to fairly non-ignorable errors for noise calculation. The section 4 of this paper provide further discussion about this. To solve this problem, the reference flight track is segmented directly with equal time increment Δt, which is short enough to ensure that the flight track segment numbers are sufficient (for example $\Delta t = 0.2$ s). As shown in Figure 6, the reference flight track $\mathrm{P}\text{-}\mathrm{Q}$ contains segments from Q'_L to Q'_m. For the segment $\mathrm{Q}'_k \in \mathrm{Q}'_L, \mathrm{Q}'_m$, assume that the airplane complete an entire test run with the corresponding constant engine power and constant climb angle. The PNLT_r-P-D database can be established based on this engine power and flyover height $\mathrm{K}'\mathrm{D}'_k$ .As shown in Figure 6, D'_k is the intersection of the extension of this flight track segment and $\mathrm{K}'\mathrm{D}'_k$. The corresponding noise emission angel can be calculated by the position of this flight track segment and flyover noise measuring point. Then PNLT_r can be interpolated by the $\mathrm{PNLT}_r\text{-P-D}$ database. In the same way, due to the reference flyover height is a constant, the PNLT_r can be obtained by liner interpolation with parameters engine power value and sound emission angle in turn. The PNLT_r history of engine spool down phase can be obtained by merging the PNLT_r of segments from Q'_L to Q'_m. As shown in Figure 7, the constructed PNLT_r history of engine spool down phase is illustrated by the red curve marked by square symbol.

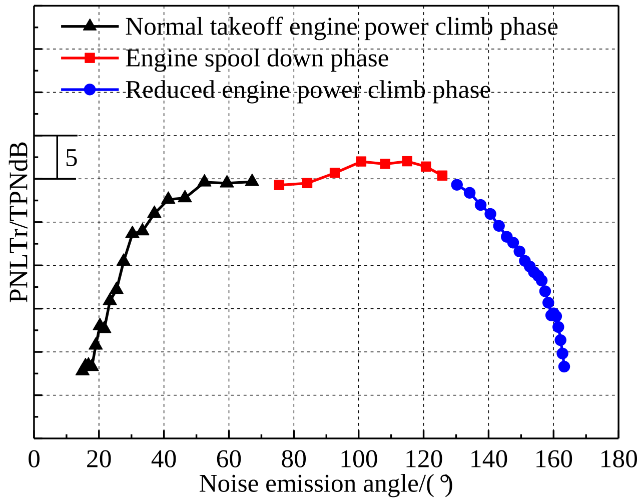


Figure 7 - A typical example of constructed flyover noise PNLT_r history

So far, the PNLT_r history of $\mathrm{PNLT}_r\mathrm{M}-10$ dB-down of flyover noise can be obtained by merging the sub-histories established above, include normal take-off engine power climb phase, reduced engine power climb phase and engine spool down phase, as shown in Figure 7.

The noise emission angle must be calculated when establishing the $\mathrm{PNLT}_r\text{-P-D}$ and PNLT_r history. It is known that, the reference flight track is pre-determined and the actual flight track and noise measuring point can be measured directly. So the noise emission angle of *k*th flight track (the reference flight track or actual flight track) can be calculated by the spatial geometry illustrated in Figure 8. In this figure, the subscript "*e*" indicates the airplane position at the time of noise emission.

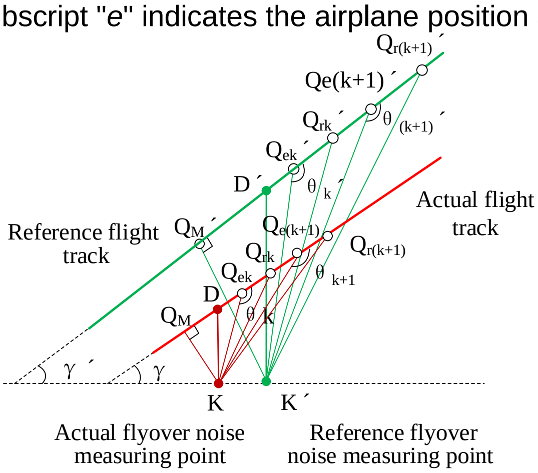


Figure 8 - Schematic diagram of noise emission angle and sound propagation time calculation

