Numerical Simulation of Real-Time Trajectory Optimization for Helicopter Noise Abatement

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Abstract
This study was an attempt to obtain optimal landing approaches for helicopters to reduce ground noise impact. Simulations and real flight tests in our previous study confirmed that flights along pre-calculated optimal trajectories resulted in lower noise levels than flights along conventional approach paths. However, some experiments did not show the expected optimization effects because of unforeseen disturbances. This paper therefore improves the algorithms in order to realize practical real-time optimization, which can involve external disturbances. To validate the effect of the new method, various computer simulations were conducted under real flight experimental scenarios. The obtained optimal solutions were characterized by steep flight path angles, which can avoid the generation of loud noise, the avoidance of noise sensitive points, and short flight times. These are different from conventional landing approaches. The optimal trajectories resulted in noise reduction on the ground, which shows the effectiveness and potential of the proposed real-time trajectory optimization method.

Key words: Trajectory Optimization, Helicopter, Noise Reduction

1. Introduction
Helicopters have unique maneuvering capabilities, such as hovering and vertical takeoff and landing. These abilities enable them to conduct various operations that are not feasible with general fixed-wing aircraft and make them an effective means of transport in suburban and mountainous areas. Although helicopters are used for live broadcasts, lifesaving services, rescue missions, and various other operations, their use is still limited at present. A main issue obstructing the widespread use of helicopters is the loud noise they generate. While there are many noise sources in a helicopter, (e.g., main rotor, tail rotor, engine, gearbox, and transmission), blade-vortex interaction (BVI) noise, which occurs during landing approaches, is the most annoying sound. BVI noise is caused by impulsive pressure fluctuations on the main rotor blades induced by tip vortices shed by the preceding blades. During conventional landing approaches, the tip vortices pass close to the following blades; consequently, strong BVI noise is generated. Meanwhile, in actual flights, the landing approach path selection is based on the visual flight rule (VFR) and is basically entrusted to the pilot’s manual control. When flying over densely populated areas, pilots consider both ride quality and ground noise impact based on their experience. However, since the noise level and propagation characteristics easily change due to factors such as flight and atmospheric conditions, the actual noise level at the ground is not necessarily consistent.
with the level anticipated by the pilot. In addition, the more the pilots are unfamiliar with the landscape, the higher is the possibility of excessive noise pollution. Therefore, it is necessary to minimize the damage by dispersing the noise over more tolerant areas, such as industrial areas, rivers, forests, and highways, using a precision approach system (1).

To resolve these problems and establish innovative approach systems as described above, the University of Tokyo and the Japan Aerospace Exploration Agency (JAXA) have been jointly developing a method for optimizing helicopter noise-abatement approaches. To achieve noise reduction effectively, it is very important to estimate the ground-level noise damage due to the helicopter in real-time. Therefore, noise source models and other models that are necessary for noise estimation should stay within acceptable computational loads. Although the accuracy of computational fluid dynamics (CFD) has increased with advances in computational techniques and computing power (2), it is not possible to calculate noise impact for actual flights in real-time with current computational speeds. We therefore developed empirical noise prediction and noise propagation models based on various acoustic flight experiments that were conducted by JAXA (3)(4) using its experimental helicopter “MuPAL-ε” (Fig. 1) (5). At the same time, some of us (Ikaida and Tsuchiya) have been studying numerical solution methods for optimal control problems at the University of Tokyo (6). By combining these techniques, our aim is to minimize the noise pollution during landing approaches using numerical computation methods.

Several studies related to numerical models for helicopter noise and trajectory optimization for low noise approaches are underway all over the world (7). For example, NASA established a rotorcraft noise model (RNM) that estimates noise levels three-dimensionally (8). Since RNM was built using actual flight experiment data, the noise levels around a helicopter could be predicted in real-time with current computers. For simplification, however, this model excludes various dynamic parameters (e.g., vehicle acceleration and tip-pass-plane angle of the main rotor) that affect the magnitude of the BVI noise level. As a result, the predictions are not very consistent with the observed ground noise level. The more practical quasi-static acoustic sound mapping (Q-SAM) technique is preferred for helicopter noise estimation (9). Q-SAM includes variable parameters that are critical for more accurate prediction. Its application to the noise abatement optimal control problem in numerical simulations have shown its effectiveness and feasibility (10)(11), but there have been no examples of actual flight experiments other than our previous studies (12).

