JOURNAL OF AIRCRAFT
Vol. 47, No. 1, January–February 2010

Helicopter Thickness Noise Reduction Possibilities Through Active On-Blade Acoustic Control

Gaurav Gopalan and Fredric H. Schmitz
University of Maryland, College Park, Maryland 20742

DOI: 10.2514/1.35695

A new theoretical preliminary design method, based upon linear acoustic theory, is presented to review the possibility of controlling helicopter thickness noise by on-blade control. Near elimination of thickness noise in the plane of the rotor, in the direction of forward flight, by using on-blade acoustic sources (monopoles) and in-plane forces (dipoles), has been theoretically shown to be possible at a single target observer location in the acoustic far field, with some limitations. The resulting control time histories are shown to be low frequency in nature and use the basic physics of the noise generating process to cancel the noise. When the rate of change of mass flow or the rate of change of in-plane force is the method of acoustic control, noise cancellation is effective above and below the rotor plane, but it is not as effective for small changes in the observer azimuth angle. Low harmonic controllers are effective in canceling noise over a larger off-target observer space but need larger control values, whereas higher frequency controls are effective over a small off-target region but are associated with lower values of control. Out-of-plane control forces are shown not to be an effective means of cancelling thickness noise.

Nomenclature

A_s = airfoil cross-sectional area
dS = element of blade surface
f = cost function of the optimization
M_{JET} = control source jet Mach number
M_r = source Mach number in the radiation direction
n = harmonic number
p' = acoustic pressure
rev = rotor revolution period
S = blade surface area
t = observer time
V = forward flight velocity
v = velocity of blade surface element
v_c = control source jet velocity
v_n = local normal component of blade surface element velocity
$\bar{x}$ = location of observer
$\bar{y}$ = location of source
θ_{obs} = observer elevation angle
ρ_o = ambient density of air, 1.2 $\mathrm{kg/m^3}$
ψ = rotor azimuth angle
ψ_{obs} = observer azimuth angle

Subscripts

c = control
i = dimension in fixed-space coordinates
j = index for volume controller
k = index for force controller
n = component normal to local blade surface element

I. Introduction

HELICOPTERS radiate significant impulsive noise when flown at the higher end of their speed envelope. The sound is very directional, spreading energy in a deterministic pulse near the rotor tip-path plane in the direction of forward flight. The characteristic negative-going symmetrical wave is known to be associated with blade thickness. When the advancing tip Mach number of the helicopter becomes very high (approaches 0.9), the local nonlinearities of the aerodynamic flowfield also become important. They cause the aerodynamic flowfield to delocalize and connect to the acoustic far field, sending miniature shock waves to a far-field observer [1]. The resulting noise, called high-speed impulsive (HSI) noise, is quite disturbing and can be heard for long distances.

Over the past 20 years, helicopter manufacturers have improved upon rotor designs to help address the extremes of the HSI noise. Rotor blade operational tip Mach numbers have been lowered and blade tips have been thinned to reduce HSI noise radiation. In some cases, rotor blade tips have been tapered and swept to help delay acoustic delocalization and reduce HSI noise. Although the HSI noise problem has been mitigated from the early Vietnam era designs, it has not been eliminated. In most cases, the characteristic negative thickness noise pulse still radiates sound that is annoying and can alert the enemy that a helicopter may be approaching.

Active rotor control to reduce blade–vortex interaction (BVI) noise has also been tried, with some success [2,3]. The general concept has been to periodically change the lift forces on each blade, using higher harmonic or individual blade control in a manner that will reduce the radiated BVI noise. Many research efforts, both theoretical and experimental, have shown that noise reductions at selected observer locations are possible, with many reasons put forward for their success. Unfortunately, the noise reduction problem is very complex and depends to a great extent on the characterization and details of the rotor blade wake system, which is still under active research. It is also generally known that these acoustic gains do not come for free. For a limited authority higher harmonic control system, controlling the rotor to minimize noise radiation causes increases in vibration, whereas controlling the rotor to minimize vibration causes increases in noise over the baseline case [3].

This paper (first presented in 2007 [4]) presents a different approach to the reduction of thickness noise. The approach looks at the problem as an ideal far-field acoustics problem and asks questions. How much noise reduction is possible using ideal on-blade point controllers in a far-field near-in-plane observer space in the direction of flight of the helicopter; and what is the nature, effectiveness, and robustness of these controls? It suggests the use of various on-blade acoustic controls and evaluates the ideal acoustic effectiveness of each controller. Thickness noise was chosen because the problem may be more amenable to on-blade control than BVI noise. Thickness noise is periodic and deterministic, with relatively low frequency content (providing the flow is not delocalized),

Received 17 November 2007; revision received 19 November 2007; accepted for publication 11 October 2009. Copyright © 2009 by the American Institute of Aeronautics and Astronautics, Inc. All rights reserved. Copies of this paper may be made for personal or internal use, on condition that the copier pay the $10.00 per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923; include the code 0021-8669/10 and $10.00 in correspondence with the CCC.

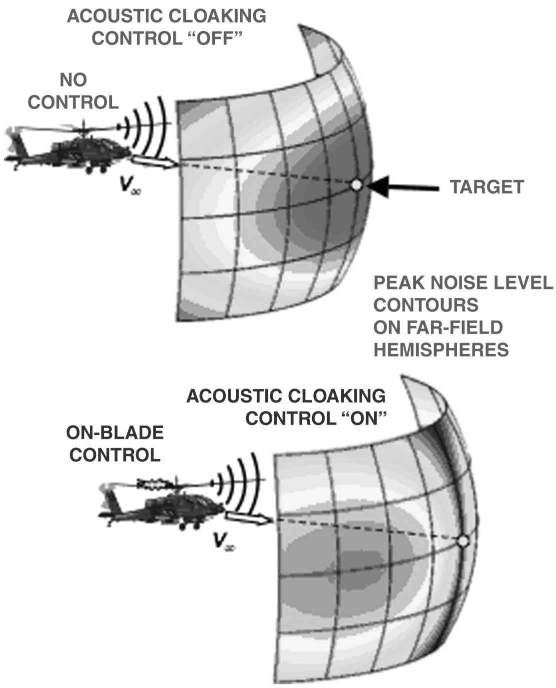

Fig. 1 A sketch of far-field thickness noise radiation with and without active on-blade acoustic control.

radiating energy in a localized region ahead of the helicopter. These features may make it feasible to cancel the noise radiation with relatively low frequency control inputs.

II. Thickness Noise Cancellation Approach

A. Noise Reduction Goal

Consider a relatively modern helicopter in steady high-speed forward flight. Each main rotor blade generates a thickness noise pulse that radiates forward and ahead of the helicopter, reducing in intensity from the straight-ahead in-plane position, as depicted in Fig. 1a. It is also assumed for this paper that the acoustic pulse is not delocalized and is mostly symmetrical. The negative acoustic pulse near the tip-path plane of the rotor, in the direction of forward flight, gradually decreases on both the advancing and retreating sides of the disk. Above and below the plane of the rotor, the pulse decreases more quickly.

The primary goal of on-blade acoustic control is to cancel the radiated thickness noise as much as possible in the peak amplitude direction, for an observer straight ahead and in the tip-path plane of the rotor. A secondary goal is to evaluate noise in the vicinity of this peak amplitude position, after this on-blade control is applied, to get an estimate of the cancellation effectiveness at other nearby observer positions. A longer-range goal is to minimize the noise radiation within a cone of silence, which is depicted in Fig. 1b.

B. Thickness Noise Modeling

Linear acoustic theory, in the form of the classical Ffowcs Williams and Hawkings formulation [5] for surfaces in motion as applied to rotorcraft problems [6], has done quite well predicting the symmetrical negative impulsive signature of thickness noise below the delocalization Mach number of the rotor, in both hover [7] and forward flight [8]. Near-in-plane noise levels and shape, in the direction of forward flight, have been shown to be dependent upon the blade thickness and the in-plane force time history of the rotor. Out-of-plane force also influences the noise radiation but only at the out-of-plane observer locations.