The *k*th noise emission angle θ'_k of reference flight track can be calculated by

$$\theta'_k = \mathrm{asin}\left|\mathrm{K}'\mathrm{Q}_M'\right| / \left|\mathrm{K}'\mathrm{Q}'_{ek}\right| \tag{5}$$

where $\left|\mathrm{K}'\mathrm{Q}_M'\right|$ is the vertical distance from the reference flyover noise measuring point K' to the reference flight track. $\left|\mathrm{K}'\mathrm{Q}'_{ek}\right|$ is the distance from the sound emission point Q'_{ek} to the reference flyover noise measuring point K'. Actually, $\left|\mathrm{K}'\mathrm{Q}'_{ek}\right|$ is the sound propagation path length and can be calculated by the following expression

$$\left|\mathrm{K}'\mathrm{Q}_{ek}{}'\right| = \Delta t_{rk} c_r \tag{6}$$

where c_r is the speed of sound at reference conditions. Δt_{rk} is the sound propagation time of the corresponding reference flight track segment.

3.3 The method of time increment $\Delta t_r\ k$ calculation

According to the constructed PNLT_r history, EPNL_r of the engine power cutback take-off flyover noise can be obtained by equation (4). But it also need to calculate the time increment $\Delta t_r\ k$ for each reference flight track segment. As shown by the flight track adjustment schematic in Figure 2, in order to measuring noise at high signal-to-noise ratio, the target flyover height for flight test is lower than reference flyover height. So the time increment $\Delta t\ k$ of actual flight track segment and the time increment $\Delta t_r\ k$ of corresponding reference flight track segment are usually not equal, and most of the time $\Delta t_r\ k$ is longer than $\Delta t\ k$. As mentioned before, in order to improve the accuracy of PNLT_r history construction of engine spool down phase, the reference flight track is segmented directly with a predetermined equal time increment, which does not need to be calculated. For the normal take-off engine power climb phase and reduced engine power climb phase, the $\Delta t_r\ k$ for each reference flight track segment need to be calculated by following expression[19-20]

$$\Delta t_r\ k = \left[\Delta t_{rk} + \Delta t_{r\ k-1}\right]/2 \tag{7}$$

where Δt_{rk} is the sound propagation time of the k th segment of reference flight track, which is calculated as follows

$$\Delta t_{rk} = \begin{cases} \dfrac{\left|K'Q'_M\right|}{\left|KQ_M\right|}\ \alpha_1 + \alpha_2\ , \quad 1 \le k \le L-1 \text{ and } m+1 \le k \le n_r \\ \left[\Delta t_k + \Delta t_{\ k-1}\right]/2, \qquad\qquad L \le k \le m \end{cases} \tag{8}$$

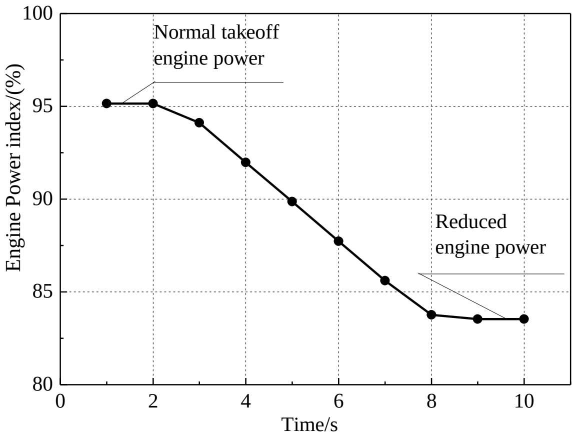
where l and m are numerical index that denote the first segment and the last segment of flight track of engine spool down phase respectively, as shown in Figure 6. α_1 and α_2 are given by

$$\begin{cases} \alpha_1 = \dfrac{V_T}{V_r}\left[0.5 - \ \Delta t_{Tp\ k+1} - \Delta t_{Tpk}\ \right] \\ \alpha_2 = \dfrac{c_T}{c_r}\ \Delta t_{Tp\ k+1} - \Delta t_{Tpk} \end{cases} \tag{9}$$