In our previous study, we verified that the noise impact on the ground was lower in the case of flights following optimal paths pre-calculated using our own noise source model than in the case of flights following conventional approach paths.
Detailed examinations of these actual flight experiments, however, revealed some results that did not show the predicted optimization effects because of unexpected external disturbances (i.e., wind, temperature, and humidity variations, and pilot tracking error) during flight experiments. Thus, to resolve these problems and improve the practicality of the optimization method, we built optimization algorithms that can realize real-time optimization. The following section demonstrates the baseline of the trajectory optimization method and improves the algorithm for real-time computation. Next, models for helicopter dynamics, the noise source, noise propagation, and the performance index are described. Trajectory optimization problems for the helicopter landing approach are then defined, and the computational optimization results for various conditions are shown to validate the effect of the proposed method.

Nomenclature

\[ d \] : distance between aircraft and observation point  
\[ d_{ref} \] : reference distance (100 m)  
\[ g \] : acceleration of gravity  
\[ h \] : altitude \((= -Z)\)  
\[ J \] : performance index  
\[ L \] : noise index  
\[ L_{ij} \] : noise level at an observation point  
\[ L_{AE} \] : sound exposure level at an observation point  
\[ L_{m} \] : energetically averaged noise level  
\[ L_{ref} \] : noise level at reference distance  
\[ \Delta L_{at} \] : noise attenuation due to atmospheric absorption  
\[ \Delta L_{sp} \] : noise attenuation due to spherical spreading  
\[ m \] : aircraft mass  
\[ N \] : number of observation points  
\[ T \] : thrust of main rotor  
\[ T_{ref} \] : reference time (1 s)  
\[ t_f \] : final time  
\[ u_w \] : horizontal wind speed  
\[ V \] : horizontal speed  
\[ W \] : descent rate  
\[ w \] : weight coefficient  
\[ X, Y, Z \] : aircraft position  
\[ \gamma \] : flight path angle  
\[ \gamma_z \] : modified flight path angle  
\[ \Phi \] : bank angle  
\[ \Theta \] : pitch angle  
\[ \Psi \] : azimuth angle  
\[ \psi_{w} \] : wind direction  
\[ (\cdot) \] : time derivative

2. Real-Time Trajectory Optimization Method

2.1 Baseline Optimization Method

A main difficulty in real-time optimization is the strict limitation of computation time. Because the flight time of the approach trajectory was assumed to be approximately 150 s in this study, the computational period should be within several tens of seconds. In the previous study, direct collocation with nonlinear programming (DCNLP) with sparse
sequential-quadratic-programming (sparse SQP) was employed as an optimization method (13). The state and control variables of the trajectory, which were originally continuous in the temporary domain, were discretized and interpolated with piecewise linear functions. The original optimal control problem was then converted into nonlinear programming. There were more than 1200 optimized variables in our previous study, and consequently the calculation time went far beyond the actual flight time. We therefore refined the optimization algorithm to realize real-time trajectory optimization.

2.2 Real-Time Optimization Algorithm

In general, the computation period for solving an optimization problem with nonlinear programming increases with the number of discretized variables. Therefore, the formulation and discretization of the trajectory optimization problem is an important issue. We propose a method we named “stage division.” Figure 2 shows a schematic image of stage division.