Because linear theory does a reasonable job predicting the amplitude and lower frequency character of the HSI noise pulse shapes, it is reasonable to assume that it can also estimate the effect of hypothetical acoustic control sources and control forces. When these control terms are added, the governing equation becomes

$$4\pi p'(\vec{x},t) \approx \underbrace{\frac{\partial}{\partial t}\iint\left[\frac{\rho_0 v_n}{|\vec{x}-\vec{y}||1-M_r|}\right]\mathrm{d}S(\vec{y})}_{\text{Term 1: Blade Thickness Noise}} + \underbrace{\frac{\partial}{\partial t}\sum_j\left[\frac{\rho_0 v_{c,j,n}\Delta S(\vec{y}_{c,j})}{|\vec{x}-\vec{y}||1-M_r|}\right]}_{\text{Term 2: volume control}} - \underbrace{\frac{\partial}{\partial x_i}\sum_k\left[\frac{F_{c,k,i}(\vec{y}_{c,k})}{|\vec{x}-\vec{y}||1-M_r|}\right]}_{\text{Term 3: force control}} \tag{1}$$

In the previous equation, the acoustic pressure p' at an observer location $\vec{x}$ and observer time t is equated to three acoustic sources on the right-hand side of the equation. The first term represents the linear acoustic pressure due to blade thickness. Note that this term is a surface integral, over the entire blade surface, taken at the correct retarded time (indicated by placing the integrand in square braces). Other terms in this expression include $\vec{y}$ as the effective source location, $|\vec{x}-\vec{y}|$ as the effective distance of propagation of the acoustic signal from the source to the observer, $|1-M_r|$ as the Doppler amplification, ρ_0 as the density of air, and v_n as the velocity of fluid normal to the blade surface element $\mathrm{d}S(\vec{y})$. The second term is the volume control or control source term and has a form very similar to that of term 1. This term assumes multiple point source controllers on the surface of the blade and uses linear superposition to add these terms to the total thickness signature of the blade. The normal velocity of the jth control source of area $\Delta S(\vec{y}_{c,j})$ located at $\vec{y}_{c,j}$ is $v_{c,j,n}$. Similarly, the blade loading control term is very similar to the second term and includes the effect of point control forces on the blade. $F_{c,k,i}(\vec{y}_{c,k})$ is the ith spatial component of the kth control force. Note that both v and F are functions of time.

The direct question is then, "How can the control source and control force terms be adjusted to minimize thickness noise?" It should be noted that this is an acoustician's view of how it might be possible to reduce thickness noise, what the acoustic control requirements would be, and how effective would they be in cancelling the noise. The approach offers guidance as to what might be possible, but as such, it does not suggest new on-blade control mechanisms.

A noteworthy attribute of this approach is that it can be used to evaluate the theoretical limits for noise cancellation. By working in the acoustic far field, the cancellation problem becomes one of determining the on-blade acoustic control source that can cancel noise. When applied appropriately, this approach can present a best possible case for active acoustic control.

C. Nominal Thickness Noise Radiation Characteristics

To keep the approach somewhat general, a representative helicopter rotor is chosen for the application of these noise reduction methodologies. The main geometrical and loading characteristics of the rotor are given in Table 1.

Because the symmetrical acoustic pulse shape is the same for each blade, only one blade is considered in this analysis. It is implicitly assumed that the advancing tip Mach numbers are below 0.88 for this 9%-thick constant chord blade, so that the nonlinearities arising from

Table 1 Nominal rotor design and operating parameters

Parameters	Values
Radius to chord	12
Radius	8 m
Constant thickness to chord	9%
Airfoil	NACA 4 series
Advance Ratio	0.3
Hover tip Mach number	0.63
Advancing tip Mach number	0.82
Disk loading	8 lb/ft^2

the delocalization of the unsteady aerodynamic transonic flowfield have [1] a small effect on the acoustics. For simplicity, the influence of the dipole force noise, both in the plane of the rotor and out-of-plane, is not included in this baseline representation of near-in-plane rotor noise. Only on-blade thickness noise calculations are shown for this baseline helicopter in forward flight.

With these assumptions, Fig. 2 shows the resulting target thickness noise field that is to be cancelled by on-blade control. The Ffowcs Williams and Hawkings solution [5] to the thickness noise problem is solved in two ways. The first approach uses a direct numerical method outlined in [1] (solid line in Fig. 2). The second is an approximate analytical approach (developed in [9]), which makes additional assumptions to simplify the problem further (dashed line in Fig. 2). This second approach assumes that the observer is truly in the acoustic far field of the rotor and that acoustic planform angles are relatively small. The acoustic time histories using both these methods are used to estimate the thickness noise radiation time histories at nine observer locations: a 15 deg grid about the target observer location directly ahead and in the plane of the rotor. The acoustic time histories using both the approaches are very similar in levels and phase and exhibit the same trends. The largest negative peak impulse occurs at the target observer position in the plane of the rotor in the direction of forward flight. Above and below the rotor tip-path plane, the peak amplitude decreases about 20% from its peak negative level, whereas only smaller decreases are shown with changes in the azimuth angle of the observer.

A power spectrum of the acoustic pulse at the target observer position is shown in Fig. 3. The radiated acoustic energy of the pulse is concentrated about the seventh harmonic of this single-bladed rotor and is typical of the relatively low- to midfrequency content of thickness noise.

To illustrate the basic mechanisms of on-blade cancellation, each control term (monopole source and dipole force) of Eq. (1) will be treated individually as a separate controlled input that will be designed to minimize the large negative acoustic pulse, due to blade thickness.

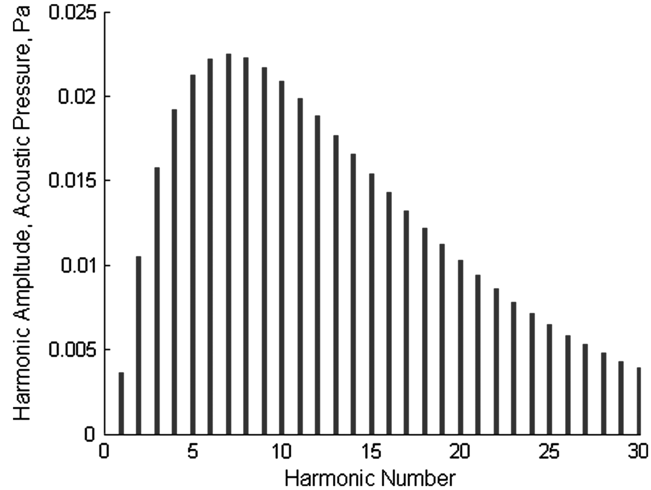

Fig. 3 Fourier analysis of thickness noise at the target observer location.

III. Noise Cancellation Using Monopole Acoustic Sources

A. Null Acoustic Thickness Control Solution

One of the most effective ways of acoustically canceling thickness noise is to introduce acoustic control sources at many locations along the span and chord of the rotor. Ideally, the rotor could employ acoustic sources and sinks of the same magnitude, but of opposite sign, that were needed to develop the basic thickness noise pulses of the noise radiation field. If these controlled acoustic sources were activated at the correct retarded times, no net noise would be radiated in all directions. This ideal cancellation is called a null solution, in which the antinoise field is produced by the same acoustic mechanisms that caused the radiated sound. In effect, the acoustic control sources cancel the blade thickness sources. It is as if the rotor

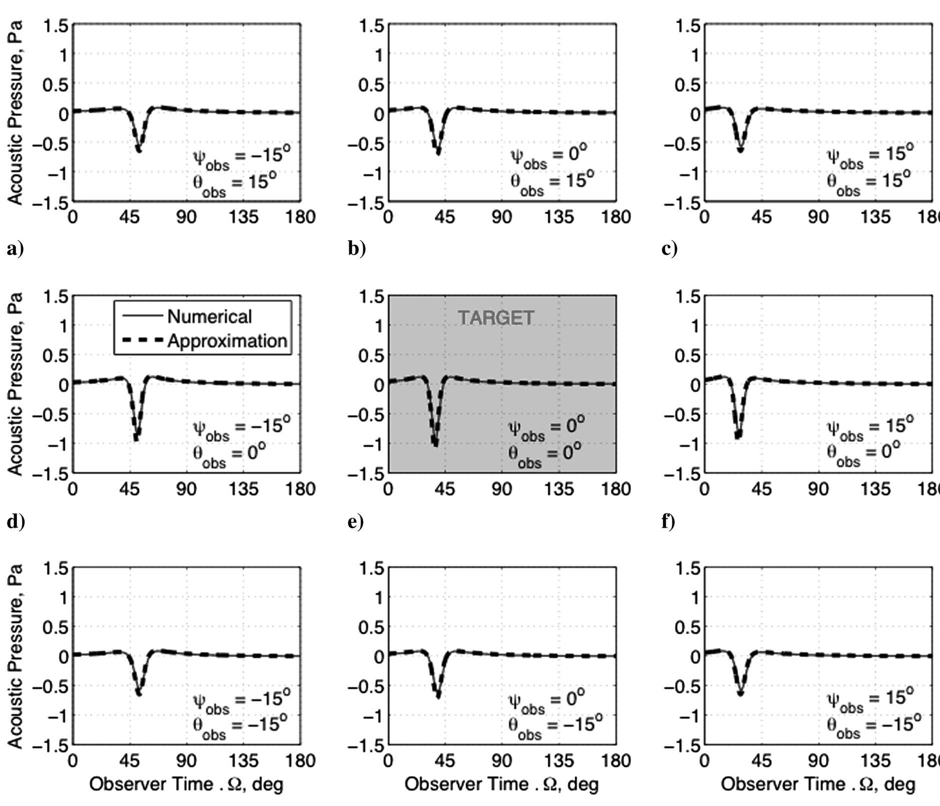

Fig. 2 Nominal helicopter thickness noise in the cancellation region.

blade has zero thickness. In the real world, this ideal null solution has several problems. A major one is that rotor blades cannot be manufactured to both carry pressure on the surface yet be porous enough to pass the required mass flow through the surface to cancel thickness noise.

