

# Aerodynamic Performance and Acoustic Impacts of Varying Tip Speeds and Tripping Conditions on Small Rotors in an Anechoic Hover Chamber

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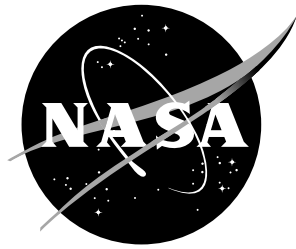
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## Abstract

Performance and acoustic measurements were taken in a hover chamber for various optimum hovering rotors (OPT2) and a commercial-off-the-shelf (COTS) rotor. A total of 10 rotors are included in this report, all of which have two blades and a tip radius of 0.1905 m (7.5 in.). For the OPT2, results for three additive manufacturing methods of fabrication are presented: stereolithography (SLA) using Accura Xtreme, SLA using FormLabs 10K resin, and selective laser sintering (SLS) using mineral-filled PA12 nylon material. All but one set of rotors were designed with a trailing edge bluntness that is 3% of the chord length, and one set was designed with a bluntness that is 1% of the chord length. Spanwise boundary layer trips were applied to the SLA, FormLabs and COTS rotors. Performance comparisons between untripped and tripped configurations demonstrate the impact of boundary layer state on rotor efficiency. Acoustic results, including periodic and broadband noise components, are presented. The effects of tripping these rotors near the leading edge are also presented. For some of the rotors, acoustic spectra of tip speed sweeps are presented to show how the frequency content changes with tip speed. Amplitude and frequency scaling methods are used to collapse broadband spectra at various tip speeds towards a unified curve. These findings contribute to the understanding of small rotor aeroacoustics and provide valuable datasets for computational model validation in urban air mobility applications.

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## Nomenclature

### *English*

|           |                                                                          |
|-----------|--------------------------------------------------------------------------|
| $c$       | Chord length, m                                                          |
| $c_o$     | Speed of sound (m/s)                                                     |
| $C_T$     | Thrust coefficient, $\frac{T}{\rho\pi\Omega^2 R^4}$                      |
| $H$       | Trailing edge bluntness thickness, m                                     |
| $He$      | Helmholtz number, $2\pi \frac{f * L}{c_o}$                               |
| $M_{tip}$ | Tip Mach number, $\frac{U_{tip}}{c_o}$                                   |
| $N_b$     | Number of rotor blades                                                   |
| $Q$       | Torque, N-m                                                              |
| $r$       | Spanwise location from hub, m                                            |
| $R$       | Blade radius, m                                                          |
| $St$      | Strouhal number relative to bluntness thickness, $\frac{f * H}{U_{tip}}$ |
| $T$       | Thrust, N                                                                |
| $U_{tip}$ | Tip speed, m/s                                                           |

### *Greek*

|                |                             |
|----------------|-----------------------------|
| $\Theta_{tip}$ | Blade tip pitch angle, deg. |
| $\omega$       | Rotor rotation rate, rad/s  |
| $\Omega$       | Rotor rotation rate, RPM    |

### *Subscript*

|          |                                                                  |
|----------|------------------------------------------------------------------|
| $bb$     | Broadband noise                                                  |
| $bb, pr$ | Broadband noise with tonal peaks removed                         |
| $c$      | Corrected rotation rate (for sea level, standard day conditions) |
| $max$    | Highest rotation rate condition                                  |
| $tip$    | Tip condition                                                    |
| 70       | 70% rotor spanwise condition                                     |

# 1 Introduction

Advanced Air Mobility (AAM) is an air transportation system that would use new technologies like electrical vertical takeoff and landing (eVTOL) aircraft to provide safe, accessible, affordable and automated transportation for passengers and cargo in urban and rural locations. This rapidly emerging new sector of the aerospace industry has led to the development of new vehicles and motivated research into characterizing the noise they produce. Within AAM, an emerging market known as Urban Air Mobility (UAM) includes larger vehicles with open rotor propulsors. Example illustrations of such UAM vehicle concepts are provided in Fig. 1.

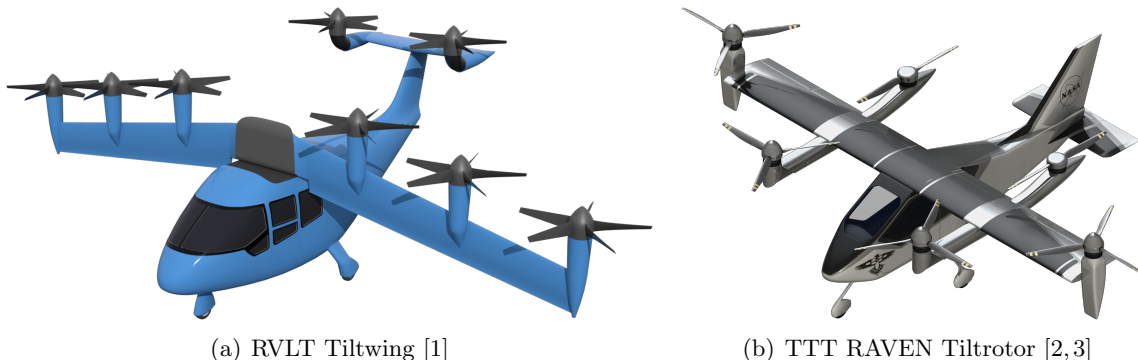


Figure 1. Renderings of UAM vehicle concepts leveraging rotors for Vertical Take-Off and Landing (VTOL) operations.