In our previous studies, an optimized trajectory was evenly discretized from the initial position to the final position, which is the end of the approach path, in the temporary domain. In contrast, the proposed method discretizes the trajectory with two types of discretization; each trajectory part is called a stage. The stage close to the current aircraft position is densely discretized, and the other stage is sparsely discretized. The densely divided stage contains 40 s of the trajectory and is discretized at 10 discrete nodes. In other words, the nodes are collocated at 4-s intervals. The sparsely discretized stage comprises the rest of the trajectory and is composed of 10 nodes. Since the total flight time is an optimized variable, the flight time and number of the stages are not determined until the helicopter arrives at the final position. The real-time optimization process proceeds as follows:

Step 1) About 30 s before the aircraft reaches the initial position for the approach operation, the optimization begins. A straight-line path leading to the initial position is defined. While the helicopter flies along this path, the trajectory from the initial position to
the final position is optimized. The trajectory, which is named Stage 1 in Fig. 2, is divided into 10 discrete nodes; the other part (Stage 1’ in Fig. 2) is also discretized at 10 nodes. When the solution that is obtained in the iterative optimization process sufficiently converges on the optimal solution or the helicopter flying along the leading path approaches the initial position, the optimization process on this step is terminated.

Step 2) The helicopter reaches the initial position and then starts to fly along the optimal trajectory obtained in Step 1. While the helicopter flies within the first 30 s of Stage 1, the subsequent trajectory is optimized again. Stage 2, as shown in Fig. 2, is densely discretized. In addition, atmospheric conditions such as wind, temperature, humidity, and pressure, which are measured with onboard instruments, are incorporated into the optimization problem. In this step, the optimal solution of Step 1 is used as an initial solution; consequently, the optimal solution can be obtained faster than in Step 1.

Step 3) The above processes are repeated until the helicopter approaches the final position.

3. Numerical Models

3.1 Helicopter Dynamics Model

In this research, the helicopter is represented as a point mass, and only the thrust of the main rotor and the gravitational force act on the aircraft as external forces. The helicopter is controlled by the thrust of the main rotor $T$, lateral direction of the thrust $\Phi$ (bank angle), and longitudinal direction of the thrust $\Theta$ (pitch angle). The motion of the helicopter is then described by the following system of differential equations:

$$
\dot{X} = V \cos \Psi - u_w \cos \Psi_w \\
\dot{Y} = V \sin \Psi - u_w \sin \Psi_w \\
\dot{Z} = W \\
\dot{V} = -\frac{T}{m} \cos \Phi \sin \Theta \\
\dot{W} = g - \frac{T}{m} \cos \Phi \cos \Theta \\
\dot{\Psi} = \frac{T}{mV} \sin \Phi
$$

The landing point is the origin of the north-east-down (NED) coordinate system. The wind acting on the helicopter (horizontal wind speed $u_w$ and wind direction $\Psi_w$) is assumed to be horizontal.

In addition, we defined some constraint conditions during the approach. This is because the helicopter, which is expressed using the simplified point mass model, has a limited flight performance and is controlled manually during the flight experiments. Thus, constraints should be defined appropriately to obtain the optimal solutions within

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Lower limit</th>
<th>Upper limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V$ [kt]</td>
<td>50.0</td>
<td>100.0</td>
</tr>
<tr>
<td>$\Phi$ [deg]</td>
<td>$h \geq 1000$ft</td>
<td>$-10.0$</td>
</tr>
<tr>
<td></td>
<td>$h &lt; 1000$ft</td>
<td>$-h \times 10^{-2}$</td>
</tr>
<tr>
<td>$W$ [fpm]</td>
<td>$h \geq 480$ft</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>$h &lt; 480$ft</td>
<td>0</td>
</tr>
<tr>
<td>$V'$ [kt/s]</td>
<td>-1.5</td>
<td>0</td>
</tr>
<tr>
<td>$W'$ [fpm/s]</td>
<td>-100.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>
operational limits and without excessive pilot workload. Pilot-in-loop simulator tests were conducted prior to this study to examine proper constraints. Based on the test results, five constraint conditions were defined as shown in Table 1.