B. Approximate Null Acoustic Control: One Sink and One Source

However, the concept of introducing sources and sinks at positions along the blade to cancel thickness noise near its source is attractive. If we restrict the acoustic control source to act at finite a number of positions along the blade radius and chord, it becomes more possible to envision a possible implementation of this idea. In the limit, one sink and one source of constant strength, positioned along the blade, might be able to cancel most of the thickness noise. Using knowledge of thickness noise computations, the most effective radial cancellation position is near the tip of the rotor, in which the acoustic amplification of acoustic control sources is large. The optimal chordwise and spanwise locations of the constant strength control source and sink can be found by minimizing the peak noise cancellation at the target observer location. Canceling this noise requires that the control sink strength be positioned ahead of the control source in the chordwise direction. A sketch of this dual-source null control scheme is shown in Fig. 4, in which it is assumed that the sink–source control is positioned at 0.91 R.

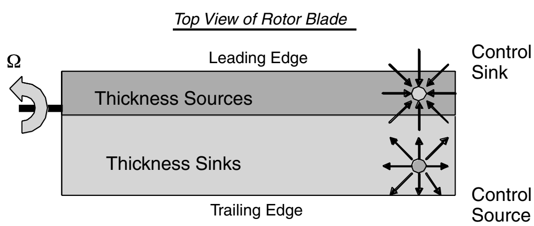

Fig. 4 Sketch of a point control sink–source pair used to cancel thickness noise.

The resulting noise cancellation from this simple sink–source pair is shown in Fig. 5. This acoustic control approach markedly reduces thickness noise (peak noise reduction ~20 dB) in the directions for which large radiation is prevalent: in front of the helicopter near the tip-path plane of the rotor. It is quite effective theoretically, because the sink–source controller uses the same mechanisms that produced the noise to cancel it.

It is instructive to review the basic physics of this noise generation to explain why this cancellation is so effective. The basic mechanism that causes the shape and level of the thickness noise pulse is described in [1] and is briefly reviewed here. The thickness terms in Eq. (1) arise because air is effectively displaced by the rotor blade as it moves through the fluid. An acoustic source is created when the leading edge of the blade pushes air out of the way. At a small but finite time later, the same amount of air is withdrawn (sucked in) by acoustic sinks (source of opposite sign). The pulse shape arises because the thickness noise generation is a noncompact phenomenon (i.e., the point of action of these opposite sign acoustic singularities that model blade thickness cannot be collapsed to a point along the blade chord). This is because these acoustic sources and sinks produce waves that arrive at an observer located in the far field at slightly different times. Far-field thickness noise is just the time derivative of the sum of these two groups of waves, with the signature negative pulse shape occurring at an observer time between the source and the sink waves. The strength of the derivative of these summed waves is directly proportional to the thickness of the blades, the thickness distribution, and the local velocities (and to acoustic amplification effects due to high advancing tip Mach numbers). Near-complete cancellation requires equal and opposite acoustic source strengths, and it also requires that these acoustic control sources and sinks be positioned appropriately along the blade.

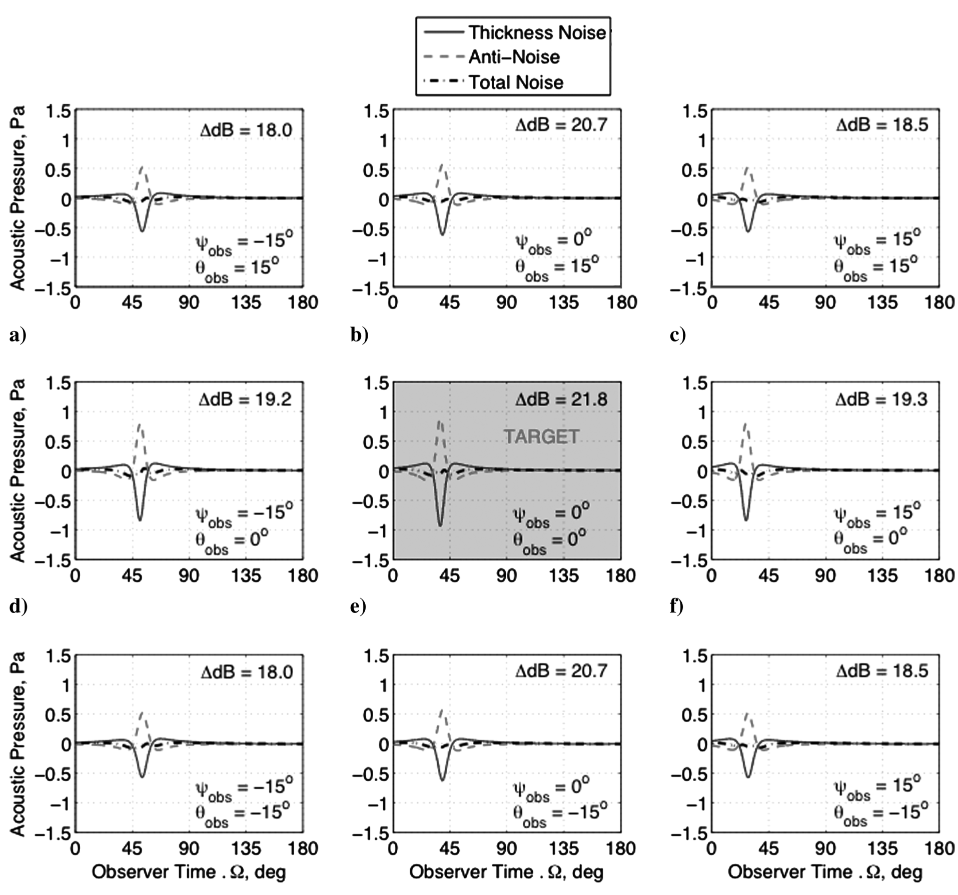

Fig. 5 Reduction of thickness noise using a single sink–source pair at 0.91 R.

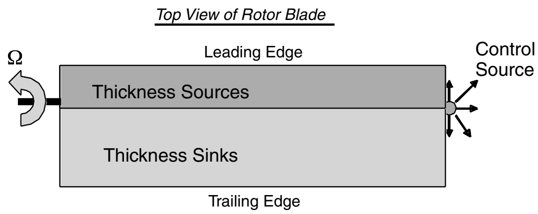

Fig. 6 Sketch of a single on-blade acoustic control source.

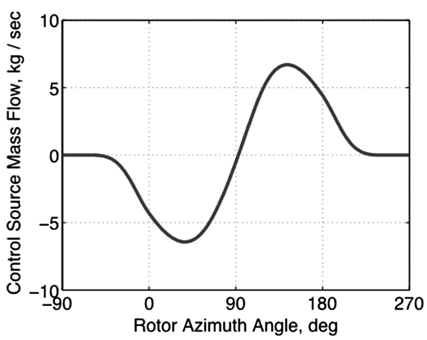

Fig. 7 Mass flow rate time history requirement for target thickness noise minimization using a multiple-frequency control source.

Unfortunately, a large amount of mass flow is required to directly cancel thickness noise in this manner (∼40 kg/s). Consider the ideal situation for which one quarter of the blade cross section is used to provide mass flow for the acoustic control source and the other quarter of the blade section is used for the acoustic control sink. Supersonic Mach numbers (∼14.3) are required in these blade sectional passages, making this idea infeasible in practice. Generating the necessary Mach numbers to provide suction does not seem practical. Also, high Mach number jet flow at the sink and source will create its own jet noise, which could be significantly higher than the noise to be cancelled.

