

Individual Propeller Source Noise Assessment from Full-Scale eVTOL Flight Test Measurements

Kyle A. Pascioni *

NASA Langley Research Center, Hampton, VA, 23681, USA

Austin D. Thai[†] and Jeremy J. Bain[‡]

Joby Aviation, Santa Cruz, CA, 95060, USA

Aircraft equipped with distributed propulsion, e.g., those utilizing many propulsors for lift and thrust, radiate complex acoustic signatures with strong dependence on the vehicle state. In an effort to better interpret acoustic measurements and characterize the major noise source mechanisms, the Vold-Kalman order-tracking filter is applied to full-scale acoustic flight test measurements of the Joby Aviation eVTOL aircraft. Using synchronized acquisition of the aircraft position, time-varying rotation rates of each propeller, and any given single-channel acoustic signal, harmonic and nonharmonic acoustic content can be separated. Furthermore, this time-domain technique can also separate harmonic content amongst individual propellers, providing additional physical insight into the total acoustic field. A 60 kt level flyover and hover are used to exemplify the effectiveness of the method. High-fidelity simulations were performed under similar aircraft conditions from the flight test, indicating very good agreement with measured overall aircraft noise levels and filtered levels of individual propellers. Results clearly demonstrate the ability to rank propellers in terms of their relative importance without the use of phased microphone arrays. Frequency- and order-domain results are provided, as well as noise hemispheres, to illustrate relative source contributions and emission angle dependence. Given the similarities in propeller states for each flight condition, acoustic differences can be associated with interactional or installation effects, highlighting the shortcomings of isolated propeller models.

Nomenclature

a_0 = Sound speed, ft/s

*Research Aerospace Engineer, Aeroacoustics Branch, 2 N Dryden St., M/S 461

[†]Acoustics Senior Engineer, Flight Physics, 333 Encinal St., Member AIAA, corresponding author, austin.thai@jobyaviation.com

[‡]CFD and Aeroacoustics Lead, Flight Physics, 333 Encinal St., Member AIAA

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A	=	Coefficient matrix of the structural equation
$A_{s,k}$	=	Amplitude of shaft s and order k for the simulated signal
f	=	Frequency vector, Hz
H	=	Multiorder difference matrix
I	=	Identity matrix
J_k	=	Loss function of the k th order for VKF error minimization
k	=	Order index
K	=	Set of selected orders
$M_{t,s}$	=	Tip Mach number for shaft s
$M_{\text{ref},s}$	=	Reference tip Mach number for shaft s
N_s	=	Number of shafts (propellers)
p	=	de-Dopplerized measured acoustic pressure, Pa
$\hat{p}$	=	Harmonic acoustic pressure, Pa
p_{ref}	=	Reference acoustic pressure, 20 μPa
p_{sim}	=	Simulated signal
PSD	=	Power spectral density, dB re. $p_{\text{ref}}/\sqrt{\text{Hz}}$
r	=	VKF weighting coefficient
r_d	=	Propagation distance, ft
s, q	=	Shaft (propeller) indices
SPL	=	Sound pressure level, dB re. p_{ref}
t	=	Reception time, s
x, y, z	=	Microphone array coordinates, ft
$x_{s,k}$	=	Complex amplitude envelope of shaft s and order k
Δf	=	Frequency binwidth, Hz
$\varepsilon_{s,k}$	=	Error in VKF structural equation for shaft s and order k , Pa
η	=	Nonharmonic (random) component of signal, Pa
σ	=	Standard deviation
τ	=	Source-time, s
$\Theta_{s,k}$	=	Complex phasor of shaft s and order k
ω_s	=	Rotation rate of shaft s , rev/s

I. Introduction

URBAN Air Mobility (UAM) is a new and imminent sector in aviation primed to thrive in the coming years. In addition to safety, efficiency, and affordability, noise is one of the leading concerns [1] and has ignited a growing number of research endeavors to investigate the physical acoustic generation mechanisms of these novel UAM aircraft configurations [2–5]. While these studies are invaluable, they are often dedicated component tests of scaled geometry. As discussed by Rizzi et al. [6], who summarized knowledge gaps and provided recommendations to assess UAM noise, full-scale measurements are ultimately essential to better understand the dominant source mechanisms and assess community impact. To that end, NASA and Joby Aviation conducted a full-scale flight test [7] as part of the National Campaign Developmental Test (NC-DT) in 2021. Acoustic measurements were acquired on the Joby preproduction prototype to initiate investigation of the noise source mechanisms, expected noise levels, and sound character of this new vehicle class. These data provided a “first look” to the public and have since been leveraged to enhance acoustic prediction and modeling capabilities [8, 9].

The acoustic signals acquired through ground-based measurements of full-scale UAM aircraft can be quite complex and difficult to interpret. Often equipped with many propulsors and high degrees of freedom (e.g., propulsor tilt, blade pitch, rotation rate), conventional processing techniques (e.g., power spectra or integrated metrics such as sound exposure level) may not be enough to fully understand UAM noise and its operational dependence. This is particularly the case for vehicles with distributed propulsion systems, which enable the usage of multiple thrusters and may introduce flight control laws that allow state variation even during constant airspeed and attitude conditions [6]. Often, these aircraft are designed for lower tip speeds relative to conventional rotorcraft, resulting in higher acoustic sensitivity to environmental conditions [10] and aerodynamic interactions [11], introducing ambiguity into the responsible source mechanisms. Thus, novel measurement or processing techniques are needed to extract greater physical insight and provide useful data to the computational community.

In an effort to further validate prediction methods and rank sources in relative importance, the order tracking Vold-Kalman filter (VKF) is applied herein to the flight test data. First introduced by Vold and Leuridan [12], this time-domain technique has the ability to separate harmonic noise from nonharmonic noise (or, loosely, tonal from broadband noise) of a single-channel acoustic measurement by tracking a complex phasor based on (known) individual time-varying rotation rates of each propulsor. Note that the terms “harmonic noise” and “nonharmonic noise” will be used to refer to shaft-coherent and shaft-incoherent content, respectively.

As demonstrated in this article, the filter can effectively separate harmonic content amongst six independently operating propulsors. This decomposition is a powerful tool for identifying whether specific propulsors dominate the vehicle’s overall acoustic signature, enabling the development of acoustically optimized operations and informing next-generation design. Furthermore, traditional methods of postprocessing flight test measurements involve segmenting the acoustic pressure time series to define levels at discrete emission angles. There is an unavoidable tradeoff between

time and frequency resolution when using traditional Fourier transforms to accomplish this. The combination of short time blocks with high frequency resolution can significantly increase uncertainty in spectral representations. As will be shown, another attribute of the VKF avoids these tradeoffs by tracking content in the order domain. Among others, Borghesani et al.[13] agrees with this sentiment, stating,

“... it is clear that the monitoring of rotating machineries is by far more effective if analyses are performed in the angular domain of the shaft rotation, rather than in time domain. The same conclusion is valid for the order domain, the spectral counterpart of the angular domain (measured in n per revolution, nX), which is always preferred to the “Hertzian” frequency domain.”

A number of examples of the VKF applied to aeroacoustics have proven its usefulness. For example, Truong [14] extracted tonal components from a small-scale ducted fan experiment to develop a novel exhaust fan source model. Shah et al. [15] extracted shaft-coherent content to independently study harmonic and nonharmonic content from a modern turbofan engine. More relevant to AAM, Tinney et al. [16] employed the VKF in conjunction with proper orthogonal decomposition to form a reduced order model of stacked rotors in hover. Truong et al. [17] found it useful to enable comparison with mid-fidelity predictions for an isolated rotor ground test. The method can also separate single-microphone measurements on a per-shaft (i.e., per propulsor) basis. For example, Stephens and Vold [18] separated harmonic content of individual (not mechanically coupled) rotors from a counterrotating open rotor system and found the VKF more effective than phase averaging. From a psychoacoustic perspective, the ability to gain signal tonality relative to broadband levels could support human response research into which sound quality metrics are predictive of annoyance [19, 20].

To the authors’ knowledge, this is the first attempt at using the VKF on a UAM aircraft. Other acoustic flight test efforts have proven its success, for example, in the work of Rachaprolu and Greenwood [21] demonstrating effective separation of the main and tail rotor harmonic content of a Bell 430 helicopter. Individual time histories and full noise hemispheres per rotor characterized their respective source directivities. Rachaprolu et al. [22] is the only example of applying this method to aircraft acoustic signals that have more than two independent rotating components. Their successful implementation on a hexacopter in forward flight exemplified the robustness of this filter to six propulsors and small spacing between order frequencies, both similarities to the work herein.

The remainder of this paper is organized as follows. First, the vehicle, acoustic instrumentation, and selected flight conditions are briefly covered. Details regarding the complementary numerical simulations are then given, followed by an overview of the Vold-Kalman filter formulated as it is applied here. Synthetic signals with similar characteristics to the measurements are used to build confidence in the results and appropriately select filter parameters. Finally, filtered measurement and computational results are provided both in terms of full aircraft and per individual propeller, along with their relative acoustic contributions.

II. Vehicle

Joby Aviation has been developing an all-electric vertical takeoff and landing (eVTOL) aircraft that is intended to operate as part of a fast, quiet, and convenient air taxi service. It is designed for high-density operations potentially near residences and workplaces, where noise is of high importance. Joby first flew subscale flights in 2015 and its first full-scale prototype in 2017 [23]. The preproduction prototype, which is the subject of this work and shown in Figure 1, is intended to carry one pilot and four passengers. The propulsion system features six (five-bladed) 9.8 ft (3 m) diameter tilting propellers to enable transition from thrustborne to wingborne flight achieving speeds up to 175 kt. The wingspan is 38 ft (11.6 m) and is 21 ft (6.4 m) nose to tail. Additional details of the aircraft are documented in previous work [8, 23, 24]. Figure 1 also provides the propeller numbering convention used throughout this paper.



Fig. 1 The Joby Aviation preproduction prototype aircraft in transition to wingborne flight. Photo credit: NASA

III. Flight Test Details

A. Instrumentation

For all acoustic measurements, 1/2" GRAS 67AX microphones embedded into 15-inch (400 mm) ground boards were used. Signal acquisition was accomplished by the second generation Wireless Acoustic Measurement System (WAMS II) at a sampling rate of 25 kS/s. Each flight condition will be assessed herein using a subset of the available microphones. Ambient conditions (pressure, temperature, and relative humidity) near the ground and vertical wind profiles were also acquired using a suite of weather instrumentation. Wind conditions were favorable and, on average, less than 3 kt at altitude during flights selected for this work. Additional details on instrumentation and the recorded data can be found in Ref. [7].