3.2 Noise Source Model

Since the tip vortices pass in close vicinity of the blades at moderate descent angles (around -5 degree flight path angle), strong BVI noise is emitted during descent. In other words, BVI noise often becomes dominant during the landing approach. The noise source model should estimate the magnitude of the BVI noise appropriately. To develop a simplified noise prediction model for use in our research, noise data obtained from flight experiments by JAXA were reduced to simple equations. In the noise model derived from these flight tests, the noise level \( L_{src} \) at a reference distance \( d_{ref} = 100 \text{ m} \) is written as functions of the flight path angle \( \gamma \), bank angle \( \Phi \), and acceleration \( \dot{V} \):

\[
L_{src} = \begin{cases} 
81.5 + 0.1\gamma_2 - 80\log_{10}\left\{\cos\left(\Phi\pi/180\right)\right\} & \text{for } \gamma_2 < -15 \text{ deg or } \gamma_2 > 5 \text{ deg} \\
84.5 + 0.1\gamma_2 + 3\cos\left(\left(\gamma_2 + 5\right)\pi/10\right) - 80\log_{10}\left\{\cos\left(\Phi\pi/180\right)\right\} & \text{for } -15 \text{ deg} \leq \gamma_2 \leq 5 \text{ deg}
\end{cases}
\]

(7)

where \( \gamma_2 \) is the modified flight path angle and can be expressed as

\[
\gamma_2 = \gamma + \frac{180}{\pi} \frac{\dot{V}}{g}.
\]

(8)

This modification is required to capture the effect of vehicle acceleration appropriately in the noise source model. The acceleration of the helicopter corresponds to a change in the angle of attack for the main rotor, and thus the distance between the main rotor and tip vortices varies. Consequently, the magnitude of the BVI noise is expected to vary according to the acceleration of the helicopter. Although helicopter noise (and particularly BVI noise)
has a strong directionality, the noise source model is represented here as an omnidirectional point source to reduce the computational cost.

3.3 Propagation Model

The noise emitted from the helicopter is attenuated during propagation. Various factors, such as distance, temperature, humidity, pressure, ground-surface damping, and wind affect noise attenuation. In this study, we considered the effects of distance and atmosphere. We used analytical models to estimate the attenuation due to omnidirectional radiation (spherical spreading) and atmospheric absorption. These models ignore the small effect of ground attenuation and weather conditions.

Spherical spreading loss is derived from the fact that the sound intensity from a point source diminishes at a rate that is inversely proportional to the square of the propagation distance. As a result, the spherical spreading loss \( \Delta L_{\text{sp}} \) [dBA] at distance \( d \) [m] can be written as

\[
\Delta L_{\text{sp}}(d) = 20 \log_{10}(d/d_{\text{ref}}).
\]

(9)

The atmospheric absorption model is based on ISO 9613\(^{(14)}\). In this standard, the model is described with an attenuation coefficient as a function of four variables: the frequency of the sound, temperature, humidity, and pressure. The atmospheric absorption model in this study reflects the noise spectrum characteristics of MuPAL-\(\varepsilon\). Figure 4 shows the resultant atmospheric absorption \( \Delta L_{\text{at}} \) [dBA] at an A-weighted noise level as a function of the distance from the helicopter. This study ignored the propagation time from the sound source to the observation point.

3.4 Performance Index

On the basis of the above models, the trajectory optimization was defined. This subsection explains the performance index of the problem. Some observation points were installed on the ground. The optimization solves the flight trajectory to minimize the noise levels at the observation points. Therefore, the performance index, which is a scalar function, is the sum of the noise levels measured at the observation points. However, there are many indexes expressing the noise levels. While the level of helicopter noise on the ground can be predicted objectively as described in the preceding subsection, determining how a person feels discomfort with the noise is a subjective problem. Not only does this performance index reflect psychological unpleasantness, but it can also be measured...
objectively. Therefore, the performance index was determined by referring to a sound exposure level based on the spatially averaged and temporally integrated noise index \((15)\). Let \(L_d(t,i)\) be the noise level estimated by the noise model at the \(i\)-th \((i = 1,2,\ldots,N)\) observation point on the ground at time \(t\). \(L_d(t,i)\) is then calculated as follows.