IV. Time-Varying Single Source Control

Another way of cancelling thickness noise is to use a single acoustic control source on the rotor blade and allow its strength to vary in time as the blade rotates over the advancing side of the rotor disk. This general control source is allowed to assume both positive and negative values, theoretically. Unfortunately, this new formulation of the problem does not cancel sound everywhere, because the control mechanism that produces the antinoise pulse is different from the thickness noise generation mechanism. However, by a proper choice of the derivative of the source time history, a noise cancellation beam can be formed and used to minimize the noise radiation in specified directions.

Fortunately, as noted, thickness noise is highly directional, with the most intense radiation occurring near the rotor tip-path plane, directly ahead of the helicopter. Therefore, the problem can be made more tractable by restricting the noise cancellation to a zone of effectiveness. This will localize the solution to the area of the disk that is primarily responsible for the noise radiation and facilitate the use of higher time rates of change of acoustic sources to cancel the noise, with some corresponding reductions in absolute source strength. Unfortunately, this localization of the antinoise control can also create additional noise at other far-field observer positions outside the zone of effectiveness.

Consider a single-point acoustic control source placed at the tip of the blade, as depicted in Fig. 6. The following problem is posed. Is it possible to completely cancel thickness noise at a target observer location using linear acoustics with one time-varying volume source

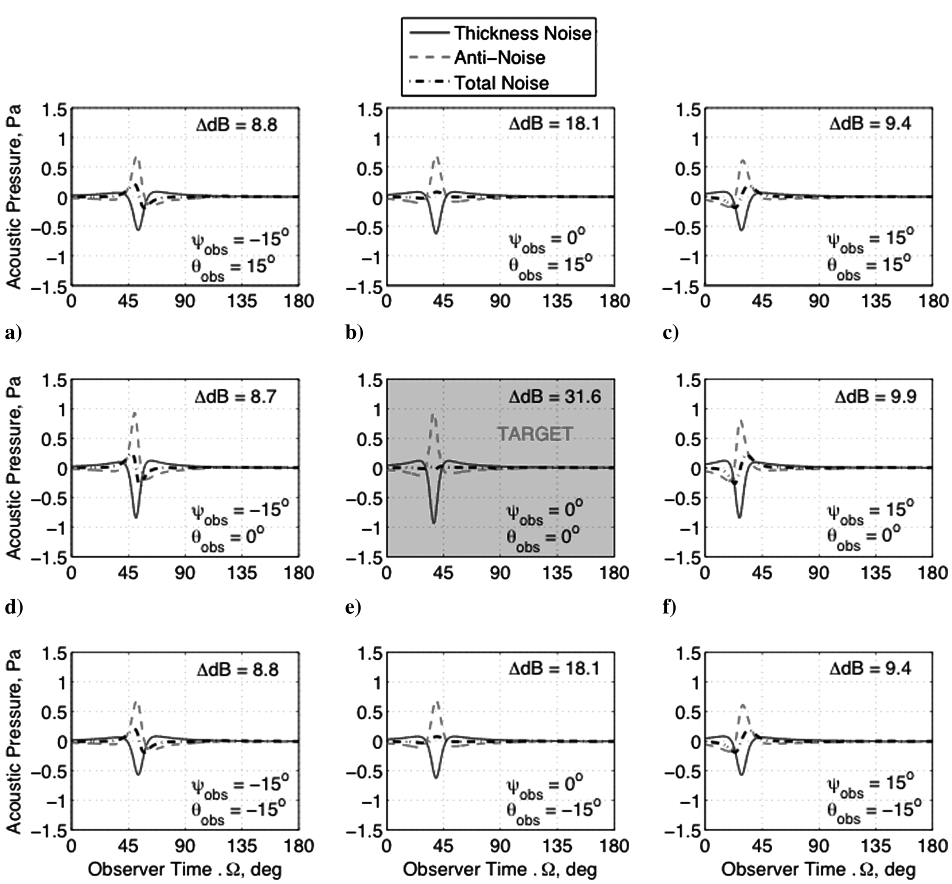

Fig. 8 Reduction of thickness noise using a multiple-frequency control source solution.

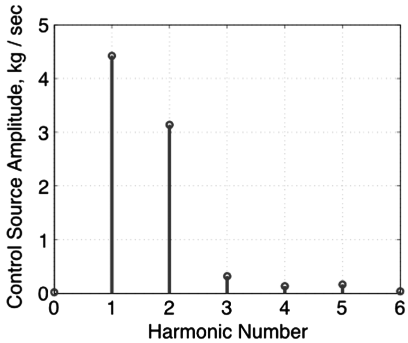

Fig. 9 Fourier analysis of the multiple-frequency control source mass flow time history solution (Fig. 7).

on the blade? In essence, a solution is sought to the following differential–integral equation:

$$0 \approx \underbrace{\frac{\partial}{\partial t}\iint\left[\frac{\rho_0 v_n}{|\vec{x}-\vec{y}||1-M_r|}\right]\mathrm{d}S(\vec{y})}_{\text{Blade thickness noise}} + \underbrace{\frac{\partial}{\partial t}\left[\frac{\rho_0 v_{c,n}\Delta S(\vec{y}_c)}{|\vec{x}-\vec{y}||1-M_r|}\right]}_{\text{Single control source}} \quad (2)$$

An approximate time-domain solution for the single-control source problem has been found numerically using a frequency domain optimization method. A single acoustic source is located the tip of the blade at the quarter chord, and a multiple harmonic solution (up to 6/rev) is assumed. The objective of the optimization is to minimize the resulting peak (positive or negative) of the noise at an in-plane target observer position in front of the helicopter:

$$\text{cost function, } f = \text{maximum}[|p'(t)|]$$

This optimal solution is then evaluated for its effectiveness in reducing the noise at other off-target near-in-plane observer locations. The mass flow rate requirements to reduce the peak of in-plane noise by 31.6 dB are shown in Fig. 7. As before, negative mass flows (suction) are required at some azimuth angles, making this noise control less feasible.

It should be noted that, in the control solution shown in Fig. 7, negative values of mass flow are required to be able to construct a positive slope on the rate of change of mass flow versus azimuth curve near the vicinity of the 90 deg rotor blade azimuth, which corresponds to the time of the negative peak of the thickness noise pulse at the target observer position. The positive rise in the mass flow cancels the noise in this critical region.

The mass flow requirements for nearly-complete cancellation of thickness noise are still fairly large, even though they are almost an order of magnitude smaller than the requirements for the approximate null solution, using a steady sink and source pair. Part of the reason that these high mass flow rates are required is that the acoustic source control necessary to eliminate the noise is being designed to nearly cancel noise at all times at the target observer position. As the control operates further away from the 90 deg azimuth location, the Doppler amplification drops, and relatively large control values are needed to achieve even small antinoise levels.

The pulse in the center of Fig. 8 illustrates the cancellation effectiveness of a single control source located at the tip of the blade for the target observer position, in the tip-path plane of the rotor in the direction of forward flight. Thickness noise has been reduced to nearly zero at this one observer location ($\sim$31.6 dB peak noise reduction). The ability of this on-blade source to cancel noise at other nearby positions is also shown. As expected, the noise cancellation is less effective at these nontarget observer positions. This is especially true, as the observer azimuth angle is moved off the target observer position.