B. Flight Conditions

The aircraft performed a constant true airspeed level flyover at 60 kt, holding a semi-thrustborne condition representing an instant of the transition procedure to forward flight. The six propellers were at a tilt of approximately 47°

(VTOL mode defined to be 90°), similar to what is shown in Fig. 1. Fig. 2(a) provides the flight track geometry relative to a subset of microphones that form a linear array perpendicular to the flight path. Figure 2(b) displays the azimuth and elevation angles covered as the aircraft maintained 370 ft (113 m) altitude for a travel distance of $\pm 2,000$ ft (610 m). The angular mapping is on a Lambert projection, which is a two-dimensional representation of a hemisphere following underneath the aircraft. This projection will be used for results in later sections as it minimizes contour distortion. Labels to define orientation relative to the aircraft are provided. The majority of microphones map out port-side emission angles. Physical field constraints hindered additional measurements on the starboard side.

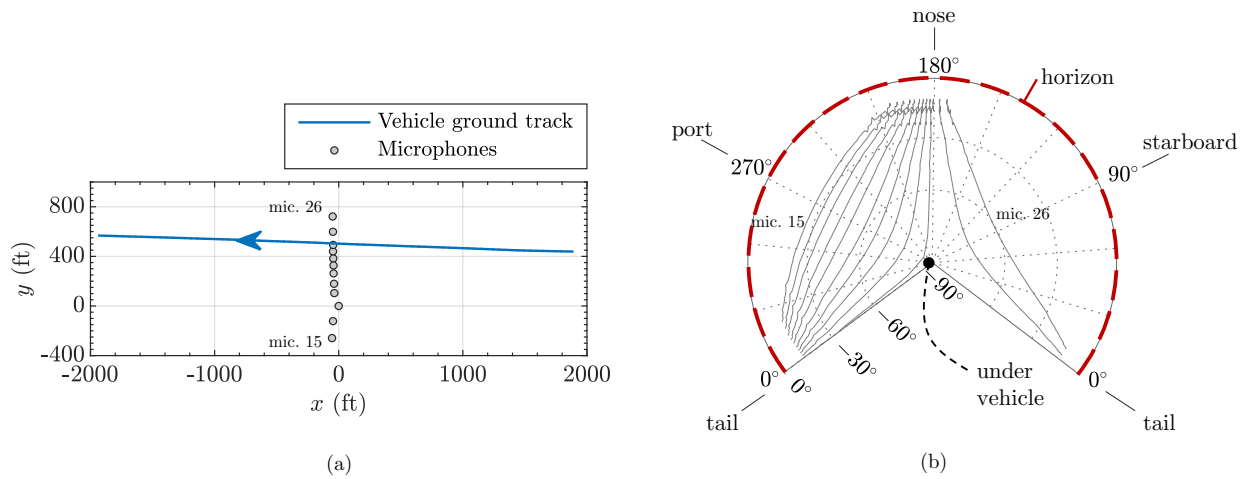
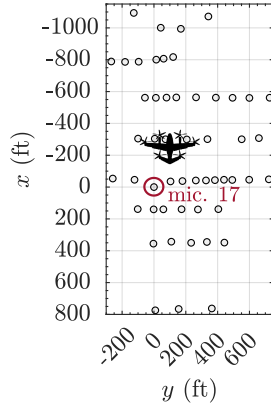


Fig. 2 Geometry of the 60 kt flyover showing the (a) vehicle ground track relative to the microphones and (b) the microphone traces over azimuth and elevation.

An out-of-ground effect hover was also conducted at an altitude of approximately 218 ft (66 m) over the microphone array. Figure 3 and Table 1 give details of the aircraft location and orientation relative to the 52 microphones that will be assessed for this condition. A time interval of 18 s under stable hover was chosen, during which the aircraft maintained its position nearly within one foot ($2\sigma \lesssim 1$ ft [0.3 m], in which σ is the standard deviation) in all three directions. Propellers were maintained at constant blade pitch and tilt in VTOL mode.

On-board vehicle data are crucial to the success of the methods described below. Position, attitude, and individual propeller states were recorded at 100 Hz and Coordinated Universal Time (UTC)-stamped to synchronize with the acoustic signals. Figure 4 provides the time-varying rotation rates over the flyover and hover events. It should be noted that the control system at the time of the flight test is not indicative of the control laws intended for the production aircraft.



	Avg. (ref. mic. 17)	2σ
x , ft [m]	-262.3 [79.9]	0.15 [0.05]
y , ft [m]	96.7 [29.5]	1.01 [0.31]
Altitude, ft [m]	217.8 [66.4]	0.48 [0.15]
True heading	261.5°	0.21°

Fig. 3 Hover position over the microphone array. Aircraft silhouette defines heading.

Table 1 Aircraft position and heading during hover.

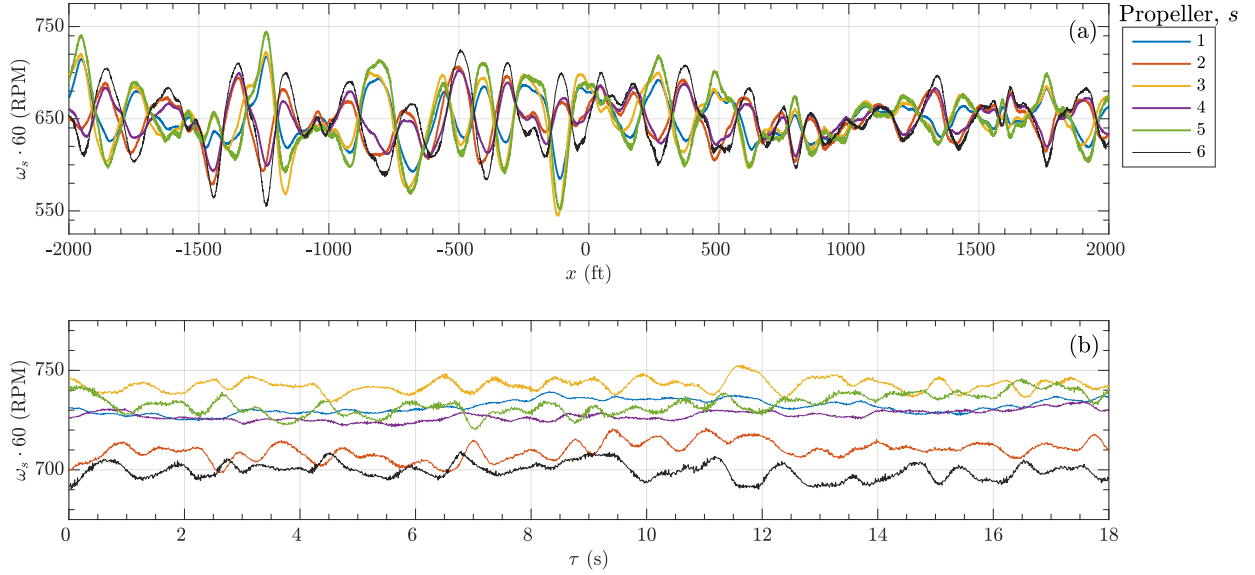


Fig. 4 Individual propeller rotation rates for the (a) flyover and (b) hover cases. Note the difference in the ordinate scales.

IV. Aeroacoustic Simulations

A. Computational Setup

High-fidelity computational fluid dynamics (CFD) simulations of the Joby aircraft in hover and in steady level flight were conducted using the overset grid solver NASA OVERFLOW version 2.3e [25–27]. Delayed Detached Eddy Simulation (DDES) terms were used with the Spalart-Allmaras (SA) model for turbulence closure [28, 29]. Laminar-turbulent transition was predicted using the Amplification Factor Transport (AFT) model [30]. The simulation implemented the Harten-Lax-van Leer-Contact (HLLC) upwind scheme [31] and improved Successive Symmetric Overre-

laxation (SSOR) algorithm [27] with 5th-order spatial differencing scheme and 2nd-order backward differencing in time. For both simulation cases, propeller phasing was randomized to mitigate effects of aerodynamic or acoustic interference, although these effects should be explored in the future. The simulations used a quarter-degree time step and after the solution was converged, one revolution was extracted for acoustic postprocessing. The main blade surface grid contains 123 points along the span and 249 points in the chord direction. The total grid system, illustrated in Figure 5 contains approximately 220 million points. This is the same grid used in Thai et al. [8], in which the aircraft acoustic predictions were verified with flight test measurements.

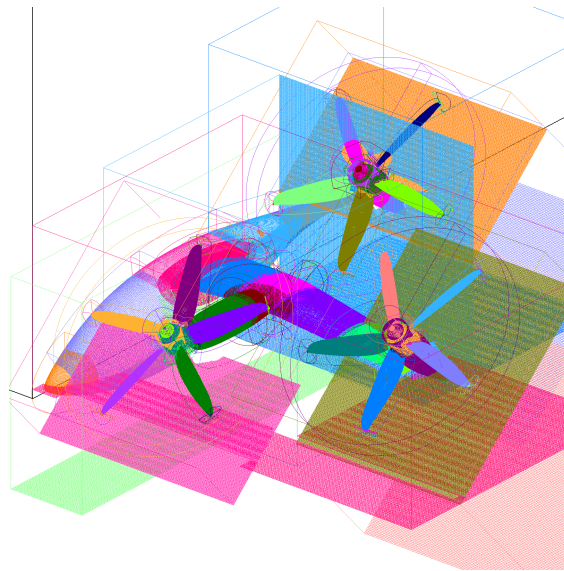


Fig. 5 Grid system used for the aerodynamic simulation.

The impermeable (solid) surface Farassat Formulation 1A implementation within PSU-WOPWOP [32] was used to compute the far-field acoustics with compact chordwise sources from the propellers only. The presence of the airframe was not accounted for. Thai and Bain [33] demonstrated good agreement using this method for approach and departure noise. The propellers were simulated separately in PSU-WOPWOP so that their individual acoustic levels could be compared to Vold-Kalman filtered measurement data.