The development of UAM vehicles with multiple rotors requires, as a starting point, an understanding of and validation data for isolated rotors. In order for these vehicles to operate and integrate in the urban and rural environment, the noise produced from these vehicles, which is in large part due to the rotors, must be characterized and understood. The noise produced by rotors can be divided into two categories: tonal and broadband. A subset of broadband noise falls under the category of self-generated airfoil noise, and noise mechanisms in this category are described in Ref. [4]. Low-fidelity predictions of broadband noise have attributed the self-noise to a combination of turbulent-boundary layer (TBL) trailing edge noise, TBL separation noise, tip vortex shedding noise, and trailing edge bluntness vortex shedding noise. Another self-generated source known as laminar boundary layer vortex shedding (LBLVS) can occasionally be present in rotors as well.

While it is currently unknown as to how directly small-scale rotors relate to full-scale vehicle propulsors, the relative behavioral trends of tonal and broadband noise are anticipated to be applicable, particularly for rotor operating conditions at low tip speeds ( $M_{\text{tip}} \leq 0.4$ ). Furthermore, exploration of the performance and acoustic behaviors of such small-scale rotors undergoing forced transition (i.e., tripping) is warranted. Such treatment of small-scale test articles could increase their applicability to larger-scale platforms. With this in mind, a series of experiments was conducted in an anechoic chamber to investigate the noise and performance of a 2-bladed optimum hovering rotor design (OPT2) and a 2-bladed commercial-off-the-shelf (COTS) rotor. For the optimum hovering rotor, various rotor materials were tested. For both rotors, various tripping methods were employed for the purpose of identifying and mitigating low-Reynolds number effects on rotor performance and acoustics.

To move away from COTS blade designs and explore additive manufacturing techniques, Refs. [5] and [6] presented empirical measurements and computational results of an ideally twisted rotor (as defined in Ref. [7]) in hover. Following this, Refs. [8] and [9] presented empirical measurements and computational results of an optimum hovering rotor in hover. Advantages of choosing the

ideally twisted and optimum hovering rotors include easier-to-model uniform inflow properties, as well as the ability to release the geometry to the public. Both the ideally twisted rotor and optimum hovering rotor experiments have and will provide the community with rotor datasets that are theoretically easier to model since they were designed with analytic equations from Ref. [7].

In Ref. [10], acoustic measurements for the ideally twisted rotor were compared to tonal and broadband noise predictions. Additionally, simplified spectral scaling methods were implemented for various tip speeds. While spectral scaling proved advantageous in identifying noise sources such as LBLVS, it was noted that the data were not perfectly collapsing with frequency when using a Strouhal number scaling based on the fixed length scale corresponding to the blade trailing edge bluntness. This was attributed to the changing boundary layer parameters, which are responsible for different frequencies of interest, and using a fixed geometric length scale did not capture this change. This is consistent with the findings of Ref. [4].

In Ref. [8], experimental data were acquired in both a hover chamber and a wind tunnel for three rotor blade sets: COTS rotors and optimum hovering rotors manufactured using either stereolithography (SLA) or selective laser sintering (SLS). The optimum hovering rotor fabrications consisted of resin-printed blades with a sand grit boundary layer trip (SLA-tripped), as well as SLS-printed blades that were observed to possess a noticeable surface roughness caused by the additive manufacturing process. The data acquired included performance and acoustic measurements of the three rotor sets in hover and forward flight conditions. The SLA-tripped and SLS rotors produced 9.0% and 7.4% less thrust, respectively, than the COTS blades, which was attributed to the turbulent character of the boundary layer of these blade sets [6, 11]. A comparison of the total noise contribution between the COTS and SLS rotors was made in Ref. [8] for installed rotors, with SLS rotors producing less noise. These vehicle-installed configurations were pitched 10 degrees forward at a wind tunnel speed of  $M_\infty = 0.046$ . However, these comparisons included high levels of background noise, due to the presence of the vehicle, for frequencies up to 2 kHz for the highest thrust condition. For this reason, isolated rotor data are important to examine. While the three tested thrust conditions indicated the possibility of identifying broadband noise trends, a larger range of thrust conditions was deemed necessary to identify transitional acoustic behavior across various blade tip speeds. After previously identifying the reduction in broadband acoustic content between the tested rotors, this report will publish additional cases to identify trends and provide further data interrogation (i.e., spectral scaling).