\[
L_d(t,i) = L_{av} - \Delta L_{air} - \Delta L_{air}.
\] (10)

The averaged noise level \(L_m(t)\) at time \(t\) can be obtained by energetically averaging \(L_d(t,i)\) over the points. Then, \(L_m(t)\) is energetically integrated along the temporary domain to obtain the noise index \(L\). \(L_m(t)\) and \(L\) are written as

\[
L_m(t) = 10\log_{10} \left( \frac{1}{N} \sum_{i=1}^{N} 10^{\frac{L_d(t,i)}{10}} \right)
\] (11)

\[
L = 10\log_{10} \int_{T_0}^{T} 10^{\frac{L_m(t)}{10}} dt
\] (12)

where the reference time \(T_0\) is defined as 1 s so that \(L\) represents the sound exposure level from the energetically averaged noise level. In our previous study, using only Eq. (12) as the performance index sometimes caused a solution with oscillating control variables. To avoid the oscillations, the sum of the square of the control variables was added to the noise index \(L\), and the resultant performance index \(J\) is written as:

\[
J = 10^{\frac{L}{10}} + \int_{T_0}^{T} \left( \frac{T}{mg} - 1 \right)^2 + \Theta^2 + \Phi^2 dt
\] (13)

where a weight coefficient \(w\) is determined so that the second term on the right hand side of Eq. (13) has a smaller value than the first term. Furthermore, the noise impact should be estimated at each point as well.

The sound exposure level at the \(i\)-th point, \(L_{SE}(i)\), is determined in the same way as Eq. (12); it is written as:

\[
L_{SE}(i) = 10\log_{10} \int_{T_0}^{T} E_{i}(i,t) dt
\] (14)

where \(E_{i}(i,t)\) is the energy-based noise index and expressed as

\[
E_{i}(i,t) = 10^{\frac{L_d(i,t)}{10}}
\] (15)

As a consequence, using Eq. (14) the noise index \(L\) can be rewritten as

\[
L = 10\log_{10} \left( \frac{1}{N} \sum_{i=1}^{N} 10^{\frac{L_{SE}(i)}{10}} \right)
\] (16)

This equation shows that the noise index \(L\) represents an energetic average of sound exposure levels.
4. Computational Optimization Results

4.1 Optimization Problem

The computational optimization problems were formulated in accordance with real flight conditions. Actual flight experiments were conducted at Taiki Multi-Purpose Aeronautical Park in Hokkaido. The length of the runway is 1000 m, and the azimuth angle is 73.2 degree. The helicopter landed at the east end of the runway. The origin of the coordinate system was located at the touch-down point. Five observation points labeled as \( i = 1, \ldots, 5 \) were located around the airspace, as shown in Fig. 5 and Table 2.

The initial and final conditions of the trajectory were defined as shown in Table 3. Since the helicopter was flown manually, the altitude of the final position was more than 0 for safety. If the helicopter continued to fly at the final flight-path angle from the final position, it would reach the touch-down point. The final altitude was defined in this way.

![Diagram of observation points and initial flight trajectory](image)

**Table 2** Observation positions

<table>
<thead>
<tr>
<th>Observation points</th>
<th>( X ) [NM]</th>
<th>( Y ) [NM]</th>
<th>( Z ) [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-2.3679</td>
<td>-1.6623</td>
<td>3.61</td>
</tr>
<tr>
<td>2</td>
<td>-1.7946</td>
<td>-2.3959</td>
<td>-5.60</td>
</tr>
<tr>
<td>3</td>
<td>-1.2573</td>
<td>-1.3044</td>
<td>3.46</td>
</tr>
<tr>
<td>4</td>
<td>-0.3589</td>
<td>-1.3578</td>
<td>-0.63</td>
</tr>
<tr>
<td>5</td>
<td>-0.6455</td>
<td>-0.9036</td>
<td>2.96</td>
</tr>
</tbody>
</table>