For the flyover, CFD simulations were conducted as a half aircraft assuming symmetry about the nose to tail. The aircraft was trimmed using blade pitch and aircraft angle of attack to lift, drag, and pitching moment. The propellers were simulated at an equal constant 650 RPM at 47° tilt mimicking the average conditions from the flight test. A rendering of the flow visualization can be seen in Fig. 6(a). The simulation is able to capture the stronger tip vortices on the advancing side of the propeller disk. In this condition, there is aerodynamic interaction between the front propellers and the tail propellers, which is thought to affect performance and noise. The observers were placed on the 100 ft (30.5 m) hemisphere to be consistent with previous efforts [34, 35] and the selected reference distance to process

the measured data, discussed in more detail in Section IV.B.1. The total aircraft levels were obtained by summing the simulated acoustic spectra incoherently. Propagation effects such as acoustic scattering and atmospheric attenuation (< 1 dB at 300 Hz and 1500 ft [457 m], the highest frequency and largest propagation distance of interest, respectively) were not included in the model.

The hover simulations modeled the full airframe and all six propellers with the aircraft trimmed to lift using blade pitch. The six propellers were simulated at a constant speed of 700 RPM, and the phase of each propeller was randomized at the beginning of the simulation. Flow visualization from the hover simulation, depicting iso-surfaces of Q-criterion colored by vorticity magnitude, can be seen in Fig. 6(b). The flow solver is able to capture the generation of the tip vortices and their propagation into the wake. For this hover case, the ground observers were placed at the same locations as the flight test microphones relative to the aircraft. Individual propeller pressures were summed incoherently in the frequency domain to arrive at the total aircraft acoustic levels. Previous efforts have shown that the sound field radiated from distributed propulsors rotating at different rates, i.e., greater than 1%, tend to approximate overall levels if added incoherently [36]. The alternative superposition method, to sum (coherently) the acoustic pressure over all propulsors in the time domain, would not mimic the assumed coherence, or lack thereof, found in the source field during the flight test measurements as evidenced by the disparate rotation rates (see Fig. 4(b)).

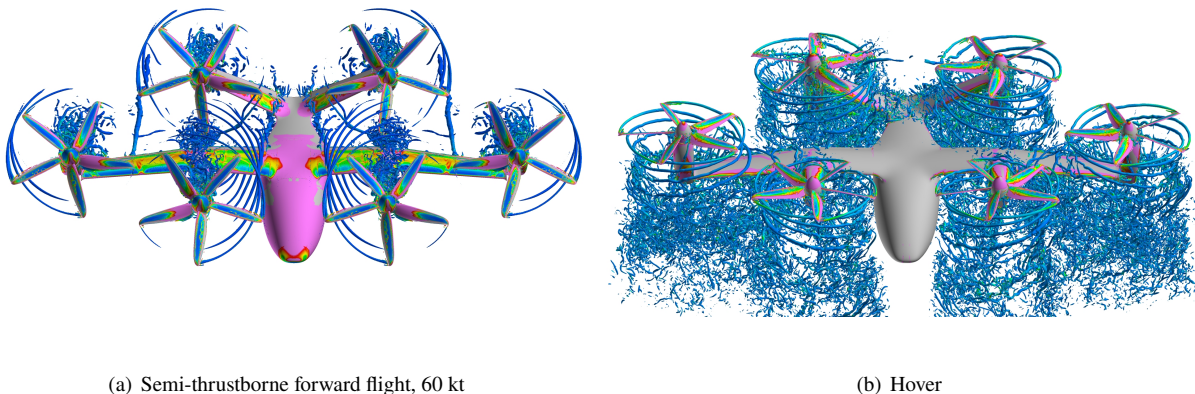


Fig. 6 Flow visualization of the Joby aircraft in (a) 60 kt steady level flight and (b) hover. Iso-surfaces of Q-criterion are colored by vorticity magnitude.

B. Model Validation

1. Semi-thrustborne flight

A comparison of the predicted and measured band-limited sound pressure levels (from 12 Hz to 2 kHz) on the 100 ft (30.5 m) hemisphere is shown in Fig. 7. Note that this frequency range is selected to ensure good signal-to-noise ratio in the measurements while also encompassing the relevant harmonic content. Measured data were processed in an identical fashion to Ref. [7] to arrive at this representation, accounting for spherical spreading, atmospheric attenuation,

and correcting for the presence of the ground-board by assuming sound-hard doubling. Although the experimental measurement does not cover the entire hemisphere, there is excellent agreement in peak levels, which were below 84 dB. There is also a good agreement in the directivity, with higher levels below the aircraft and lower levels forward. There is an overprediction towards the rear and in front of the aircraft, which could indicate some modeling deficiency. Previous work that explored airframe acoustic scattering for this exact condition revealed a potential for acoustic shielding to have an impact in these regions of the directivity [8]. Nonetheless, the CFD is capturing the overall levels quite well considering the assumptions in the model.

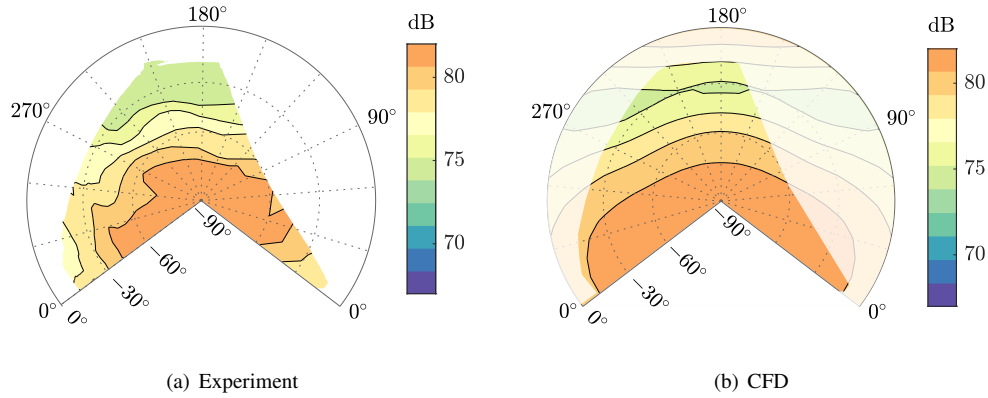


Fig. 7 Comparison between measured and predicted band-limited sound pressure levels for the Joby aircraft at 60 kt on a 100 ft (30.5 m) hemisphere.

2. Hover

The computed and measured hover ground contours of band-limited sound pressure level are plotted in Fig. 8. The microphones are denoted by white circles. The contour area of the highest level, located directly under the aircraft, is larger in the computations than in the experiments. In reality, the presence of the fuselage and the propeller downwash will affect the measurements and acoustic propagation. Overall, the ground contours show very good agreement. The band-limited sound pressure level difference is computed relative to the time-averaged measurements, illustrating levels are often within 2 dB. Due to the variability in levels over time, the minimum and maximum levels at each frequency were determined from the spectral time history, computed using Welch's method on 0.5 s time segments, identifying the measurement range. The prediction generally lies within this measurement range for each microphone [37].

V. Methodology

A. Acoustic Measurement Preprocessing

The Vold-Kalman filter (VKF) extracts acoustic information that aligns with integer multiples of the time-varying shaft (i.e., propeller) rotation rates. The measured signals, however, are Doppler shifted due to the source motion

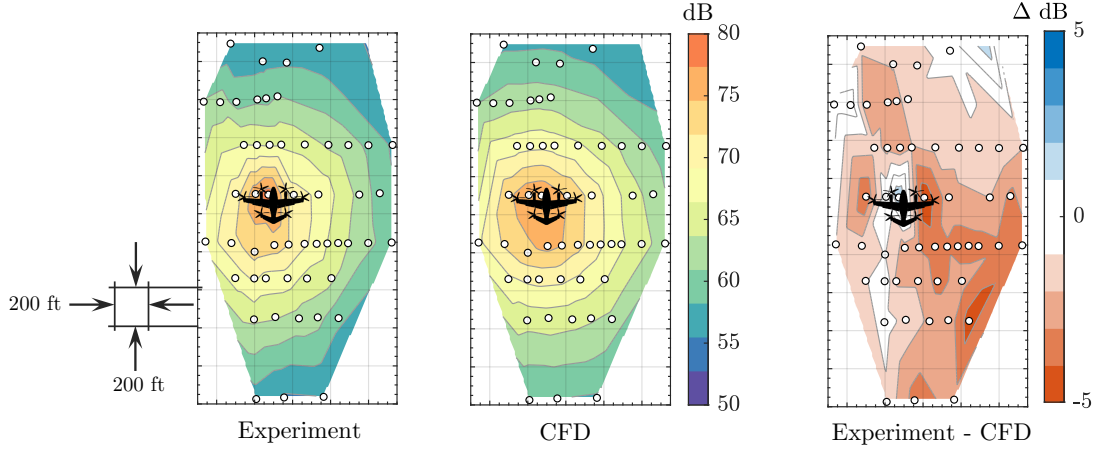


Fig. 8 Band-limited sound pressure level comparison between the time-averaged measurements and predictions for hover. Vehicle silhouette (not to scale) indicates its heading.

relative to the observer. For example, consider a source moving relative to a stationary observer emitting an impulse train. If the impulses are occurring at a constant time interval, the impulses are received by the stationary observer at smaller intervals while the source is approaching, and at larger intervals when the source is receding. To remove this effect and align the measured signal frequencies with the propeller rotation rates, a time-domain de-Dopplerization technique [38] is applied to each microphone signal using the vehicle tracking data. The retarded-time equation provides the relationship between reception and emission time, t and τ , respectively, for arbitrary relative movement,

$$\tau = t - r_d(\tau)/a_0, \quad (1)$$

in which $r_d(\tau)$ is the propagation distance from the vehicle center determined by the flight path at a given emission time, and a_0 is the sound speed. A de-Dopplerized pressure time series is accomplished by interpolating the measured pressure time series at times τ . This transformation from reception to emission time results in a varying sampling rate of the resultant signal. For convenience, the emission time-based signal is interpolated to a constant sampling frequency of 20 kHz (20% reduction from the measured sampling rate). Note that convective amplification is not accounted for since it is a small effect (≈ 1 dB or less) for the forward flight case.

In all results to follow, the pressure time series amplitudes are also halved to account for pressure doubling by the sound-hard ground boards [39] to mimic free-field conditions. Levels are also adjusted for spherical spreading to a reference distance of 100 ft (30.5 m) from the aircraft center.