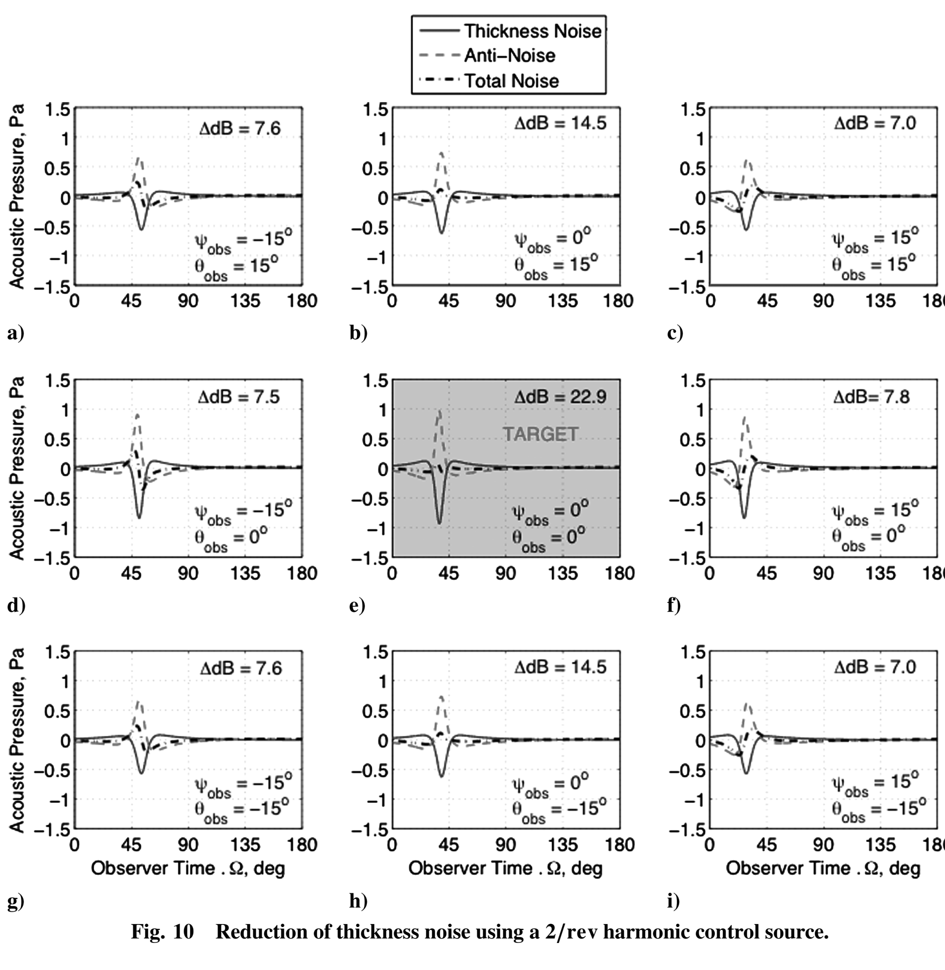

Fig. 10 Reduction of thickness noise using a 2/rev harmonic control source.

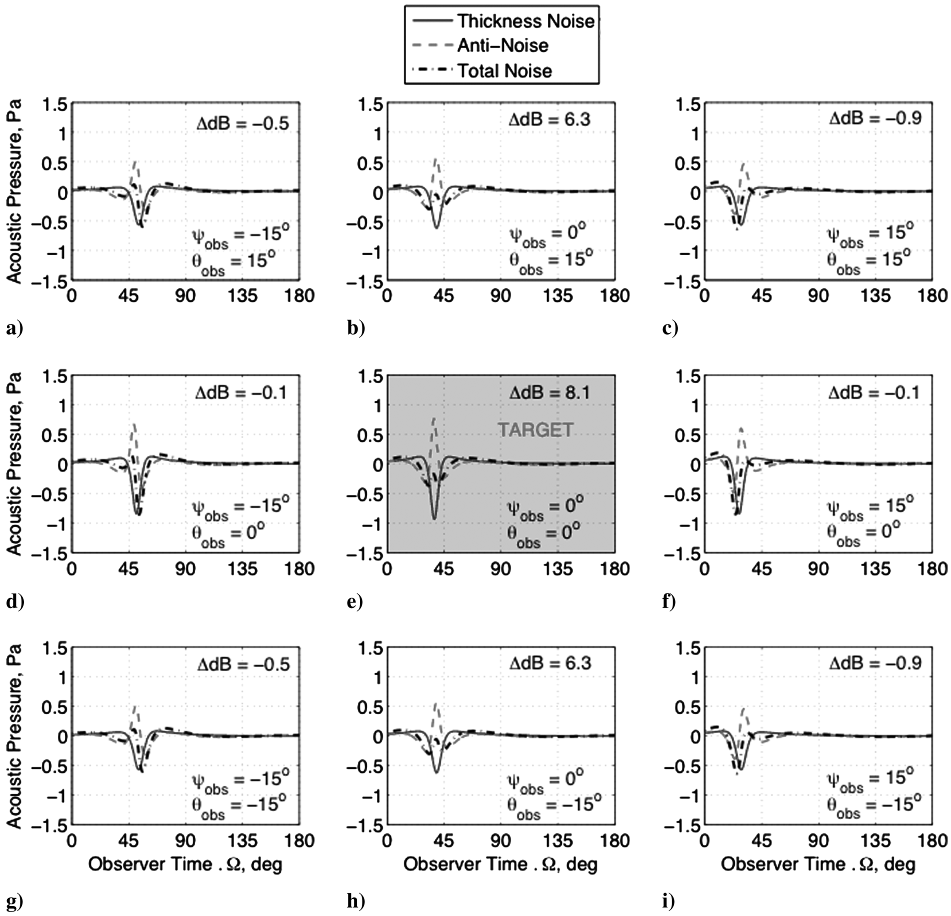

Fig. 11 Reduction of thickness noise using a 4/rev harmonic control source.

Although the mass flow requirements are quite high for near-complete cancellation of the noise by using a single control source, it is instructive to investigate the nature of the variation a little further. The control solution in Fig. 7 is decomposed into harmonic components of the main rotor in Fig. 9. It can be seen that the lower frequency harmonics are very efficient at reducing the level of thickness noise.

By definition, the harmonics of the source control are defined over a complete rotor cycle. This means that each discrete harmonic has a frequency and corresponding phase angle that also define the control over the complete rotor cycle. However, it is known that, at moderate to high advancing tip Mach numbers, only those source control inputs from the advancing side of the rotor disk will be effective at reducing HSI noise in the direction of forward flight near the plane of the observer. The control inputs from the remaining azimuth angles may actually increase the radiated noise in other observer directions. To minimize these effects in practice, the control source input can be turned on when the rotor blade is between azimuth angles of 0 and 180 deg.

V. Single-Frequency Harmonic Acoustic Control Source

Another way of formulating the antinoise problem is to consider the use of individual single-frequency harmonic source controllers. This approach is instructive, because it highlights the advantages and

Table 2 Mass flow rate and blade duct Mach numbers for a range of single-frequency harmonic control sources

Harmonic number	Peak mass flow rate, kg/s	Peak jet Mach number	Control phase angle, deg	Acoustic pressure peak noise reduction, dB
1	10.83	1.94	3.58	19.12
2	5.94	1.06	8.59	22.90
3	3.58	0.64	10.61	12.74
4	2.30	0.41	13.52	8.10
5	1.36	0.24	18.55	5.59

Table 3 Peak force and target noise reductions for a range of in-plane single-frequency harmonic force controllers

Harmonic number	Peak in-plane force, N	Peak in-plane force/(T/N_b)	Control phase angle, deg	Acoustic pressure peak noise reduction, dB
1	4018.20	0.0696	5.77	22.75
2	2074.16	0.0359	7.64	15.99
3	1167.62	0.0202	11.88	10.55
4	759.03	0.0131	14.67	7.23
5	474.15	0.0082	18.72	5.18

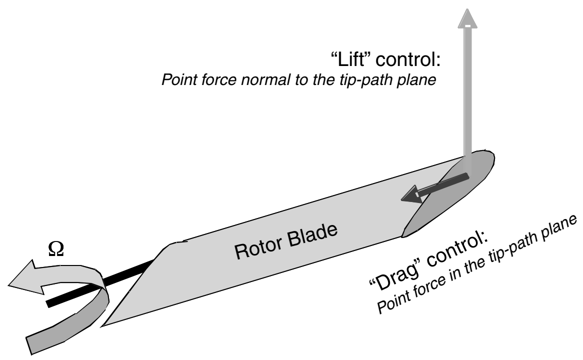

Fig. 12 Sketch of on-blade force (dipole) controllers.

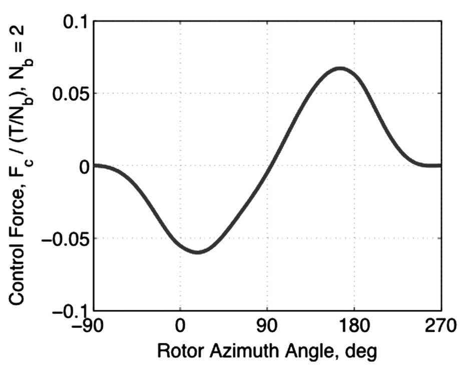

Fig. 13 In-plane point control force requirement for target thickness noise minimization using a multiple-frequency control force.

limitations of using both low- and high-frequency antinoise control inputs. In this study, 2 and 4/rev single source controllers are investigated individually to see how effective they are at minimizing the peak of the thickness noise pulse. Individual frequencies have less cancellation authority than the solution, using a combination of frequencies shown in the previous section. Near complete cancellation of thickness noise at the target observer location is not possible using a single-frequency harmonic controller. The maximum possible peak noise reduction at the target observer is explored for each single-frequency harmonic controller.