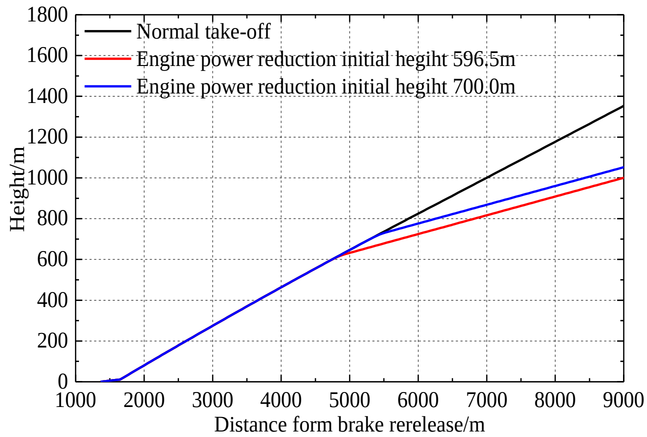
where V_r is the ground speed of the airplane at reference conditions. V_T is ground speed of the airplane at flight test conditions. Δt_{Tpk} is the sound propagation time of the k th segment of actual flight track at flight test conditions. c_T is the speed of sound at flight test conditions.

4. Validation of the equivalent method

Flyover noise flight test results of a civil jet airplane ARJ21-700 [17-18, 23] are used for validating the equivalent calculation method of engine power cutback flyover noise level. This airplane is a twin-engine regional airliner, the maximum take-off mass is 40500kg. The noise certification flight tests were carried out in accordance with CCAR-36 [5] and 14 CFR Part 36 [6]. In order to verify the method proposed in this paper, two engine power reduction initial height 596.5m (Case 1) and 700.0m (Case 2) are selected. The airworthiness approved engine power reduction value is $\mathrm{P}^0_{\mathrm{cutback}}$, the engine spool down time history obtained by flight test is depicted in Figure 9(a). Based on the engine spool down characteristics, the reference flight tracks are calculated as illustrated in Figure 9(b). For case 1, the reference flight track section corresponding to $\mathrm{PNLT}_r\mathrm{M}$-10 dB-down lies entirely after the engine spool down phase, which is consistent with the case shown in Figure 3(c). As mentioned above, the flyover noise level of this case can either be calculated based on the N-P-D database by Eq. (3) or calculated by the equivalent method proposed in this paper. So the correctness of the equivalent method can be verified by comparing the results of the two ways. For case 2, the reference flight track section corresponding to $\mathrm{PNLT}_r\mathrm{M}-10$ dB-down contains three phase as follow: the normal take-off engine power climb phase section, the engine spool down phase section and the reduced engine power climb phase section, which is consistent with the most complicated case shown in Figure 3(b). This case is employed to verify of the general applicability of the equivalent method and analyze the improvement of the flyover noise level calculation accuracy.