For the present work, isolated rotor data are presented for various rotors in hover. First, Section 2 describes the optimum hovering rotors and COTS rotors. This is followed by a description of the testing facility and instrumentation used to acquire measurements in Section 3. Following this, experimental measurements are presented for hover conditions, starting with performance measurements in Section 4, followed by processed acoustic data acquired for isolated rotors in the anechoic hover chamber in Section 5. The acoustic results include spectral trends at various tip speeds, periodic and broadband noise results, and noise impacts of tripping rotors. In Section 6, amplitude and frequency scaling methods are employed for the various rotors at various tip speeds. Finally, Section 7 provides concluding remarks and describes future work for research on characterizing the noise mechanisms associated with these types of small rotors.

## 2 Rotor Design Approach

The data presented in this document include those for the OPT2 rotor and a COTS rotor for comparative purposes. Descriptions of the rotors tested in this study are provided in Table 1.

Table 1. Descriptions of tested rotors.

| Rotor                              | Design  | Trip          | Material      | $H$ , mm <sup>1</sup> |
|------------------------------------|---------|---------------|---------------|-----------------------|
| SLA 1%                             | OPT2    | smooth        | Accura Xtreme | 0.272                 |
| SLA 3%                             | OPT2    | smooth        | Accura Xtreme | 0.816                 |
| SLA 3%-tripped                     | OPT2    | spanwise grit | Accura Xtreme | 0.816                 |
| SLS                                | OPT2    | full surface  | PA12 nylon    | 0.816                 |
| FormLabs                           | OPT2    | smooth        | 10K resin     | 0.272                 |
| FormLabs-partial trip <sup>2</sup> | OPT2    | spanwise grit | 10K resin     | 0.272                 |
| FormLabs-partial trip <sup>3</sup> | OPT2    | spanwise grit | 10K resin     | 0.272                 |
| FormLabs-tripped <sup>4</sup>      | OPT2    | spanwise grit | 10K resin     | 0.272                 |
| COTS                               | T-motor | smooth        | carbon fiber  | 0.762                 |
| COTS-tripped                       | T-motor | spanwise dots | carbon fiber  | 0.762                 |

<sup>1</sup>Trailing edge bluntness thickness measured at 70% span

<sup>2</sup>Tripped from 50 to 100% span

<sup>3</sup>Tripped from 60 to 100% span

<sup>4</sup>Fully tripped from 20 to 100% span

## 2.1 Optimum Hovering Rotor

The optimum hovering rotor, shown in Fig. 2(a), is a 190.5 mm radius rotor designed using analytical equations from Ref. [7]. The rotor blade has a NACA 5408 airfoil profile along the entire span. The optimum design was used for various blade sets, each made of different materials. The optimum hovering rotor blades have a linear chord distribution. The twist distribution results in a minimum induced power requirement, and the taper distribution results in a minimum profile power requirement. Some design parameters and conditions for the rotor in this study are summarized in Table 2. Using a two-part clam-shell hub, the blades were set to a collective root pitch angle of  $\Theta_{\text{root}} = 20.5^\circ$ , as measured at a radial location of  $r/R = 0.20$ . More detailed information on the geometry and design of this optimum hovering rotor blade design is described in Ref. [9].

Table 2. Optimum design parameters.

|           | Parameter             | Value                  |
|-----------|-----------------------|------------------------|
| Geometry  | $R$ (mm)              | 190.5                  |
|           | $c_{\text{tip}}$ (mm) | 19.05                  |
|           | $c(r)$                | $c_{\text{tip}}/r$     |
|           | $H(r)$                | $.03c(r)$ or $.01c(r)$ |
| Operating | $C_T$                 | 0.0096                 |
| Condition | $M_{\text{tip}}$      | 0.2316                 |

The blade sets shown in Figs. 2(a) and 2(b) were made of an “ABS-like” material manufactured via SLA [12]. These SLA blades were gritted with 0.01 inch glass beads along the quarter chord location of the blade suction side to create a trip, which prevented laminar boundary layer vortex shedding behavior [9]. This blade set will hereby be denoted as “SLA 3%-tripped.” Two sets of untripped blades of this material (not pictured) are denoted as “SLA 3%” and “SLA 1%,” with 3% and 1% referring to the trailing edge bluntness thickness of  $H(r) = .03c(r)$  and  $H(r) = .01c(r)$ , respectively. Another blade set, in Fig. 2(c), was manufactured via SLS of a material called PA-12, which is a 25% mineral-filled nylon material [13]. These blades have a rough, gritted homogeneous surface which results in tripping of the flow. These blades are denoted as “SLS.” The SLS blades had a trailing edge bluntness thickness of  $H(r) = .03c(r)$ . A set of FormLabs





(a) Optimum design rotor



(b) SLA 3%-tripped blade



(c) SLS blade

Figure 2. Images of optimum hovering rotor blade sets tested.

printed blades were also manufactured for the OPT2. Untripped FormLabs blades are referred to as “FormLabs” in this report. For tripped testing, a trip was applied near the leading edge, similar to the trip applied to the SLA 3%-tripped rotors. This trip was applied to the same rotor at three spanwise lengths: full length, from tip to 50% span, and from tip to 60% span. Thus four blade set configurations (untripped and the three tripped sets) of FormLabs rotors were tested. Photos are not currently available for these rotors, but they have the same geometry and hub hardware configuration as the SLA rotors, with the only difference being the material of the blade and the partial trip configuration. The FormLabs blades had a trailing edge bluntness thickness of  $H(r) = .01c(r)$ . All optimum design blade sets utilized a “clam-shell” aluminum hub that was designed in-house.