The noise control effectiveness for a low single-frequency 2/rev control source input is shown in Fig. 10 for the target observer and the eight surrounding observer points. The peak noise level has been reduced by nearly 23 dB at the target position. This approach is also very effective (>14 dB) at observer positions above and below the tip-path plane. At positions to the side of the target observer, the peak noise level reductions are lower (∼7 dB) but respectable.

The effect of using a 4/rev harmonic control source solution is a maximum peak noise reduction of 8 dB at the target microphone position, as shown in Fig. 11. This cancellation reduced slightly for the out-of-plane observers (∼6 dB). This fourth harmonic control source actually results in a slight increase in noise level in the off-target locations, either on the left or the right. This indicates that a 4/rev volume controller has a lower antinoise effectiveness along the azimuthal direction when compared with a 2/rev controller.

The mass flow requirements in the supply duct to supply this single control source are given in Table 2 for several single-frequency harmonic controllers (1–5), along with Mach numbers corresponding to a duct outlet area of half the blade cross section. The lower single-frequency controllers result in the maximum peak noise reduction at the target, but they require larger mass flow rates, and hence require the largest Mach numbers in the blade supply ducting. The higher frequency single source controller requires less mass flow rates, and hence lower Mach numbers, but suffer from the problem of

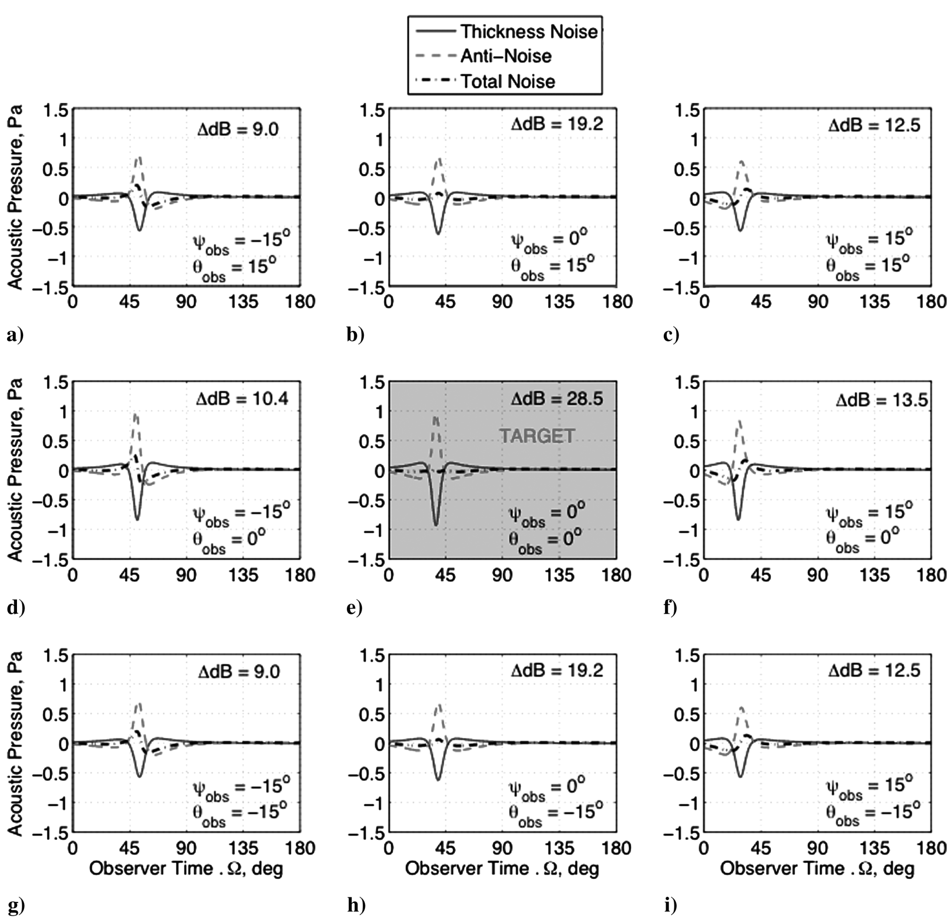

Fig. 14 Reduction of thickness noise using a multiple-frequency in-plane control force solution.

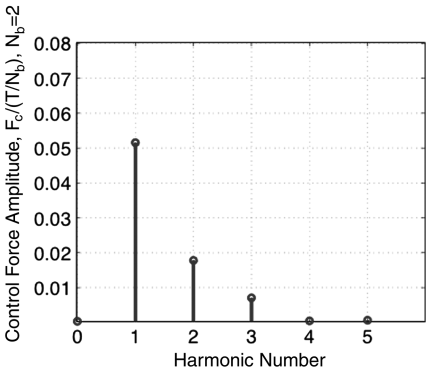

Fig. 15 Fourier analysis of the multiple-frequency in-plane control force solution in Fig. 13.

lower peak noise reductions at the target location and not having good cancellation effectiveness over a wider observer azimuth angle range.

It should also be noted that, by choosing a single harmonic controller to cancel the peak value of thickness noise, other harmonics of radiated noise (higher and lower) are generated. This effect can be seen in the resulting time histories for both the 2 and 4/rev single harmonic control at the target observer positions (Figs. 10 and 11). This arises because the single control source input is modified by the acoustic amplification process to produce additional harmonic inputs to the acoustic equations, which also affects the resulting noise at the observer positions.

VI. Noise Cancellation Using Acoustic Dipoles (Force)

These same ideas can be used to evaluate the possibility of using an on-blade control force dipole to cancel thickness noise at a target observer in the acoustic far field. In this case, the third control term of Eq. (1) is activated and the second term is now set to zero. Because the acoustic equations are normally written using an on-blade axis system, it is consistent to do this analysis in the same system. If we neglect out-of-plane motions of the blade (which are usually quite small), the rotor forces can be decomposed into in-plane and out-of-plane forces in the tip-path plane axis system. These forces radiate noise as acoustic dipoles that, when controlled in the correct fashion, can be used to minimize thickness noise. A sketch of the in-plane and out-of-plane on-blade point force controllers is shown in Fig. 12.

A. General In-Plane Single Force Control

Using in-plane acoustic dipoles to cancel thickness noise is a logical choice. Past knowledge of dipole directivity shows that dipoles primarily radiate along their major axis, which is aligned parallel to the tip-path plane, the same direction as that of maximum thickness noise radiation. Performing analysis similar to that used for acoustic control sources yields the in-plane control force time history, shown in Fig. 13, that is needed to minimize thickness noise for this nominal rotor. The control force is theoretically applied at the tip of the blade, at the quarter chord, and along the drag direction. Similar to the controlled source, the resulting in-plane dipole force control shape is quite smooth, and lower harmonic in nature.

The character of the pulse shapes for the volume control and the force control are quite similar. The peak negative amplitude of the thickness noise pulse, which is being cancelled, occurs when the rotor blade reaches the 90 deg azimuth position. The in-plane drag force that is necessary to cancel this noise increases at its maximum rate at this same rotor azimuth angle.

The acoustic effectiveness of this in-plane force control applied at the tip of the blade is shown in Fig. 14. At the target observer position, the peak noise level is very close to zero (~28 dB peak noise reduction). Above and below this observer location, acoustic