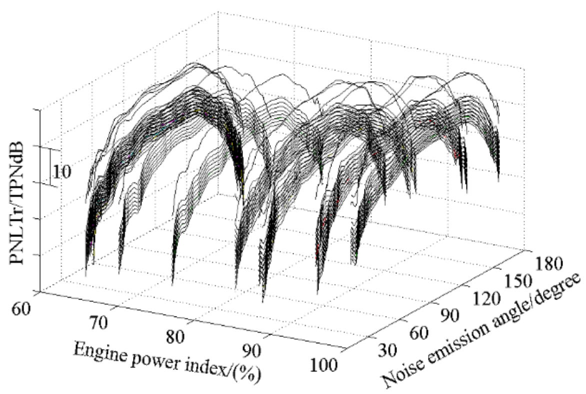
(a) Engine spool down time history



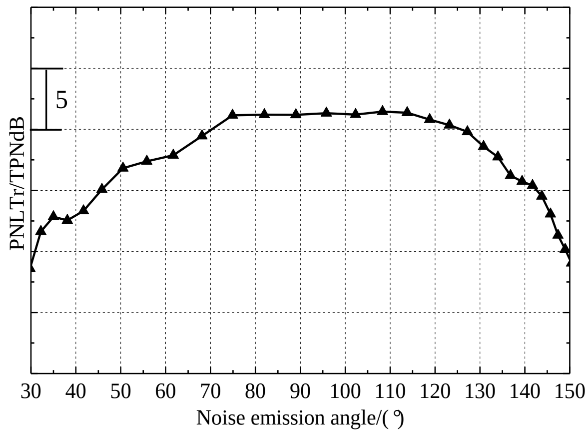
(b) Reference flgiht track

Figure 9 - The engine spool down characteristics and reference flight track of ARJ21-700

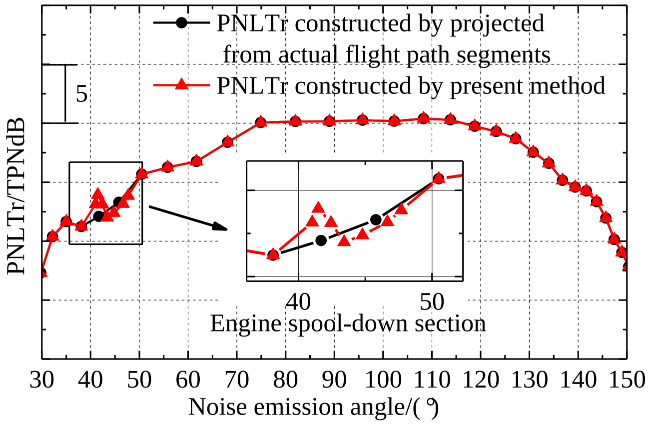
Base on the flight test data, the $\mathrm{PNLT}_r\text{-}\mathrm{P}\text{-}\mathrm{D}$ database can be established as shown in Figure 10(a), which is a dataset of $\mathrm{PNLT}-\theta$ history versus engine power index. According to the reference flight track shown in Fig 9(b) and $\mathrm{PNLT}_r\text{-}\mathrm{P}\text{-}\mathrm{D}$ database shown in Fig 10(a), the PNLT_r history of case 1 and case 2 are constructed by the method proposed in this paper, as shown in Fig 10(b) and Fig 10(c). Then the flyover noise levels can be calculated equivalently and given in table 1. Table 1 shows the EPNL_r of the engine power cutback flyover noise calculated by the equivalent method proposed in this paper which use Eq. (3) based on the N-P-D database. For case 1, the EPNL_r of the two methods are basically in the same. It shows that the present method can calculated the flyover noise level correctly. For case 2, only the present method is applicable. This means that the method proposed in this paper can be applied to all engine power cutback situations, as illustrated in Figure 3. It also can be seen from Figure10(c) that, there are much more data of the $\mathrm{PNLT}_r-\theta$ history corresponding to the engine spool down section constructed by the method presented in section 3.2. That's why the accuracy of noise calculation is improved.