## 2.2 COTS Rotor

The COTS rotor, shown in Fig. 3(a), is a 190.5 mm radius, single-piece carbon fiber 15x5 rotor manufactured by T-motor.

The COTS blades have a continuously varying airfoil profile along the span. Reference [14] published some geometric properties as well as 3-D laser scans of the airfoils at different spanwise locations. The bluntness at 70% span was measured to be 0.762 mm. The rotor was found to generate 8.34 N of thrust at a tip Mach number of  $M_{\text{tip}} = 0.2316$ . For a set of experiments, trip dots of uniform spacing were applied near the quarter-chord location, and can be seen in Fig. 3(b). These trip dots have a nominal height of 0.08 mm, a diameter of 1.5 mm, and a pitch of 3 mm.



(a) T-Motor COTS rotor

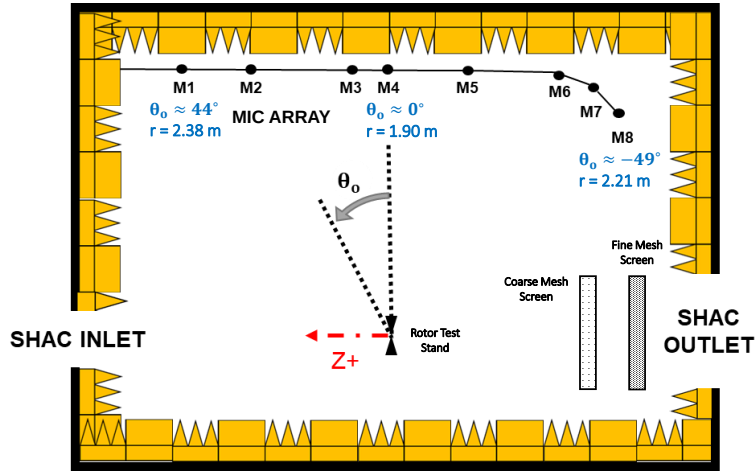


(b) T-Motor COTS rotor tripped

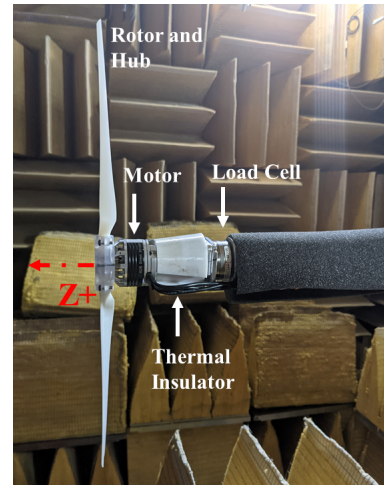
Figure 3. Images of COTS blade sets tested in the SHAC.

### 3 Testing Facility and Instrumentation

The rotors were tested in the NASA Langley Small Hover Anechoic Chamber (SHAC). A schematic and photograph of the setup are shown in Fig. 4. The SHAC is acoustically treated down to 250 Hz and has working dimensions (wedge tip to wedge tip) of 3.87 m x 2.56 m x 3.26 m. The test setup in the SHAC was similar to that of Ref. [5]. A Brüel & Kjær (B&K) LAN-XI data acquisition (DAQ) and BK Connect software system were used for data acquisition. Six B&K Type 4939 and two B&K Type 4954B free-field microphones are located in the upper corner of the SHAC and span a range of  $+44^\circ$  above the plane of the rotor to  $-49^\circ$  below the plane of the rotor. They are shown in the diagram in Fig. 4(a). These microphones are located at a minimum of 10 rotor radii away from the rotor, which is in the geometric far-field. A laser sensor tachometer located directly below the rotor was used to monitor the rotation rate of the rotor, and a 6-component ATI-IA Mini40 multiaxis load cell was used to measure the aerodynamic forces and moments. Each rotor was powered using a KDE Direct 3510 XF 475 KV brushless motor and a 40A optoelectronic speed controller. A photograph of a mounted rotor in the SHAC is shown in Fig. 4(b).



(a) Top view of SHAC facility (not to scale)



(b) Rotor mounted on test stand

Figure 4. SHAC facility and acoustic measurement configuration.

## 4 Performance Results

In this section, the aerodynamic results are presented for the various rotors in hover conditions.