B. Vold-Kalman Filter Overview

The second-generation multiorder version of the filter is chosen for this work. The mathematical formulation follows the work of several others [14, 16, 40, 41], while the code implementation was inspired by van der Seijs [42]. Using the Wold decomposition, it can be assumed the measured de-Dopplerized acoustic pressure time series can be decomposed,

$$p(\tau) = \hat{p}(\tau) + \eta(\tau), \quad (2)$$

in which $\hat{p}(\tau)$ is shaft-coherent content and $\eta(\tau)$ is random and uncorrelated with any shaft in the system. The total shaft-coherent information over a prescribed set of K orders (i.e., time-varying harmonics) is the superposition of those signals over N_s shafts,

$$\hat{p}(\tau) = \sum_{s=1}^{N_s} \sum_{k \in K} x_{s,k}(\tau) \Theta_{s,k}, \quad (3)$$

and

$$\Theta_{s,k}(\tau) = \exp \left(2\pi i k \int_0^\tau \omega_s(u) du \right). \quad (4)$$

The time-varying amplitude envelope, $x_{s,k}(\tau)$, is what the Vold-Kalman filter attempts to determine. The complex phasor in Equation 4 of order k tracks the time-varying rotational rate, $\omega_s(\tau)$, of shaft s , and is the result of an angular frequency integration. Note that these rates are required inputs that are known and sampled at a rate high enough to capture their variations. Plugging in Equation 3 into 2, and rearranging to form an error for the so-called data equation,

$$\eta(\tau) = p(\tau) - \sum_{s=1}^{N_s} \sum_{k \in K} x_{s,k}(\tau) \Theta_{s,k}(\tau). \quad (5)$$

Personal computer memory constraints inhibit simultaneously computing all orders over all shafts for the large number of samples in the measured signals. Therefore, a subset of orders is chosen and multiple instances of the filter are run consecutively. It is most important to compute orders together that have similar frequencies, particularly if those time-varying frequencies momentarily cross (e.g., a shaft order increasing in frequency briefly overlapping another shaft order decreasing in frequency). The benefit of multiorder computation with similar order frequencies is to avoid assigning the same content of the original signal to more than one shaft [43]. As will be discussed shortly, an error is minimized between the original signal and the multiorder filter output. This error is composed of the superposition of the selected orders. Independent computation of each order would not constrain the error by superposition. To that end, the order subsets are chosen to be each order k for all propellers, yielding six waveforms ($N_s = 6$) to be simultaneously solved. Expanding Equation 5 for order k for all propellers (and dropping the k subscript) gives the following equation

in matrix form,

$$\begin{bmatrix} \eta(\tau_1) \\ \eta(\tau_2) \\ \vdots \\ \eta(\tau_N) \end{bmatrix} = \begin{bmatrix} p(\tau_1) \\ p(\tau_2) \\ \vdots \\ p(\tau_N) \end{bmatrix} - \sum_{s=1}^{N_s} \begin{bmatrix} \Theta_s(\tau_1) & & & \\ & \Theta_s(\tau_2) & & \\ & & \ddots & \\ & & & \Theta_s(\tau_N) \end{bmatrix} \begin{bmatrix} x_s(\tau_1) \\ x_s(\tau_2) \\ \vdots \\ x_s(\tau_N) \end{bmatrix}. \quad (6)$$

A structural equation is also used to constrain envelope smoothness. To keep bandwidth (Δf) small, which will be discussed in the next section, the single-pole structural equation for time τ_i is formed using a difference equation,

$$\nabla^1 x_s(\tau_i) = x_s(\tau_i) - x_s(\tau_{i+1}) = \varepsilon_s(\tau_i), \quad (7)$$

which can also be cast in matrix form such that the finite difference coefficients form an upper bidiagonal matrix,

$$\begin{bmatrix} \varepsilon_s(\tau_1) \\ \varepsilon_s(\tau_2) \\ \vdots \\ \varepsilon_s(\tau_N) \end{bmatrix} = \begin{bmatrix} 1 & -1 & & \\ & 1 & -1 & \\ & & \ddots & \ddots \\ & & & 1 & -1 \end{bmatrix} \begin{bmatrix} x_s(\tau_1) \\ x_s(\tau_2) \\ \vdots \\ x_s(\tau_N) \end{bmatrix}. \quad (8)$$

A loss function can now be defined using both errors from the data and structural equations, η and ε , respectively.

For the k th order over all shafts, the loss function takes the form:

$$\begin{aligned} J &= r^2 \sum_{s=1}^{N_s} \varepsilon_s^T \varepsilon_s + \eta^T \eta \\ &= r^2 \sum_{s=1}^{N_s} x_s^H A^T A x_s + \left(p^T - \sum_{s=1}^{N_s} x_s^H \Theta_s^H \right) \left(p - \sum_{s=1}^{N_s} \Theta_s x_s \right), \end{aligned} \quad (9)$$

in which A is the coefficient matrix of Equation 8, and $(\cdot)^T$ and $(\cdot)^H$ denote the transpose and conjugate transpose, respectively. From Tuma [40], the weighting factor for a second-generation single-pole filter is defined by the desired bandwidth,

$$r \approx \sqrt{\frac{\sqrt{2} - 1}{2(1 - \cos(\pi \Delta f))}} \approx \frac{0.2048624}{\Delta f}. \quad (10)$$

The derivative of the loss function is taken with respect to the conjugate form of each amplitude envelope and set to zero to minimize the error,

$$\frac{\partial J}{\partial x_s^H} = 0 \text{ for } s = 1, 2, \dots, N_s \quad (11)$$

to arrive at an equation for determining the k th order complex envelopes,

$$x(\tau) = \mathcal{H}^{-1} \Theta^H p(\tau), \quad (12)$$

in which

$$\mathcal{H}_{sq} = \begin{cases} r^2 A^T A + I & \text{for } s = q \\ \Theta_s^H \Theta_q & \text{for } s \neq q. \end{cases} \quad (13)$$

Equation 12 is solved using the Cholesky solver of the Matlab backslash operator and is called N_k times. Once the complex envelopes are known, Equation 3 can be used to determine the harmonic content, $\hat{p}$.

C. Selection of Filter Characteristics

The optimal pole count and bandwidth (defining r in Equation 10) are case-dependent. A two-pole filter is most commonly found in the literature as it provides a good middle ground between roll-off behavior and numerical stability. However, there is a limitation on how small the bandwidth can be before the numerics become ill-conditioned, and this is an increasing limitation with pole count. In this work, a small bandwidth is desired given how close the propeller rotation rates (thus, order frequencies) are relative to each other. Therefore, a single-pole filter is selected.

A known simulated signal is generated to understand the effect of bandwidth. To be directly applicable to the measurements, a signal with similar characteristics is formulated,

$$p_{\text{sim}}(t) = \sum_{s=1}^{N_s} \sum_{k \in K} A_{s,k} \left(\frac{M_{t,s}(t)}{M_{\text{ref},s}} \right)^4 \text{Re} \left\{ \exp \left(2\pi i k \int_0^t \omega_s(u) du \right) \right\} + \eta(t). \quad (14)$$

As will be shown in Section VI, the fundamental blade passage frequencies (BPFs) of the six propellers typically have the largest amplitudes in the measurements relative to their harmonics and subharmonics. To emulate this, the amplitudes are set to be $A_{s,k} = \{1/4, 1/2, 1(\text{BPF}), 1/2, 1/4, 1/8, 1/16\}$ for all six simulated shafts, s , and the selected shaft orders of interest, $k = 2, 3, 5(\text{BPFs}), 10, 15, 20, 25$. To introduce amplitude variation, the amplitude is scaled by the instantaneous tip Mach number of each individual shaft and tracks the measured unsteady rotation rates, ω_s , of the measurements for the hover case (Fig. 4(b)). Here, $M_{\text{ref},s}$ was defined as the mean tip Mach number throughout the hover duration. The power of four was chosen to be in the range of previous power law scalings for tonal content of a propeller [44]. Additional random (nonharmonic) noise, $\eta(t)$, is added and defined by its peak being 20 dB down from the BPF amplitudes, $A_{s,5}$. The spectral shape of the added noise is tuned to be representative of the broadband shelf of the measured signals, and is defined by applying a first order Butterworth bandpass filter to a random white noise signal using frequency cutoffs of 20 and 100 Hz.

Figure 9 demonstrates the effect of the VKF bandwidth by comparing the spectral representations of the full simu-

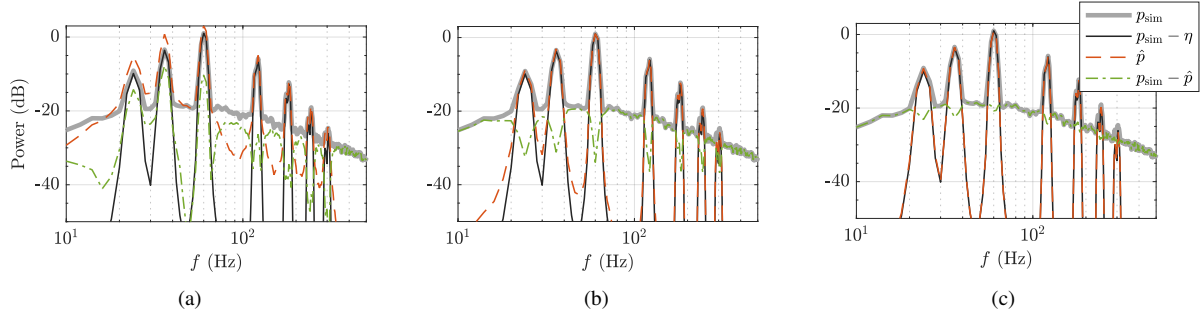


Fig. 9 Effect of extracting harmonic components from a known simulated signal with decreasing filter bandwidth of (a) 5, (b) 1, and (c) 0.1 Hz. The BPF is 60 Hz.

lated signal, p_{sim} , the known harmonic content, $p_{\text{sim}} - \eta$, and the filter-extracted harmonic content, $\hat{p}$. For the largest bandwidth (5 Hz), the filter overextracts energy at the lowest orders because it lacks resolution, i.e., the bandwidth is much larger than the difference in harmonic frequencies amongst shafts at the same order. The second-largest bandwidth (1 Hz) provides a better estimate of harmonic levels; although, the difference between the simulated signal and filter-extracted content, $p_{\text{sim}} - \hat{p}$, which should bypass random noise, shows clear divots at the order frequencies. These divots, which should be avoided as suggested by Truong et al. [17], indicate the filter is inappropriately extracting random noise along with the harmonic components. The smallest bandwidth (0.1 Hz) is most suitable and provides a good estimate of harmonic levels while showing indifference to random noise. For the results in the following section, the bandwidth will be chosen with this thought process in mind.