**Table 3** Initial and final conditions

<table>
<thead>
<tr>
<th>State variables</th>
<th>Initial condition</th>
<th>Final condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( X ) [NM]</td>
<td>-2.701</td>
<td>-0.136</td>
</tr>
<tr>
<td>( Y ) [NM]</td>
<td>-2.374</td>
<td>-0.450</td>
</tr>
<tr>
<td>( h = -Z ) [ft]</td>
<td>1200</td>
<td>170 ~ 320</td>
</tr>
<tr>
<td>( V ) [kt]</td>
<td>100</td>
<td>50</td>
</tr>
<tr>
<td>( W ) [fpm]</td>
<td>0</td>
<td>free</td>
</tr>
<tr>
<td>( \Psi ) [deg]</td>
<td>free</td>
<td>73.2</td>
</tr>
</tbody>
</table>
4.2 Feasibility of Real-Time Optimization

A limitation of offline trajectory optimization was revealed. Offline optimization optimizes the entire flight trajectory discretized with equally spaced nodes over a long time. In numerical computations, we used a personal computer with an Intel Core 2 Duo T7200 (2 GHz) CPU. Figure 6 shows the initial trajectory of the optimization computed iteratively. The 6-degree descent flight is a conventional approach for a helicopter manually controlled by a pilot. Figure 7 shows the relationship between the number of discretized nodes, computational time of the offline optimization, and value of the performance index $J$. Figure 7 demonstrates that the offline optimization method, which has many discretized nodes, cannot catch up with the actual flight duration in computational speed. The proposed real-time optimization should be solved within 30 s so that it can reflect the effect of external disturbances during flight. In addition, the value of the performance index $J$ was almost the same even though the number of the discretized nodes increased. Therefore, from Fig. 7, we decided that real-time optimization should have 20 nodes (10 for the densely discretized stage and 10 for the sparsely discretized stage) to respond to the flight environment in real time and to obtain an accurate solution. Figure 7 also illustrates that the performance index $J$ is the minimum value when the number of discretized nodes is 10. However, this was because the formulation and discretization were incorrect due to too few discretized nodes.

A solution obtained using real-time optimization was compared with the offline optimization solution. The results are shown in Figs. 8–13. Here, the offline optimization optimized the entire flight trajectory with 100 equally spaced nodes. The noise source model used in this study reached its maximum value when the flight path angle was around –5 degree as shown in Fig. 3. The optimal solutions therefore attempted to avoid this flight path angle and minimize the total flight time as much as possible. The figures illustrate that the flight path angle passed through the vicinity of –5 degree quickly, and the helicopter decelerated rapidly at the end part of the trajectory. These characteristics of the optimal solutions in the longitudinal plane are also evident in the altitude history. The helicopters kept the initial altitude and delayed the descent; consequently, they flew along a decent rate limit of 800 fpm. On the other hand, a distinctive aspect of the lateral movement was that the aircraft had to turn frequently to maintain a distance from the observation points. Accordingly, the bank angle changed significantly over the whole trajectory. The most noticeable difference between the offline and online optimization was in the velocity profile. This discrepancy was caused by the difference in the number of nodes. Since the number of nodes in the real-time optimization was smaller, the real-time optimization had a computation error.