An atmospheric correction was applied to thrust and torque based on density. The density-corrected thrust  $T^*$  and torque  $Q^*$  are defined as

$$T^* = T * \frac{\rho_{std}}{\rho_{\infty}}, \quad (1)$$

and

$$Q^* = Q * \frac{\rho_{std}}{\rho_{\infty}}, \quad (2)$$

where  $\rho_{\infty}$  is the measured density and  $\rho_{std}$  is density at sea-level standard day (SLSD) conditions, which is 1.225 kg/m<sup>3</sup>. The following definition in Eqn. 3 is used to calculate the coefficient of thrust:

$$C_T = \frac{T}{\rho_{\infty} A \omega^2 R^2}, \quad (3)$$

where  $A$  is the area of the entire rotor and hub assembly,  $\omega$  is the rotation rate of the rotor in rad/sec, and  $R$  is the radius of the rotor.

Uncertainties in measured thrust and torque loads are presented in the form of error bars. These error bars correspond to the 95% confidence intervals relative to the full-scale load capabilities of the utilized load cell calibration range, which were provided by the manufacturer. Specifically, the thrust uncertainty is  $\pm 0.75\%$  of the 66.72 N full-scale load, or  $\pm 0.5$  N, while the torque uncertainty is  $\pm 2.0\%$  of the 1.13 N\*m full-scale load, or  $\pm 0.023$  N\*m. This constant dimensional uncertainty in thrust is also presented in the nondimensional plots of  $C_T$ , which decreases with increasing tip speed.

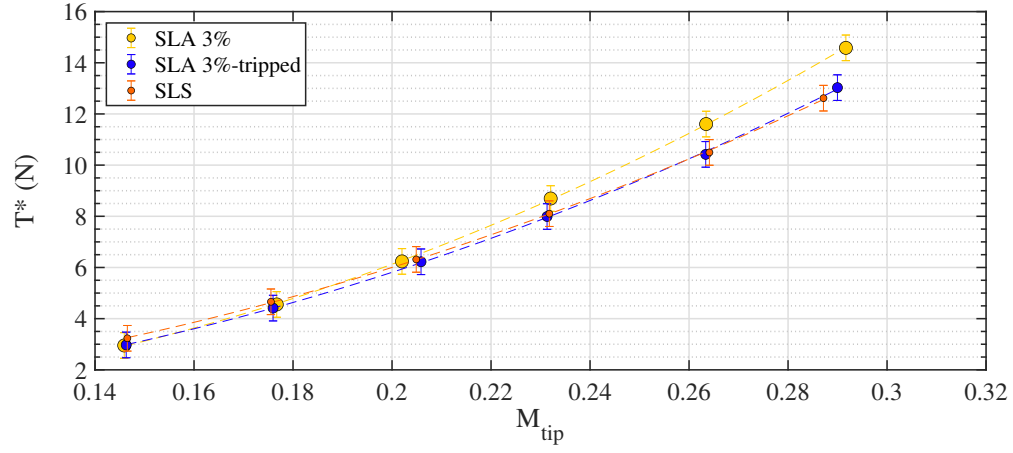
Figures 5 through 7 are the corrected thrust, corrected torque, and coefficient of thrust as functions of rotor tip speed for the various rotor datasets. Quadratic fits were applied to the corrected thrust and torque plots, and linear fits were applied to the thrust coefficient plots. All tested rotors except the SLA 1% rotors are included in these figures. However, Appendix A tabulates performance for all tested rotors in this report.

For the SLA/SLS rotors presented in Fig. 5, thrust decreases 8.1% for SLA 3%-tripped rotor and 6.9% for the SLS rotor when compared to the untripped SLA 3% rotor for the measurements at approximately the design speed of  $M_{tip} = 0.2300$ . The corresponding torque measurement decreases by less than 1% and increases by 5.17% for the SLA 3%-tripped and SLS rotors, respectively, when compared to the untripped SLA 3% rotor measurement at this condition. The thrust coefficients of the variously tripped SLA/SLS rotors are plotted in Fig. 5(c). The coefficients for the fits are 0.01366, 0.00629 and 0.00059, for the SLA, SLA 3%-tripped, and SLS blades, respectively. Thus, curve fits flatten out as you go from the SLA to the SLA-tripped, and finally to the SLS blades. One interpretation of this is that a higher linear fit coefficient or slope in  $C_T$  as a function of tip speed implies that the nondimensional form presented in Eq. 3 is not an adequate representation. Specifically, the normalization of the dimensional thrust by  $(\omega R)^2$ , which is equivalent to  $(M_{tip} c_{\infty})^2$ , does not fully represent the physics of the blade. A constant  $C_T$  implies that the thrust generated by the rotor is balanced by the Mach operating condition of the rotor. Having a nonzero thrust coefficient slope with tip Mach number, however, indicates that this normalization does not capture the pertinent physics. This points to low-Reynolds number effects. It is important to point out that the near-zero slope of the SLS-fabricated blade set, which has very coarse-textured blades, implies tripped, or fully turbulent flow over the blades.