Given that the simulated signal is a superposition of six independent waveforms, each composed of seven harmonic orders, the total signal is very complex with no apparent repeating waveform pattern over the nominal shaft period. Figure 10 compares the filter-extracted content with the full simulated signal, both with and without random noise, for the best performing bandwidth from Figure 9(c). The filter does an outstanding job of estimating the amplitude- and frequency-varying total waveform in the time domain. Individual shaft waveforms also compared favorably. These results provide confidence in applying this method to measurements in which the true levels of the harmonic content are unknown. Although this paper does not include time-domain results for the measurements, this filter could prove extremely valuable to extract waveforms, per shaft [21], for direct comparison with prediction tools.

VI. Results

The Vold-Kalman filter will now be applied to the flight test measurements and compared to the predictions. Shaft orders for analysis were selected based on prevalence and coincide with the fundamental blade passage frequencies for these five-bladed propellers, $k = 5$, their harmonics, $k = 10 - 25$ in increments of 5, and two subharmonics, $k = 2, 3$. Following the procedure of selecting the bandwidth to maintain the estimated broadband shelf for appropriate harmonic

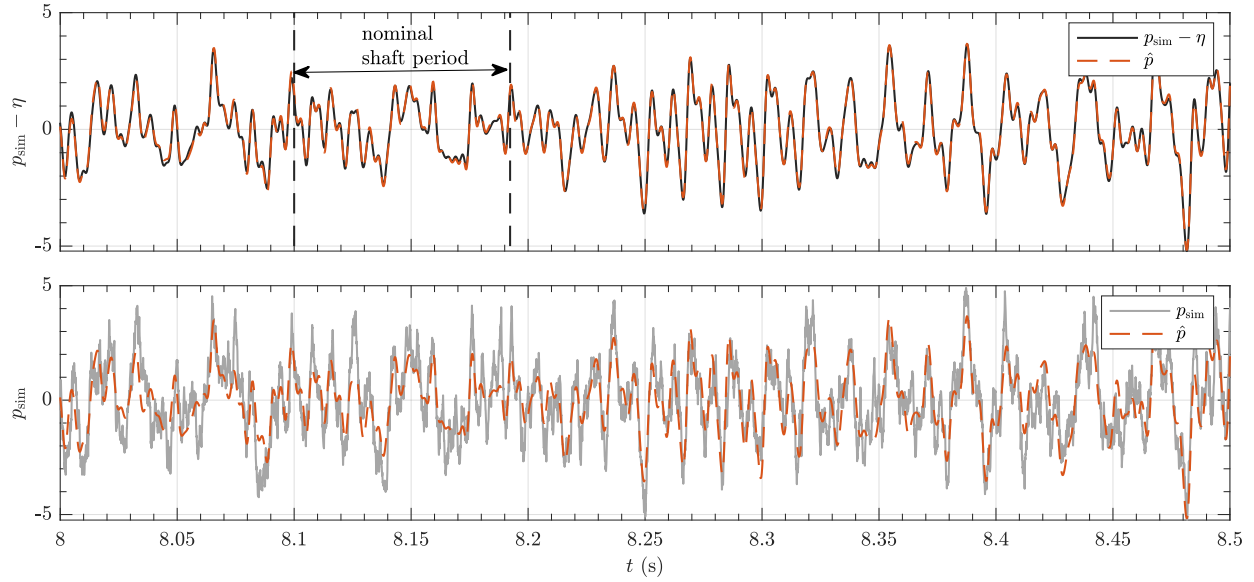


Fig. 10 Time-domain comparison over an arbitrarily chosen segment between the filter-extracted content and the simulated signal (a) without and (b) with random noise.

extraction, a bandwidth of 1 Hz was selected for all results to follow. As a reminder, all acoustic measurement data are scaled to a reference distance of 100 ft (30.5 m) from the aircraft center and corrected for atmospheric absorption [45].

A. Semi-Thrustborne Forward Flight

An overview of the data is given in spectral form for various emission angles in Figure 11 using 0.5 s blocks of data. Each plot compares the spectral estimates of the original de-Dopplerized signal, the harmonic content identified by the VKF summed over all shafts and orders, and the residual. This residual is the time-domain difference between the original and total VKF signal. The harmonic content has very similar levels to the original signal at low shaft orders (i.e., low frequencies). The difference between these increase with order, which is expected since the higher-order levels approach the level of the broadband shelf, thereby representing a smaller portion of the original signal level. The fundamental blade passage frequencies ($k = 5$) are found to dominate the spectra over most emission angles, with the exception being far aft of the vehicle. The spectra here are representative of other microphones in the flyover subset, which produce similar trends. The bar charts represent the total energy of the harmonic content per shaft for each emission angle. The tail propellers are identified as the dominant contributors, particularly in front of and underneath the aircraft, as compared to the four wing propellers.

The sound pressure level per order and per shaft index was computed for a single observer near -90° elevation and compared to filtered experimental data. The results are plotted in Fig. 12. The CFD predicts a dominant BPF across all

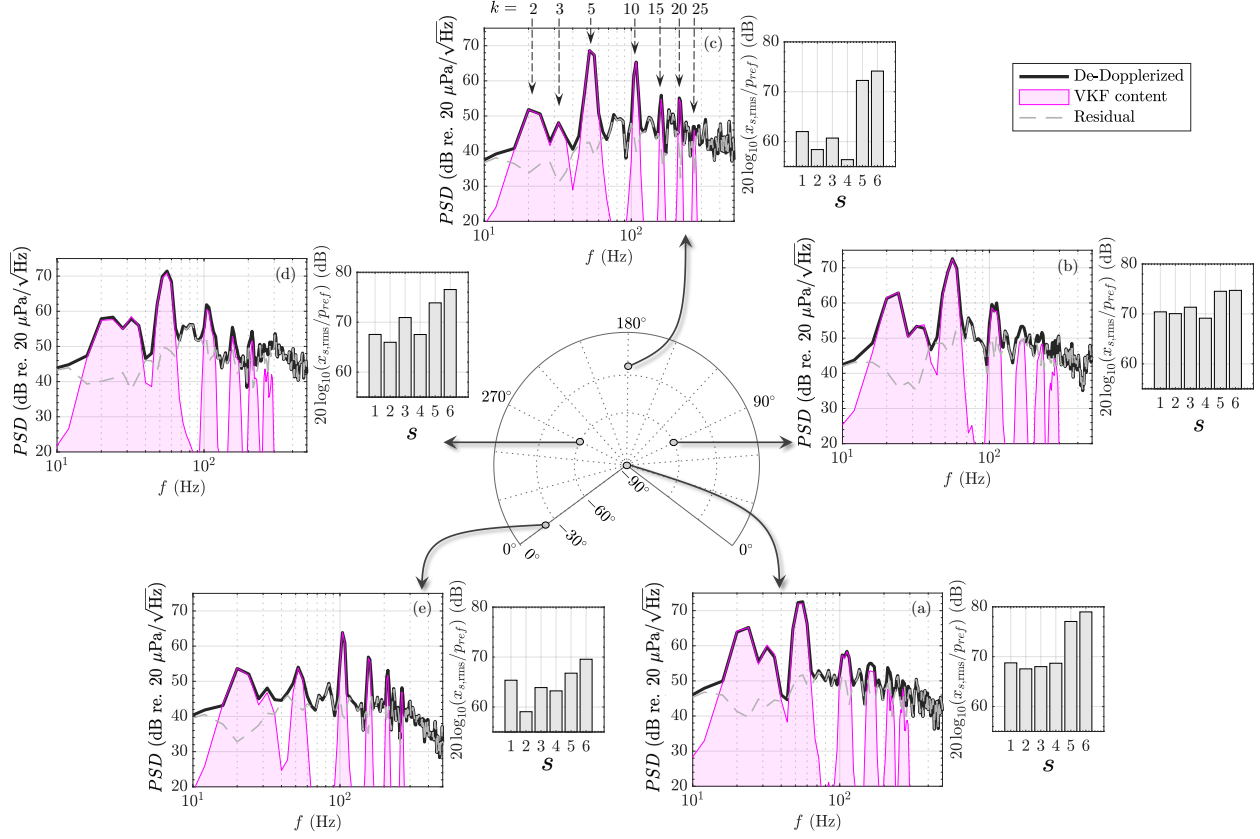


Fig. 11 Vold-Kalman filter-extracted total and individual propeller content for semi-thrustborne flight at 60 kt (a) under the vehicle, (b) starboard, (c) in front of, (d) port, and (e) aft.

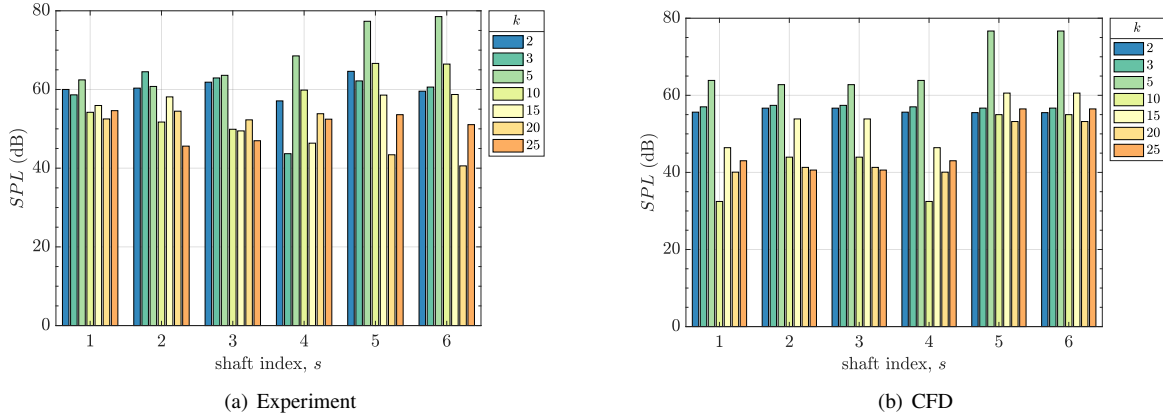


Fig. 12 Comparison between (a) measured and (b) predicted shaft sound pressure levels per order for semi-thrustborne flight. Microphone -90° elevation.

propellers, with a level that is at least 5 dB greater than the other shaft orders. The experiment reflects a similar trend except for the inboard propellers ($s = 2, 3$), where the lower three orders are relatively similar in magnitude ($k = 2, 3, 5$).