(a) $\mathrm{PNLT}_r\text{-}\mathrm{P}\text{-}\mathrm{D}$ database



(b) $\mathrm{PNLT}_r-\theta$ history of case 1



(c) $PNLT_r - \theta$ history of case 2

Figure 10 - The constructed $PNLT_r$-P-D database and $PNLT_r - \theta$ history of ARJ21-700

Table 1 - Flyover noise calculated results of ARJ21-700

Calculation method	Flyover noise level ($EPNL_r$) (EPNdB)	
	Case 1:Cutback initial height is 596.5m	Case2 : Cutback initial height is 700.0m
The method based on the N-P-D database using Eq. (3) [17-18]	82.09	Not applicable
The equivalent calculation method proposed in this paper	82.24	81.87

5. Optimization of flyover noise level

The airplane/engine noise source and the sound propagation characteristics are changed when the engine power cutback take-off procedure is employed. As shown in Figure 3, even though the engine power reduction value is determined, there are three cases of the reference flight track section corresponding to $PNLT_rM-10$ dB-down time interval. The length of noise propagation path changes and affects the flyover noise level. According to the related provisions of airworthiness regulations [4-7], the engine power cutback manner, such as the engine power reduction initial height and the derated engine power value, can be selected by type certification applicant under some technical limitations. It means that the flyover noise could be optimized by finding the optimal engine power reduction initial height and the derated engine power value reasonably.

Based on the equivalent evaluation method of engine power cutback take-off flyover noise level proposed in this paper, the flyover noise levels can be calculated for any selectable engine power cutback manner. The flyover noise optimization can be achieved by searching for the minimum of the flyover noise level dataset. This can be performed by the following steps:

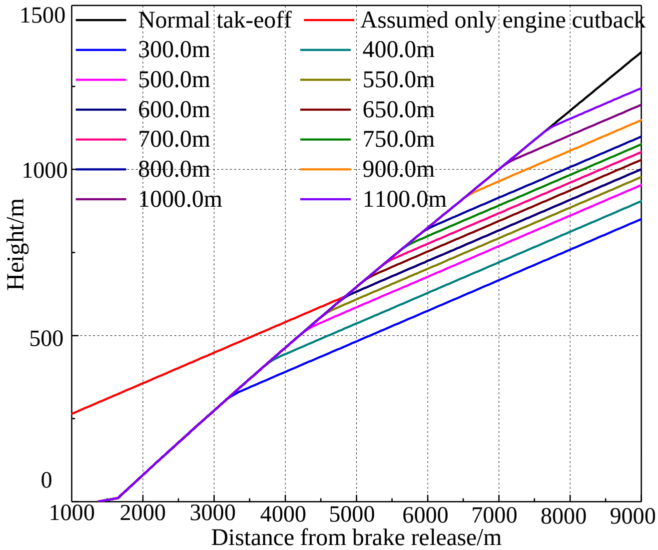
(1) to establish $EPNL_r - H_{cutback}$ dataset (dataset of $EPNL_r$ versus engine power reduction initial height $H_{cutback}$) of a pre-determined derated engine power value. Assume that a series of engine power reduction initial height which meet the limitations of airworthiness regulations [4-7] are selected. The reference flight track of engine power cutback take-off procedure can be calculated. And then the $EPNL_r$ for each supposed engine power reduction initial height $H_{cutback}$ can be calculated by the present equivalent evaluation method.

(2) to establish $EPNL_r - H_{cutback}$ dataset of other selectable engine power reduction value by means of above-mentioned process.

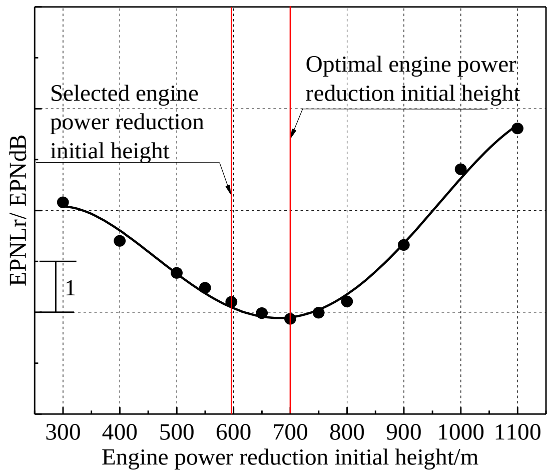
(3) to establish $EPNL_r - H_{cutback} - P_{cutback}$ database by combining the $EPNL_r - H_{cutback}$ dataset obtained from above-mentioned two steps.