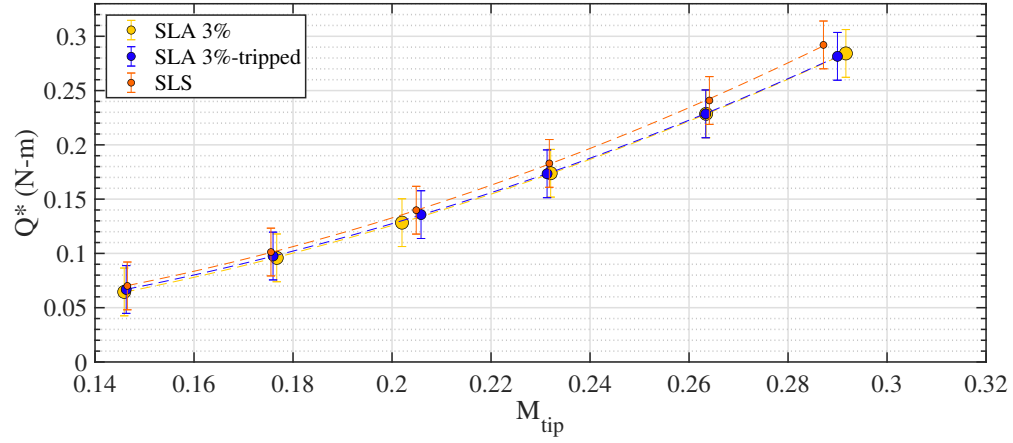
For the FormLabs rotors presented in Fig. 6, thrust decreases 11% for the FormLabs-tripped rotor when compared to the untripped FormLabs rotor at approximately the design speed of  $M_{\text{tip}} = 0.2300$ . Torque changes negligibly for the FormLabs-tripped rotor when compared to the smooth FormLabs rotor. The thrust coefficients of the various tripped FormLabs rotors are plotted in Fig. 6(c). The coefficients for the fits are 0.0053, 0.00186, 0.00187, and -0.00193, for the FormLabs, FormLabs 60 to 100% tripped, FormLabs 50 to 100% tripped, and FormLabs-tripped, respectively.

For the COTS rotors presented in Fig. 7, thrust decreases 3.41% and torque decreases 2.98% when the trip dots are added at approximately the design tip speed of  $M_{\text{tip}} = 0.2300$ . The effect of tripping on these performance parameters is less than that of the OPT2 rotors in Figs. 5 and 6. Thrust coefficients are plotted in Fig. 7(c), with coefficients for the fits being 0.00274 and 0.00045, for the COTS and COTS-tripped rotors, respectively. While the coefficient value is lower for the the COTS-tripped rotor than the untripped COTS rotor, the untripped COTS rotor coefficient is already at a very low value so the flattening is less prominent than that of the OPT2 rotors.

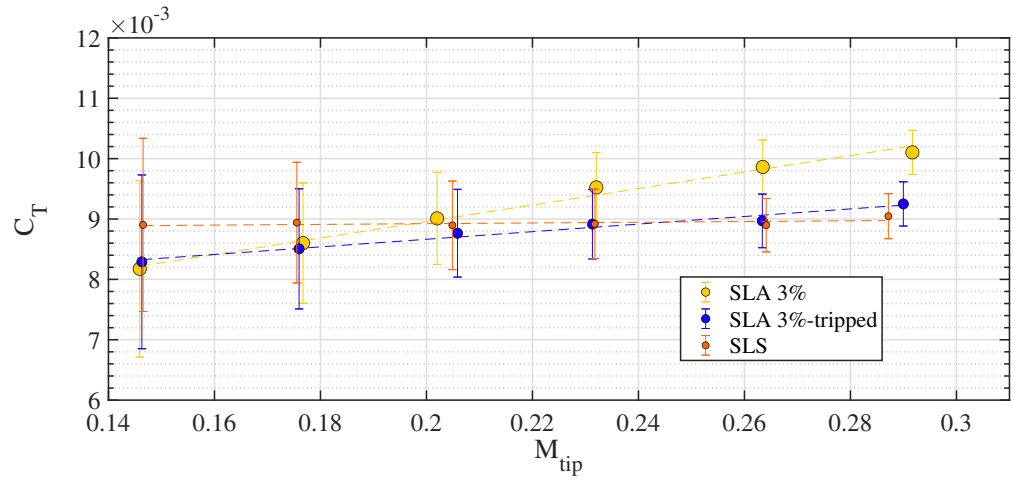
Finally, certain cases were designated to be “low,” “mid,” and “high” tip speed conditions, and will be referenced as such in the acoustic results portion of this report. They are tabulated in Table 3.