Looking at both the filtered measurements and CFD results, the influence of the tail propellers is further highlighted here. Interestingly, the CFD results in higher levels at $k = 20$ and $k = 25$ for the tail propellers compared to the others, but the measurement does not. Inspecting the aircraft symmetry for this microphone, the mean difference in levels between propellers in a pair across all orders is 6.10 dB for the wingtip propellers, 2.85 dB for the inboard propellers, and 1.93 dB for the tail propellers. This is significantly different from that of hover (discussed in the next section), where the mean difference is 2.66 dB. This could indicate that, if the VKF separation method is working correctly, the wingtip propellers could potentially experience greater acoustic variability at this flight condition. The CFD result has no difference due to the symmetry assumption. It should be noted that this flight condition is not typical of the nominal mission profile, as the aircraft is typically in transition at this airspeed. Application of the VKF to a greater variety of flight conditions could yield further insight into the noise sources and aid in determining quieter trim states.

It is also worthwhile to view these data over all measured observer angles. Contours of band-limited (12 Hz to 2 kHz) or filtered sound pressure levels are given in Figure 13, with Fig. 13(a) being a reproduction of Fig. 7(a) for reference. Comparing the original signals (Fig. 13(a)) to only the harmonic content (Fig. 13(b)), the directivity

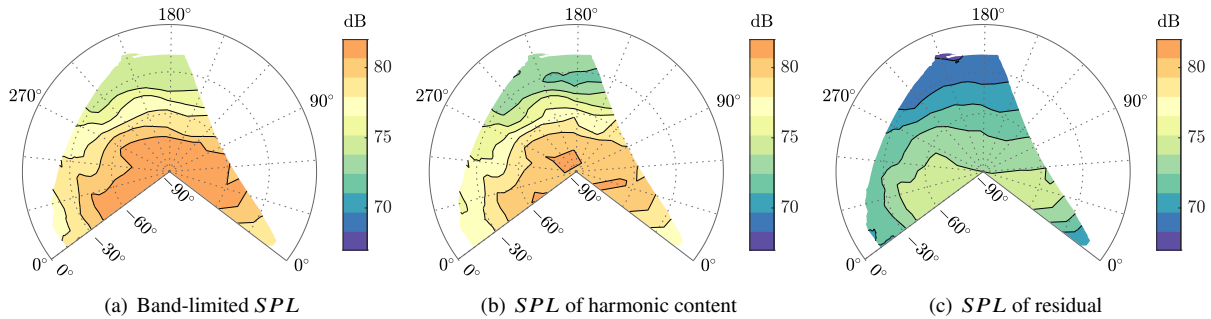


Fig. 13 Hemisphere representation of the (a) de-Dopplerized signal, (b) the total Vold-Kalman filter-extracted content, and (c) the residual for semi-thrustborne flight at 60 kt.

features look similar. The similarity is expected given the dominance of harmonic information indicated by the spectra over various emission angles (Fig. 11). The highest levels are found underneath the vehicle with the lowest levels in front of the vehicle. The residual is again plotted in Fig. 13(c). At first glance, the directivity pattern looks similar to what would be expected from broadband self-noise, peaking at angles aft of the aircraft. Accounting for propeller tilt, these aft angles correspond to out-of-plane angles with respect to the propellers. Broadband noise likely dominates this residual, although there could be additional shaft-coherent content that were not extracted (e.g., $k > 25$). Removing all harmonic content would enable the residual to be a useful broadband characterization and has been conducted by others [14, 21].

Perhaps the most interesting visualization is a plot of individual propeller harmonic content over all measured emission angles (Fig. 14). The four propellers along the wing are similar in their peak levels. They also exhibit similar

directivity patterns with highest levels either along or just aft of the 90° - 270° azimuths, which emanate out from the starboard and port wings, respectively.

As compared to the wing propellers, the tail propellers produce nearly 10 dB higher peak levels, with peak levels found more aft. What makes this even more noteworthy is that the rotation rates, tilt, and blade pitch were all, on average, very close over all propellers, indicating the resulting noise difference is an aerodynamic interaction or installation effect. The CFD visualizations corroborate this given the clear trajectory of the inboard wing propeller wakes introducing nonuniform inflow at the tail propellers. The blade passage frequencies, which dominate the overall harmonic levels (see Fig. 11), have a wavelength on the order of a semispan. Thus, acoustic scattering may not be the driver in these differences. Speculating for a moment, the tail propellers may produce more noise due to interactional effects, particularly if they are ingesting nonuniform inflow introduced by the wake of the inboard wing propellers. In any case, this type of source ranking can be invaluable to researchers to design quieter vehicles, validate prediction tools, impose operational constraints to avoid noisy conditions, or apply noise reduction technologies.

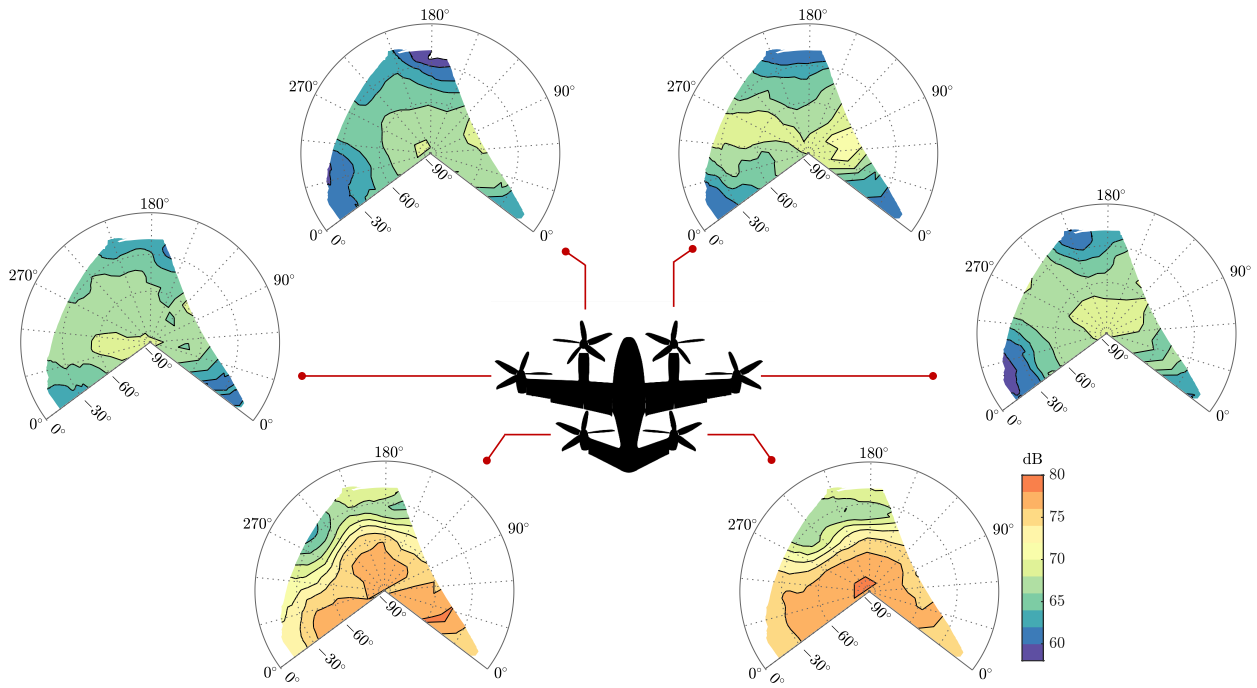


Fig. 14 Individual propeller acoustic hemispheres of the Vold-Kalman filtered measurements for semi-thrustborne flight at 60 kt.

To complement Fig 14, the predicted individual contributions are provided in Fig. 15. Note that the Vold-Kalman filter was not applied to the predictions. There is good agreement in both directivity and magnitude between the CFD-predicted and filtered measurements. Both prediction and measurement highlight the tail propellers as the dominant source of shaft-coherent levels over nearly all observer angles. The impacts of rotation direction and placement of the

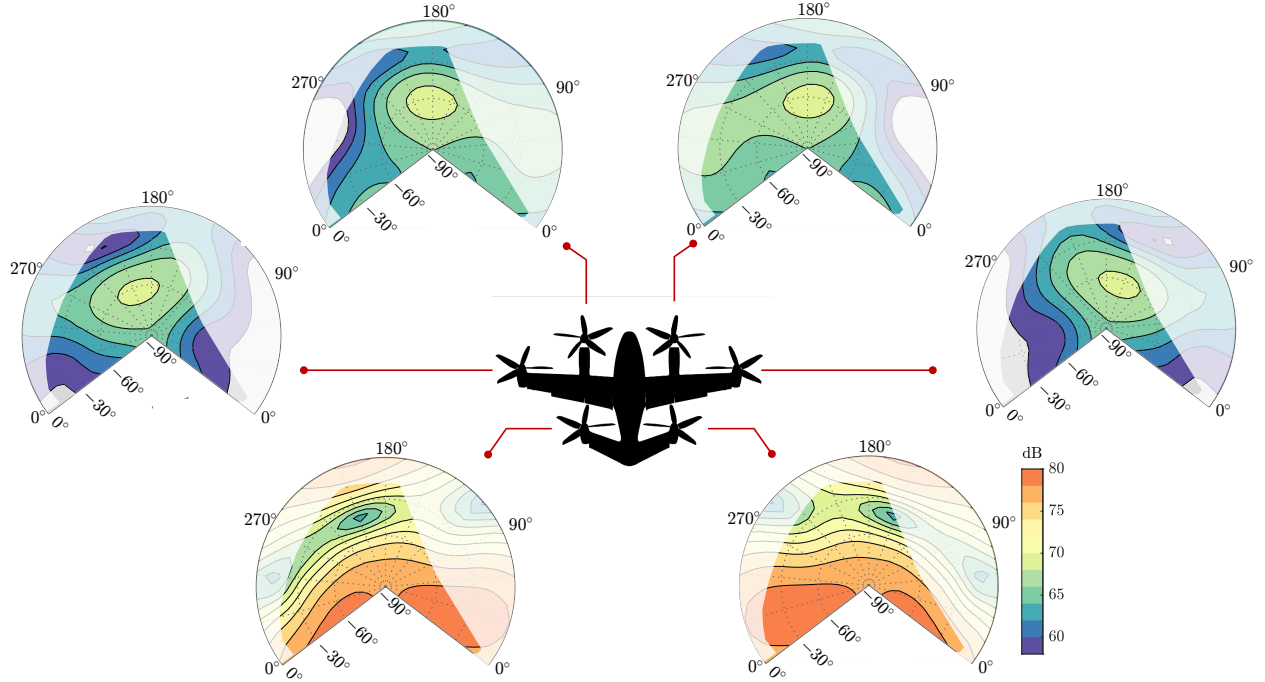


Fig. 15 Individual propeller acoustic hemispheres from numerical simulations for direct comparison with Fig. 14.

propellers with respect to the airframe are more obvious from the cleaner prediction results. Port-starboard propeller pairs are symmetric due to the assumptions of the CFD model. Although the filtered measurement results are not symmetric, there is some agreement in the hotspots, which are generally near lower elevation angles.