Fig. 6 Initial trajectory for optimization
The number of nodes

Computational time [s]

Performance index

Fig. 7  Computational time and performance index value due to variation in the number of nodes

Fig. 8  Optimized trajectories on XY plane

Fig. 9  Optimal solutions (altitude history)
Fig. 10  Optimal solutions (horizontal velocity history)

Fig. 11  Optimal solutions (descent rate history)

Fig. 12  Optimal solutions (flight path angle history)

Fig. 13  Optimal solutions (bank angle history)
4.3 Noise Reduction Effect

This subsection demonstrates the effectiveness of noise abatement by the real-time optimal flight. The noise of the real-time optimal flight was compared with the noise of the following two conventional landing approaches. One was the 6-degree descent approach trajectory shown in Fig. 6, and the other was a 3-degree descent approach trajectory (Fig. 14). At present, landing approaches of helicopters are entrusted to manual control, and the conventional descent path angle is basically around 6 degree. However, as mentioned previously, the BVI noise under this condition is greater than that in other flight conditions. Meanwhile, the application of ILS systems, which are already in use for fixed-wing aircraft, has recently been proposed for helicopter operation in bad atmospheric conditions such as rain and fog. The current ILS system for general aviation uses a straight-line 3-degree glide-slope for safe landing even under the instrument flight rule (IFR). We therefore assumed that these two types of trajectories currently represent conventional approach paths and compared the noise reduction effects.

Figure 15 illustrates the time histories of the noise levels at each observation point for the three trajectories. The noise reduction effect was markedly significant at observation positions 3, 4, and 5. This was because observation points close to the runway are exposed not only to the closeness of the aircraft and the observation point but also to strong BVI noise caused by the moderate flight path angle in conventional approaches. Table 4 indicates the total flight times, noise indexes, and sound exposure levels $L_{AE}(i)$ at each observation point. The noise index $L$ is expressed by Eq. (12), and $L_{AE}(i)$ is defined in Eqs. (14) and (15). This table also demonstrates that noise reduction by the proposed optimization method at each observation point was estimated to be 2–6 dB in sound exposure level and 2–3 dB in the noise index $L$. Figures 16–18 show contour plots of the sound exposure levels $L_{AE}$ on the entire experimental field. The noise level of the 6-degree descent approach is smaller than that of the 3-degree descent approach, because, as shown in Figs. 6 and 14, the altitude of the 6-degree descent flight is higher. The optimized trajectory effectively narrowed the area exposed to serious noise pollution; in particular, the area exposed to a sound exposure level above 80 dB was considerably reduced. These figures validate the proposed real-time optimization as reducing not only the noise at a specific location (i.e., observation points) but also the noise over the rest of the area.

Table 4  Comparison of optimization results

<table>
<thead>
<tr>
<th>Trajectory type</th>
<th>Flight time $t_i$ [sec]</th>
<th>Noise index $L$ [dB]</th>
<th>Sound exposure levels of observation point $L_{AE}$ [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real-time Opt.</td>
<td>157.2</td>
<td>77.0</td>
<td>72.9 74.7 75.0 79.4 79.2</td>
</tr>
<tr>
<td>6-deg descent</td>
<td>171.5</td>
<td>79.4</td>
<td>74.3 74.6 80.6 83.8 82.3</td>
</tr>
<tr>
<td>3-deg descent</td>
<td>171.6</td>
<td>80.3</td>
<td>76.2 77.4 81.9 83.8 82.7</td>
</tr>
</tbody>
</table>

Fig. 14  3-degree descent approach
Fig. 15  Time history of noise level

Fig. 16  Sound exposure level contour line (real-time optimization)

Fig. 17  Sound exposure level contour line (6-degree descent approach)
5. Conclusion

This paper proposes a new optimization method to obtain the optimal landing approach for a helicopter that minimizes the ground noise impact. The optimization method should adapt to real flight environments including external disturbances, and it should be installed on board. Simple dynamics and noise models were developed based on our past studies and flight experiments, and we proposed a real-time trajectory optimization method. Optimal flight profiles for helicopter landing approaches were computed using numerical simulations. The obtained trajectories were characterized by a short flight time and steep descent angle to avoid strong blade-vortex interaction (BVI) noise. We confirmed the noise reduction effect and the possibility of real-time computation through the numerical simulations.

The next stage of our research is conducting flight experiments. We intend to ascertain whether the real-time trajectory optimization works well even in a real flight environment and if the effect of noise reduction can be observed.

References