(a) Thrust

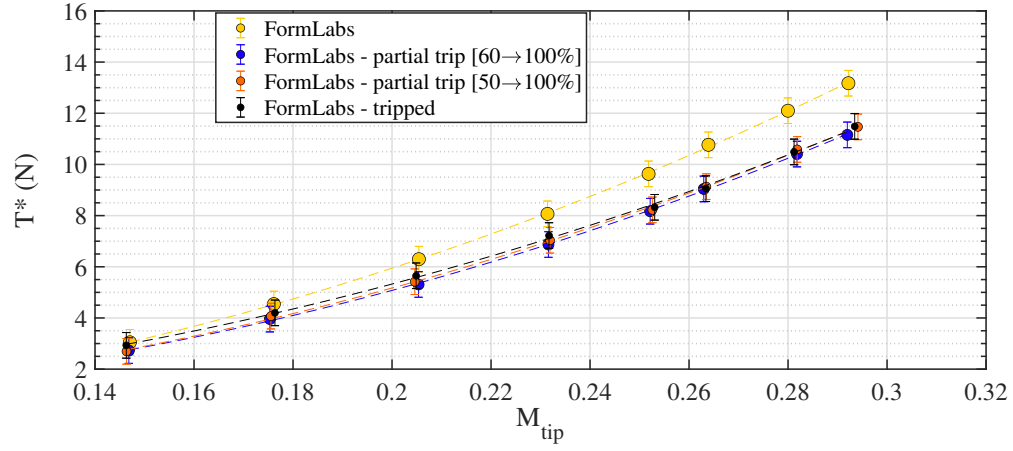


(b) Torque

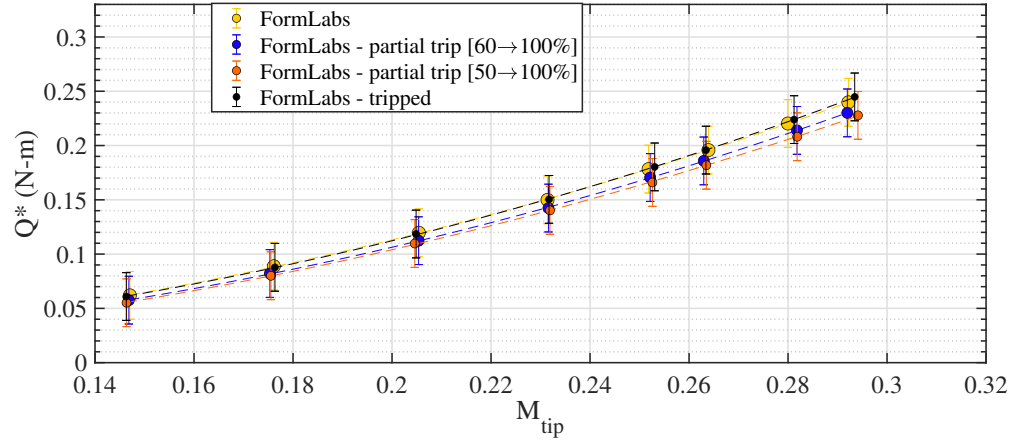


(c) Thrust Coefficient

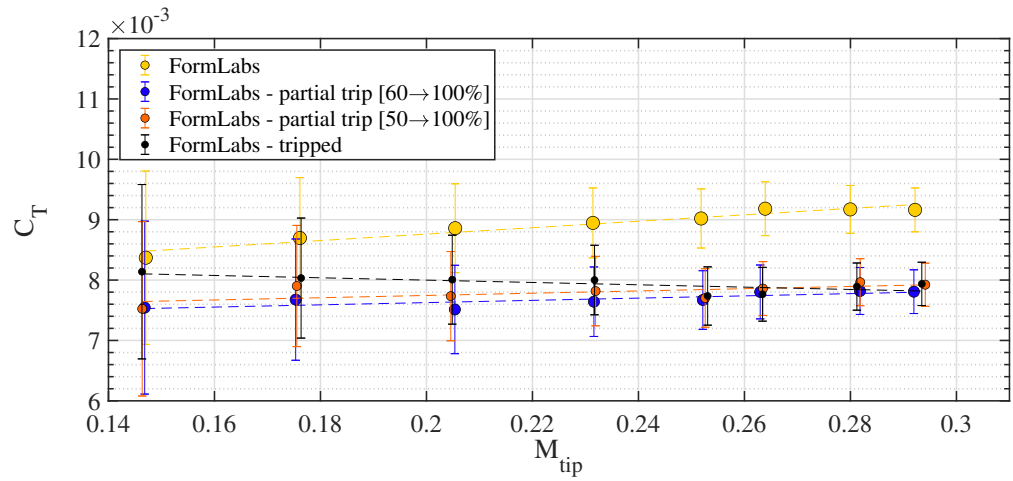
Figure 5. Performance results of optimum hovering rotors made via SLA and SLS.