B. Hover

Additional assessments of the VKF method took advantage of the hover condition to simplify the relative geometry between the microphones and aircraft. The rotation rates exhibited more steadiness relative to the forward flight case, as evidenced by Fig. 4, further simplifying the situation. To ensure the extraction/separation process was tracking the appropriate order frequency content, the peak spectral harmonic frequencies of the individual propellers were compared to the distributed rotation rates. Figure 16 gives a zoomed-in view of the spectral estimates of individual propeller waveforms over a one-second segment of data. Focusing on the highest order extracted ($k = 25, \approx 300$ Hz), as it provides the largest frequency spread, the corresponding individual rotation rates are paired with the harmonic peaks. These peaks successfully correspond to the appropriate propeller.

To visualize the extraction over the full duration of the hover, spectrograms are provided in Fig. 17 for a single microphone directly under the aircraft. The original signal has content over a broad frequency range, with peaks that correspond to the shaft orders. The residual clearly shows the removal of the majority of energy at the shaft orders. Note the absence of any signs that overextraction occurs at the shaft orders by the lack of the aforementioned spectral

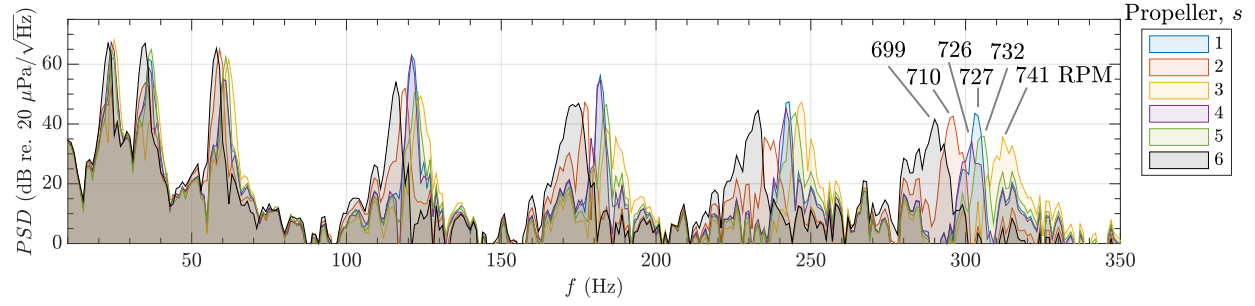


Fig. 16 High-resolution spectra of the harmonic content of each propeller obtained using the VKF. Mean rotation rates agree with the displayed frequency spread.

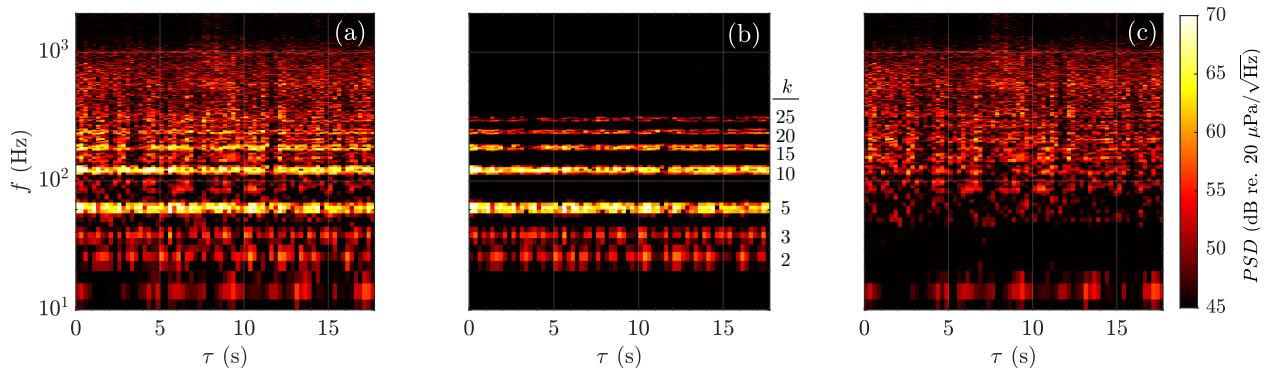


Fig. 17 Spectrograms of the (a) original, (b) harmonic content, and (c) residual signals over the full duration of the hover event for a microphone directly underneath the vehicle.

divots in the broadband content. Other microphones indicated similar behavior.

The filtered measurements and predicted results for all propellers are plotted in Fig 18 for a single microphone towards the nose of the aircraft, near -36° elevation and 176° azimuth. The measurements have similar trends in

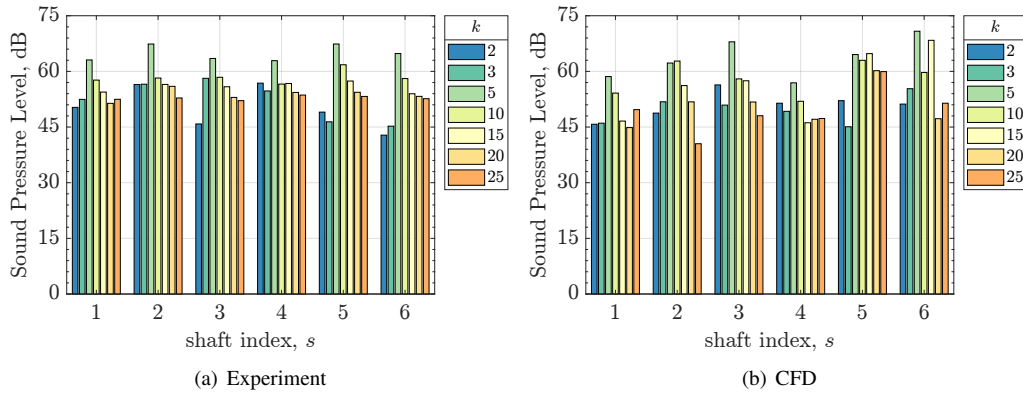


Fig. 18 Comparison between mean filtered and predicted shaft levels per order for hover at a microphone near -36° elevation and 176° azimuth.

harmonic levels across propellers, with the highest levels at the BPF. For this microphone near the aircraft centerline, one would expect similar levels among propeller pairs (inboard, outboard, tail) due to the aircraft symmetry. This is generally true for the experiment. When comparing the propeller pairs, the mean difference in levels across all shaft orders is approximately 2.35 dB for the outboard wing propellers, 2.95 dB for the inboard wing propellers, and 2.69 dB for the tail propellers. However, this is not the case for the CFD results, which yield different high-frequency results for the inboard and tail propeller pairs. The mean difference in predicted levels across all shaft orders is approximately 2.55 dB for the outboard propellers, 3.99 dB for the inboard propellers, and 6.50 dB for the tail propellers. It should be noted that the CFD is based on a single revolution with constant propeller phasing, and it is possible that introducing rotational rate variations, averaging runs with randomized phasing, or simply running more revolutions for acoustics could change the results.

The measurement data had obvious acoustic variation over the duration of the hover. To best quantify the comparison between prediction and measurement and account for realistic variability, the spectral time history using 0.5 second increments is first computed. An amplitude range, as illustrated by Fig. 19(a), is then defined over the minimum and maximum levels of the spectral time history. Similarly, the ranges of filtered shaft order levels are also computed, and the differences between the prediction and closest value in the range are determined. Those differences are then averaged over 52 microphones and provided in Figure 19(b).

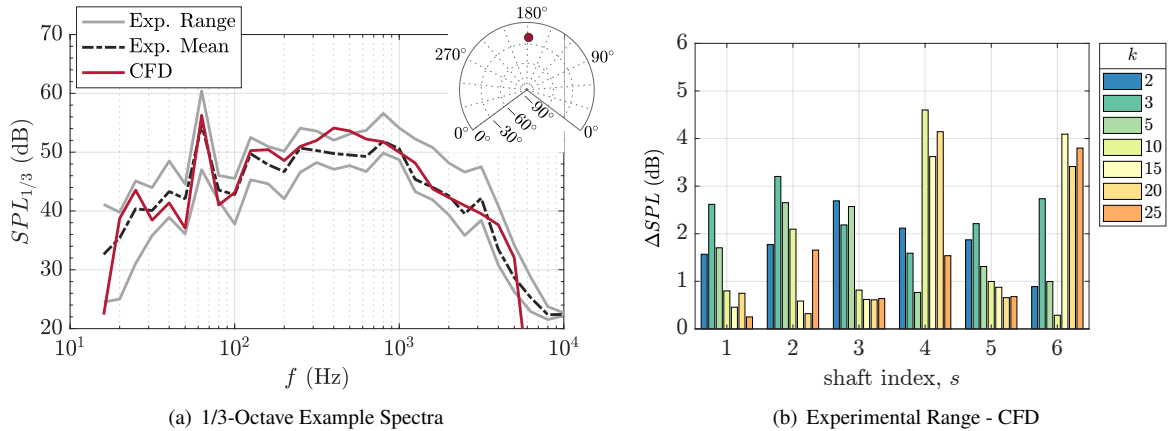


Fig. 19 Hover (a) raw spectra (-19° elevation, 174° azimuth) defining the experimental range and (b) differences between measurements and predictions.