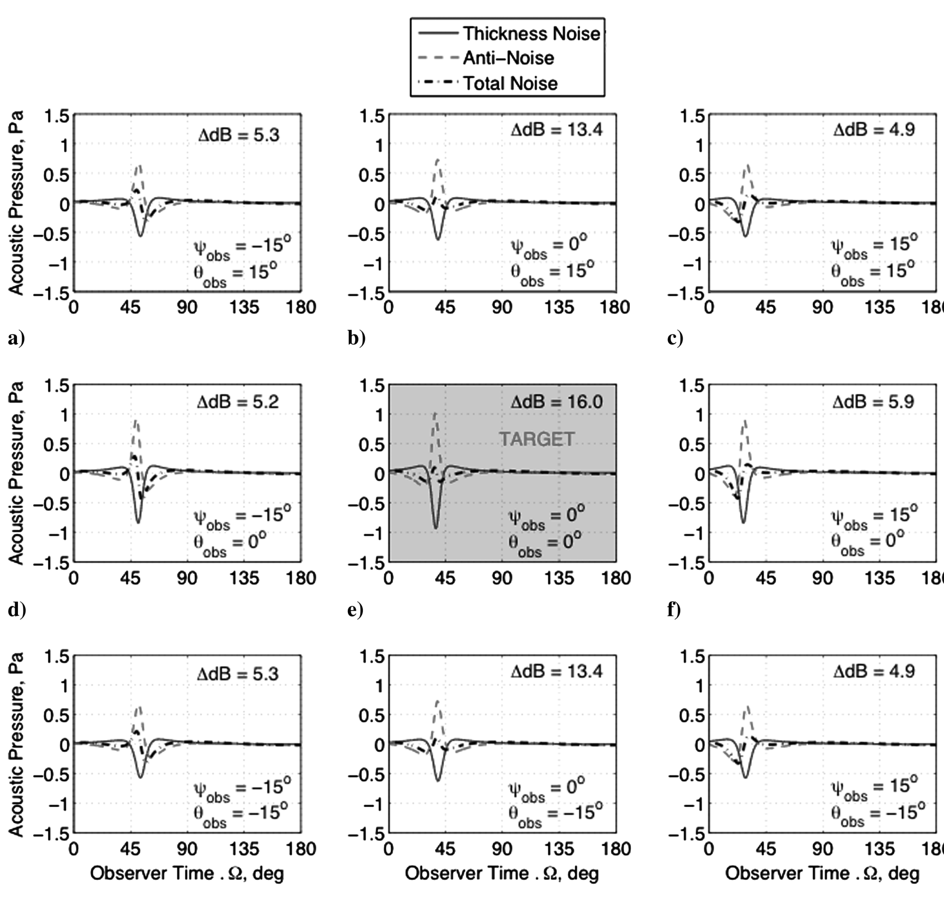

Fig. 16 Reduction of thickness noise using a 2/Rev harmonic control force.

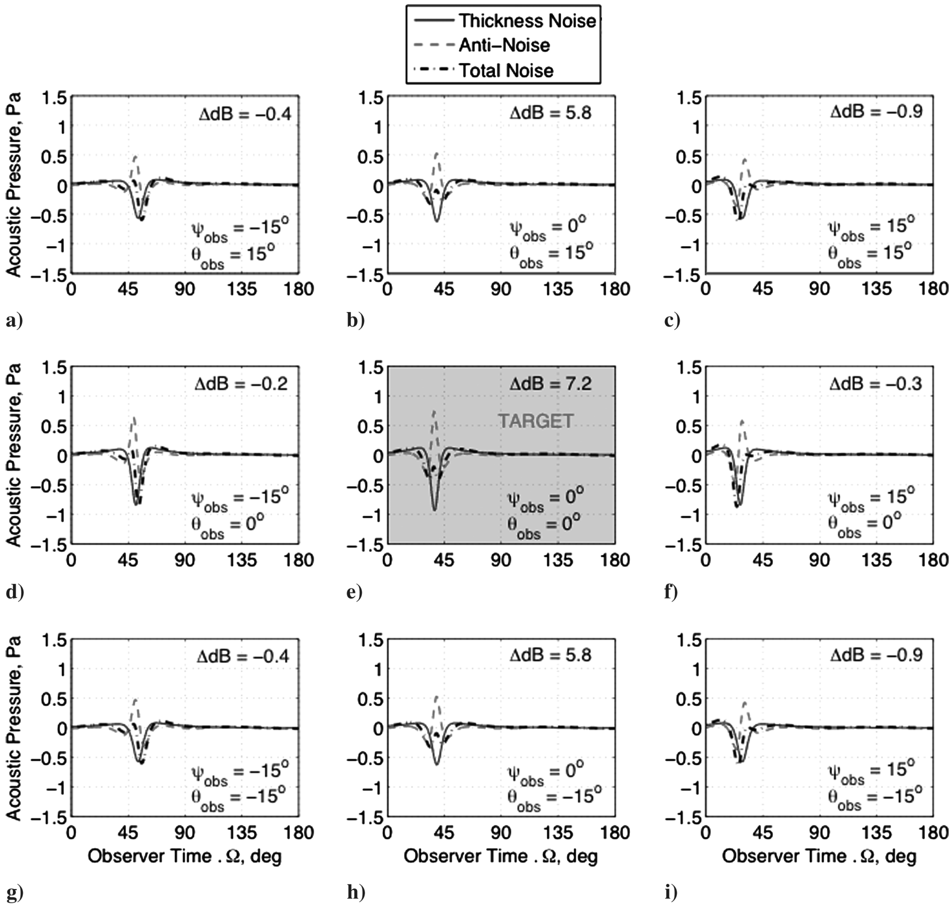

Fig. 17 Reduction of thickness noise using a 4/Rev harmonic control force.

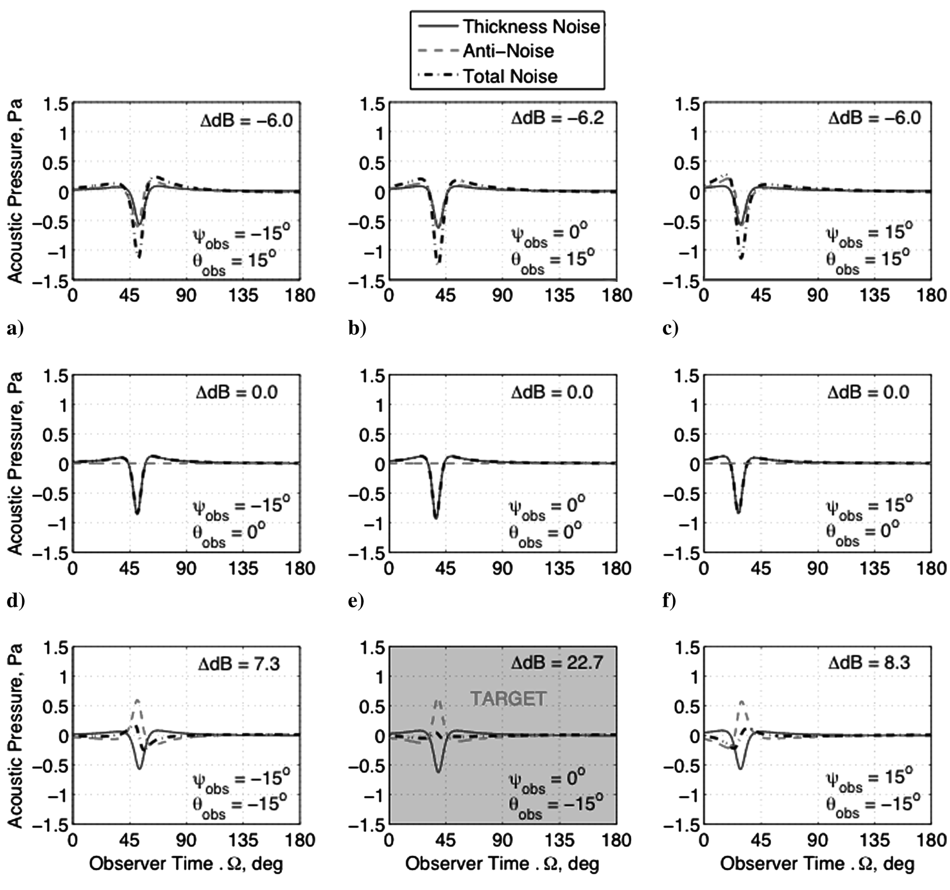

Fig. 18 2/Rev harmonic control of out-of-plane blade force control.

cancellation remains quite effective (~19 dB). For the 15 deg observer positions off to the left side, a 10.4 dB reduction is shown, whereas off to the right side, 13.5 dB peak reductions are indicated.

Figure 15 presents a harmonic analysis of the control force time history in Fig. 13. As in the volume controller, the lower frequencies are seen to be most effective in reducing thickness noise. The relative harmonic content of the control force requirement is distinctly different than the control mass flow requirement (Fig. 7). The control force solution is dominated by the 1/rev component; the amplitude of the 2/rev component is less than 40% of the 1/rev component. In the mass flow solution, the 2/rev component was nearly 66% of the 1/rev component of mass flow (Fig. 9).

Single-frequency harmonic point force controllers acting at the quarter chord at the tip of the blade are now assessed. As before for volume sources, 2 and 4/rev controllers are investigated. Figure 16 shows the acoustic cancellation effectiveness for a 2/rev force controller. The amplitude of the drag force used by the controller is 7% of the blade thrust (for a two-bladed rotor). It is seen that on-axis noise reduction effectiveness is quite good, with about 16 dB reduction in-plane and more than 13 dB out-of-plane in the directly ahead direction. Off to the sides, the reduction effectiveness reduces, and the peak acoustic reduction is of the order of 5 dB. Figure 17 shows the cancellation effectiveness of a 4/rev force controller. The amplitude of the drag force in this case is 1.3% of blade thrust (for a two bladed rotor). This controller achieves a maximum of 6–7 dB on-axis both in- and out-of-plane. Off to the sides. there is no reduction, similar to the 4/rev volume control.