(4) to find the minimum $EPNL_r$ in the $EPNL_r - H_{cutback} - P_{cutback}$ database reasonably. The corresponding engine power reduction initial height and engine power reduction value are the optimal selection for engine power cutback procedure design. But it should be noted that the optimal manner of engine power cutback does not always correspond to the minimum $EPNL_r$ in the $EPNL_r - H_{cutback} - P_{cutback}$ database. That is because the airplane take-off profile design should consider some other factors, such as the flight performance limitations, the economy and safety demands, etc.

The application analysis of this optimization process is carried out to find minimum flyover noise of the aforementioned regional civil jet airplane ARJ21-700 [17-18, 23]. Based on the pre-determined engine power reduction value $P^0_{cutback}$ and the engine spool down history shown in Figure 9(a), a series of reference flight tracks are calculated for assumed engine power reduction initial heights $H_{cutback}$ from 300.0m to 1100.0m, as illustrated in Figure 11(a). The results show that , the distribution of the reference flight track sections corresponding to $PNLT_r M - 10$ dB-down time interval are vary with the engine power reduction initial height. The equivalent calculation method for engine power cutback flyover noise level proposed in this paper can be applied to all situations. Figure 11(b) gives the $EPNL_r - H_{cutback}$ polynomial curve fitted by least square method. It shows that there exist minimum flyover noise level ($EPNL_r$) with the engine power reduction initial height increasing, that is the optimal height is about 700.0m. Actually, the selected engine power reduction initial height is 596.5m for type airworthiness certification. So, in terms of flyover noise minimization control, there is still room for flyover noise level optimization. This shows that the optimization of flyover noise level of engine power cutback has practical significance.



(a) Reference flight tracks



(b) Flyover noise ($EPNL_r$) versus height

Figure 11 - The flyover noise level optimization of ARJ21-700

6. Conclusion

According to the relevant provisions of ICAO ANNEX 16 and CCAR-36, a high-precision and widely-applicable equivalent method for calculating the engine power cutback take-off flyover noise level is proposed. This method is an equivalent calculation, that is the flyover noise $EPNL_r$ is calculated by constructed $PNLT_r$ history. A new method of $PNLT_r$ history construction based on the $PNLT_r - P - D$ database is proposed. The $PNLT_r$ history corresponding to $PNLT_r M - 10$ dB-down is merged by one or some sections of flight phase including the normal take-off engine power climb phase, the engine spool down phase and the reduced engine power climb phase. For the engine spool down phase, in order to improve the accuracy of $PNLT_r$ history construction, the reference flight track is segmented directly with a well-designed short enough time interval. The computation technique of time increment corresponding to reference flight track segment also presented. The proposed equivalent method is validated by the flight test results of jet airplane ARJ21-700. It shows that this method can get reasonable flyover noise level and can be applied to all engine power cutback situations.

This method also can be applied for flyover noise optimization by finding the appropriate engine power cutback manner. A general process for flyover noise optimization is developed to determine the optimal engine power reduction initial height for any pre-specified engine power. Based on the equivalent method of engine power cutback flyover noise level proposed in this paper, the flyover noise levels can be calculated for any selectable engine power reduction initial height and engine power reduction value, that is the $\mathrm{EPNL}_r - \mathrm{H}_{\mathrm{cutback}} - \mathrm{P}_{\mathrm{cutback}}$ database can be established. The minimum flyover noise can be achieved by searching for the corresponding engine power reduction parameters in the database reasonably. The application analysis of this optimization process is carried out to find minimum flyover noise level of jet airplane ARJ21-700. The results show that this process can obtain reliable optimal engine power cutback manner to minimize flyover noise level. Moreover, this process does not need to carry out additional flight tests, so as to avoid increasing the cost and cycle of the noise airworthiness certification.

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8. Copyright Statement

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