This difference is less than 5 dB for all shaft orders and indices. There is a larger difference at the lower frequencies for most of the propellers except for propellers 4 and 6, where there is more significant discrepancy at the higher frequencies. It is still unknown as to the source of the differences between measurement and prediction. However, the mean difference across all microphones, orders, and propellers was 1.75 dB, which gives confidence in the models.

With the aircraft not in motion, the hemisphere representation found in the previous section is less useful. In-

stead, the majority of deployed microphones are used to produce contours over the ground plane to illustrate directivity features. All levels are again scaled to a reference observer of 100 ft (30.5 m) to de-emphasize spherical spreading. Atmospheric absorption is also accounted for. Figure 20 plots individual propeller contributions over an area of approximately 2,000 by 1,000 ft (610 by 305 m) for both the measurements and predictions. In these plots, the vehicle (not to scale) is shown to indicate its stabilized heading.

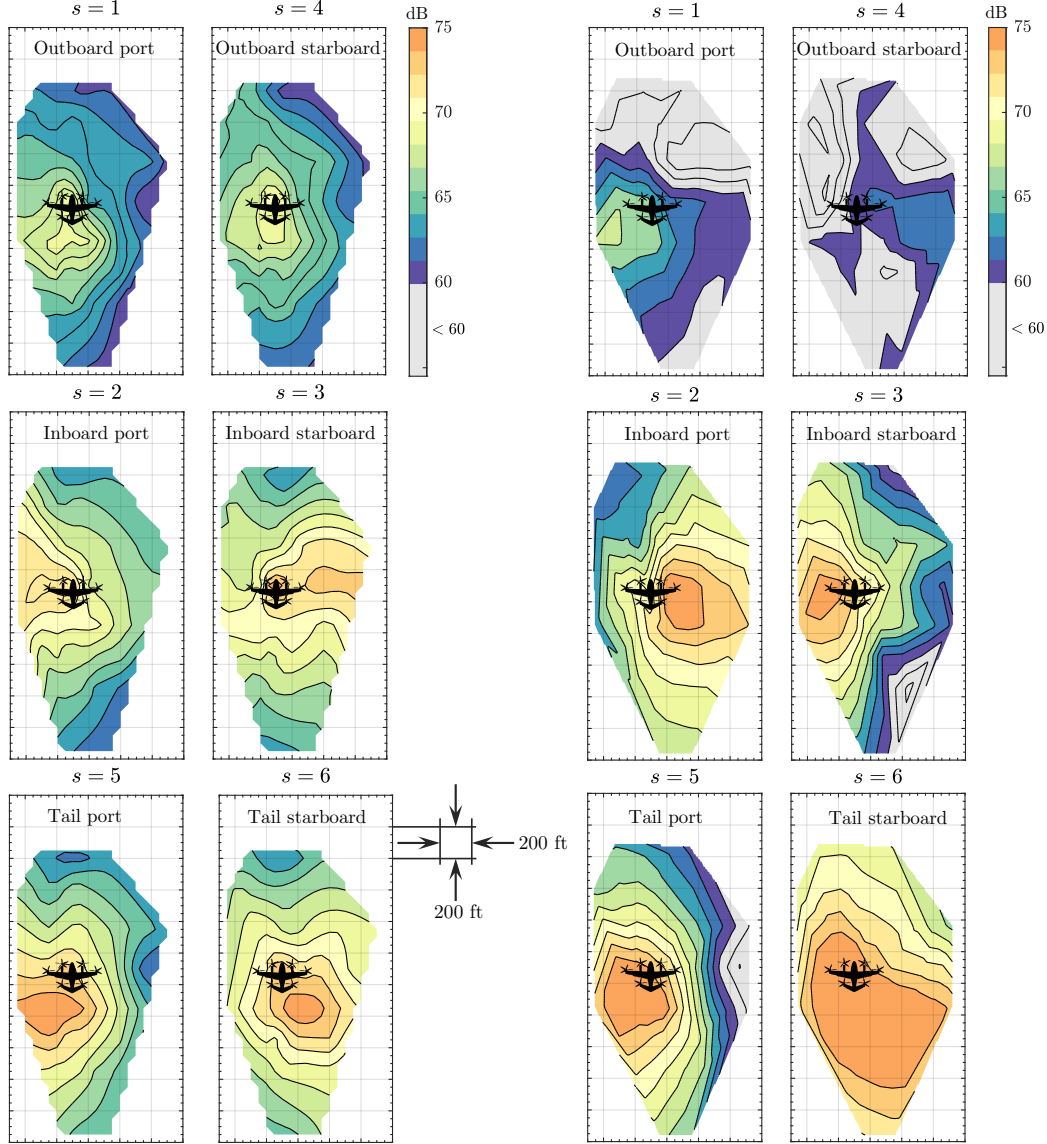


Fig. 20 Ground contours of the filtered measurements (*left*) and predictions (*right*) separated into individual propeller contributions for hover.

There are several interesting features that can be observed. Focusing on the measurement contours, the tail propellers generate the highest levels of harmonic noise, although the difference with the wing propellers is not as large

relative to the semi-thrustborne condition. The inboard propellers are identified as the secondmost dominant pair, while the outboard propellers produce the lowest levels. Focusing attention to directivity, the symmetric pairs of propellers are found to generate somewhat symmetric patterns. For example, the tail pair show peak radiation in their respective aft quadrants, and the inboard pair produce peak radiation toward their respective sideline directions. Peak levels for the outboard pair are below the aircraft with less bias in any given direction relative to the other propellers. The fact that propellers in a pair have directivities that resemble one another builds confidence that the filter is appropriately separating content amongst the propellers.

Ground contours of the predictions illustrate similar relative contributions amongst propellers, with the highest and lowest peak levels produced by the tail and outboard propellers, respectively. Directivity features are quite similar, except for the peculiar difference between the measurement and predictions for the inboard pair. While both exhibit maxima at sideline locations, the directions of peak levels oppose each other. Further investigation is required to explain this; however, the omission of propeller source noise shielding or scattering by the airframe in the predictions is the leading theory for this disparity.

The lack of forward motion and the fact that the tilt angles correspond to a VTOL configuration suggests there is also no wake interference between wing and tail propellers. Furthermore, the aircraft is static, implying aerodynamic interaction between propellers is not likely. Rotation rates for all propellers are within approximately 50 RPM, and tilt and blade pitch are all also nearly identical. Thus, the aeroacoustic differences amongst propeller pairs are attributed to propeller/airframe interaction and the differences in proximity to various airframe components. These observations highlight the fact that installed propellers can be very different than their isolated counterparts, both in terms of directivity patterns and peak levels.

Two repeats of this hover test point were also acquired during the flight test. Individual propeller directivities and peak levels were similar to those shown in Fig. 20. To summarize these data, Fig. 21 displays the dominant propeller over the ground area. This ranking is based on the root-mean-square of the individual propeller signals summed over the set of harmonics. For each of these test points, the tail propellers repeatedly dominated aft observers in a similar fashion. The observers in front of the aircraft had a mixture of the inboard and tail propellers with some spatial variation over the repeats. One interesting result is the lack of dominance from the outboard propellers, further concluding their relatively lower level signatures during hover.

VII. Conclusion

The Vold-Kalman order-tracking filter is applied to full-scale eVTOL flight test measurements in an attempt to separate harmonic content among the individual propellers from single-channel acoustic signals. Being case dependent, the pole count and bandwidth were assessed using synthetic signals with characteristics similar to the measurements.

Spectra and individual source hemispheres were compared between the original signals and shaft-harmonic content.

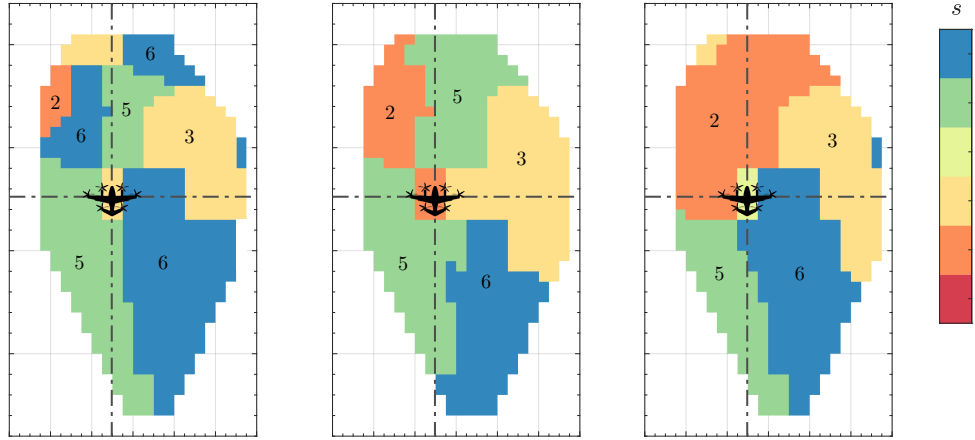


Fig. 21 Area of ground contour displaying which propeller dominated over three independent hover runs. The run on the left is the main case used in this paper.

For the 60 kt semi-thrustborne condition, the tail propellers produce peak noise levels nearly 10 dB higher than the wing propellers. These increased levels are an indication of aerodynamic interaction with the upstream inboard propellers, particularly because propeller states were nearly identical across the set, and the fact that they are consistent with flow field assessments and acoustic results of the high-fidelity numerical simulations.

Hover directivity patterns of the harmonic content were assessed using ground noise contours. In the filtered measurements, the port side propellers show similar but mirrored patterns to their respective starboard complement. The differences in levels and patterns amongst the propellers are likely the result of aerodynamic or acoustic interaction with the airframe. Despite the peculiar differences between measurement and predictions, which may be due to omission of the airframe presence in the acoustic calculation of the predictions, the averaged harmonic level difference over 52 microphones was only 1.75 dB, giving confidence in both the filter and computations. Measurement repeatability was demonstrated by comparing propeller dominance over the ground contour of three hover events.

These types of source noise separation methods are likely to be an invaluable tool when understanding the dominant noise generating mechanisms for multipropeller aircraft, without the use of a phased array, and improving prediction tools to account for interaction or installation effects. Additionally, future psychoacoustic studies could leverage this time-domain signal decomposition method to assess the importance of harmonic noise as compared to nonharmonic noise.

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