The in-plane control force requirements to minimize the peak of the target in-plane thickness noise are given in Table 3 for several single-frequency harmonic controllers (1–5). Much like in the case of control sources, the lower single-frequency control forces result in the maximum peak noise reduction at the target, but they require larger control force values. The higher frequency single force controllers require less in-plane peak force values, but they suffer from the problem of lower peak noise reductions at the target location.

B. Out-of-Plane Single Force Control

Out-of-plane force (pressure force normal to the tip-path plane, lift) control has no direct effect on in-plane noise. The acoustic effect of an out-of-plane force is equal and opposite, above and below the rotor plane. Therefore, although out-of-plane forces can be used to reduce the out-of-plane loading noise at specific observer locations, they are not effective in canceling the in-plane thickness noise field.

Figure 18 demonstrates the use of a 2/rev out-of-plane control force. The amplitude of the control force is 11.9% of blade thrust (for a two-bladed rotor). The amplitude and phase of this force is selected to minimize the peak of thickness noise at an observer location directly ahead of the rotor and 15 deg below the tip-path plane. It is seen that the resulting noise pulse is nearly equal and opposite to the thickness pulse at that observer location and can be used to reduce thickness noise almost completely. Moving left or right in the same elevation plane gives somewhat reduced reduction, but the controller remains effective up to 15 deg left and right. In the plane of the rotor, the lift control has no effect on the acoustics, and so there is no reduction. At an elevation of 15 deg above the rotor plane, the lift control effectively nearly doubles the thickness noise. The acoustic pulse associated with the lift control at these elevation angles is nearly identical to the thickness pulse. Therefore, the thickness control is seen to be effective at one elevation angle above or below the rotor disk and very ineffective in the plane of the rotor or at observer locations on the other side of the rotor.

VII. Conclusions

Some theoretical possibilities of using on-blade control to reduce the peak of thickness noise at a target observer position have been reviewed using a linear acoustic analysis with ideal acoustic control sources. For the most part, the analysis has been restricted to a typical helicopter flying at an advancing tip Mach number of 0.82, for which there is no acoustic delocalization. For a target observer located in the acoustic far field, in the plane of the rotor, in the direction of forward flight, it has been found that:

1) Theoretically reducing the negative peak of the thickness noise pulse at the target observer location by trying to null the acoustic radiation with opposing sinks and sources of constant and equal strength at an effective radial position (~0.9 R) was quite effective. Acoustic cancellation at locations surrounding the target was effective as well. However, the mass flow rates of the on-blade acoustic sinks and sources are large and pose many implementation challenges.

2) To cancel or reduce the negative peak of the thickness pulse using acoustic sources on the blade, the mass flow must increase near the 90 deg blade azimuth location. To cancel or reduce the negative peak of the thickness pulse using in-plane forces on the blade, the in-plane control drag force must also increase near the 90 deg blade azimuth location. These requirements can be directly inferred from the basic physics of the linear acoustic process, as expressed in the Ffowcs Williams and Hawkings equation [5].

3) Canceling thickness noise by using a single controlled source can reduce the negative peak of the resulting noise pulse at the target observer position. This method uses the rate of change of the mass flow to cancel the far-field noise. When this method of noise cancellation was used, the peak negative levels above and below the target observer position were also cancelled. However, at observer positions to either side of the target observer position, the cancellation was less effective for this point source controller. Restricting the control to selected single harmonic frequencies further limited the effectiveness of the source controller. Nontrivial mass flow rates to supply the acoustic source were also necessary.

4) Canceling thickness noise by using a single force controller can also reduce or eliminate the negative peak of the thickness noise pulse at the target observer. In-plane force control (drag) nearly matches the directivity characteristics of thickness noise near the target observer, and therefore was a good on-blade controller. Fairly large in-plane forces (7% of average blade thrust) were required for complete cancellation of thickness noise. As in the case of the single on-blade source, controlling the in-plane force also effectively canceled the noise above and below the target observer position. Cancellation at target observer locations to either side of the target observer position were less effective, owing to the basic physics of this cancellation method. Restricting the in-plane force control to single harmonic frequencies further lessened the cancellation effectiveness. As in the case of volume source control, lower frequencies cancel the noise over a wider azimuth angle range but require larger peak-to-peak values of the control force for the same level of noise cancellation.

5) Out-of-plane (lift) forces cannot directly control in-plane noise. They can be effective at controlling the noise at select out-of-plane observer positions. However, the noise cancellation at observer positions above or below the out-of-plane observer target position degrades quickly and can even increase the total radiated noise at those off-target positions.

6) On-blade acoustic controllers are attractive for the cancellation of thickness noise because they use the basic physics of rotor noise to provide the higher frequency, higher amplitude acoustic waves to reduce the radiated noise. A suitable lower harmonic acoustic source or force controller can be used to achieve significant noise reductions.

The current paper has focused on the lower Mach number range of the HSI noise problem, for which linear thickness noise is the dominant contributor to the HSI noise pulse and delocalization effects can be ignored. As the tip Mach number of helicopter is raised, the target negative pulse shape will grow in amplitude and become more narrow. At Mach numbers close to the delocalization Mach number, nonlinear effects will also cause pulse shape changes that will also have to be considered in the problem formulation and suggested onboard blade controllers for noise minimization. For lower advancing tip Mach numbers, the HSI pulse becomes less intense and wider in shape, making the on-blade control requirements a bit easier. However, at these lower Mach numbers, it is also known that the noise due to changing forces on the helicopter can also radiate in-plane noise and should be included in the analysis.

References

[1] Schmitz, F. H., "Rotor Noise," *Aeroacoustics of Flight Vehicles, Theory and Practice, Vol. 1: Noise Sources*, edited by Hubbard, H. H., Acoustical Society of America, Melville, NY, 1995, Chap. 2.

[2] Yu, Y. H., "Rotor Blade-Vortex Interaction Noise," *Progress in Aerospace Sciences*, Vol. 36, No. 2, Feb. 2000, pp. 97–115. doi:10.1016/S0376-0421(99)00012-3

[3] Yu, Y. H., Tung, C., van der Wall, B., Pausder, H., Burley, C., Brooks, T., Beaumier, P., Yves, D., Mercker, E., and Pengel, K., "The HART II Test: Rotor Wakes and Aeroacoustics with Higher Harmonic Pitch Control (HHC) Inputs. The Joint German/French/Dutch/US Project," *Conference Proceedings of the American Helicopter Society 58th Annual Forum*, Vol. 2, American Helicopter Society, Alexandria, VA, June 2002, pp. 1984–1994.

[4] Schmitz, F. H., and Gopalan, G., "High-Speed Impulsive Helicopter Noise Reduction Possibilities Through On-Blade Control," American Helicopter Society Specialists' International Forum on Rotorcraft Multidisciplinary Technology, American Helicopter Society, Paper 14-3, Alexandria, VA, Oct. 2007.

[5] Ffowcs Williams, J. E., and Hawkings, D. L., "Sound Generation by Turbulence and Surfaces in Arbitrary Motion," *Philosophical Transactions of the Royal Society of London, Series A: Mathematical and Physical Sciences*, Vol. A264, No. 1151, 1969, pp. 321–342. doi:10.1098/rsta.1969.0031

[6] Farassat, F., "Linear Acoustic Formulas for Calculation of Rotating Blade Noise," *AIAA Journal*, Vol. 19, No. 9, Sept. 1981, pp. 1122–1130. doi:10.2514/3.60051

[7] Schmitz, F. H., Aggarawal, H. R., and Boxwell, D. A., "Prediction and Measurement of Low-Frequency Harmonic Noise of a Hovering Model Helicopter Rotor," *Journal of Aircraft*, Vol. 37, No. 5, 2000, pp. 786–795. doi:10.2514/2.2701

[8] Visintainer, J. A., Marcolini, M. A., Burley, C. L., and Liu, S. R., "Acoustic Predictions Using Measured Pressures from a Model Rotor in the DNW," *Journal of the American Helicopter Society*, Vol. 38, No. 3, July 1993, pp. 35–44. doi:10.4050/JAHS.38.35

[9] Gopalan, G., and Schmitz, F. H., "Far-Field Near-In-Plane Impulsive Helicopter Noise Reduction Possibilities in Forward Flight," *Conference Proceedings of the American Helicopter Society 64th Annual Forum*, Vol. 1, American Helicopter Society, Alexandria, VA, 29 April–1 May 2008, pp. 675–696.