(a) Thrust

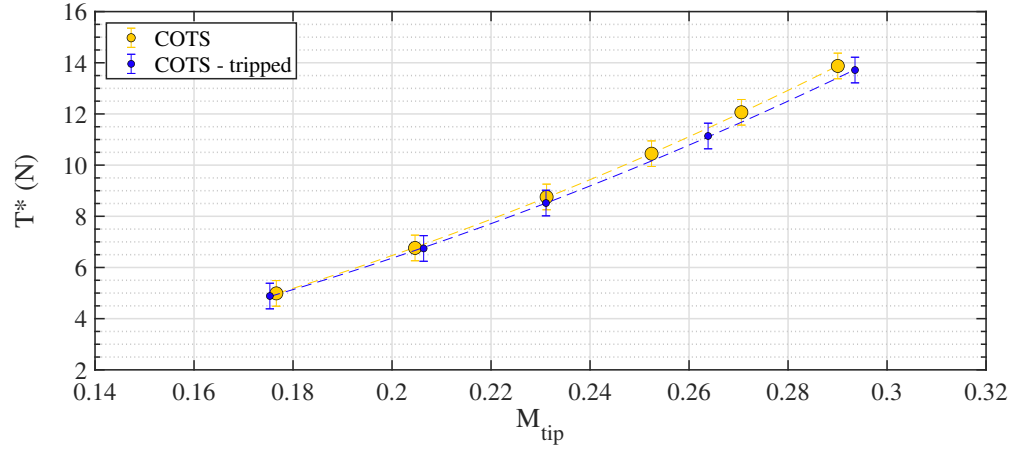


(b) Torque

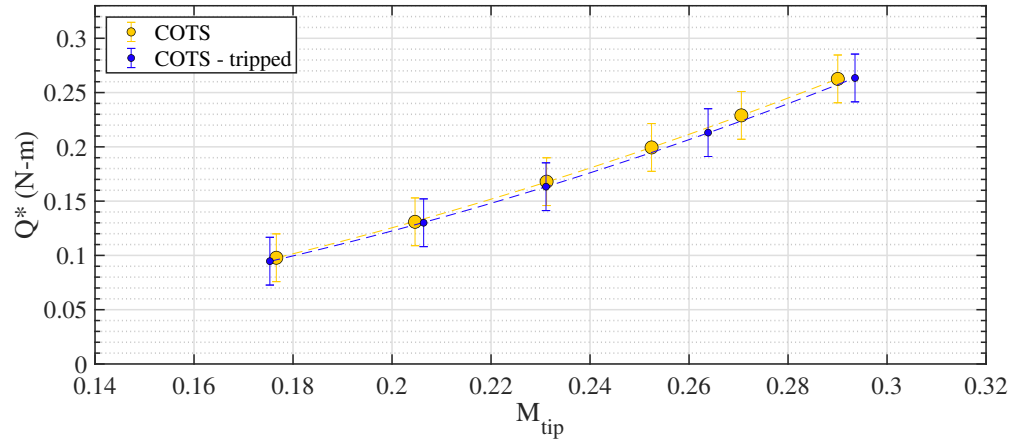


(c) Thrust Coefficient

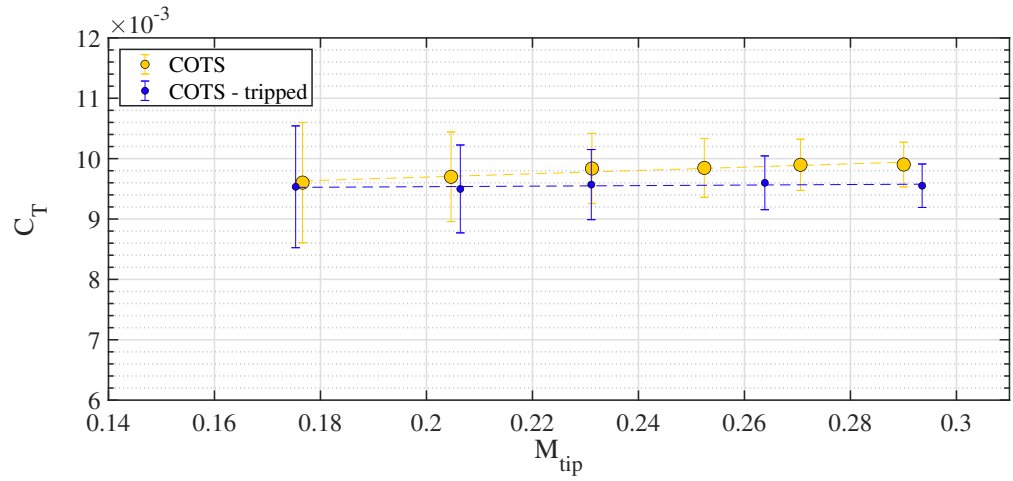
Figure 6. Performance results of optimum hovering rotors made via FormLabs.



(a) Thrust



(b) Torque



(c) Thrust Coefficient

Figure 7. Performance results of COTS rotors.

Table 3. Low, Mid, and High Tip Speed Conditions.

| Condition                                | $M_{\text{tip}}$ | $\Omega$ (RPM) | $T^*$ (N) <sup>1</sup> | $Q^*$ (N-m) <sup>1</sup> |
|------------------------------------------|------------------|----------------|------------------------|--------------------------|
| <b>SLA 1%</b>                            |                  |                |                        |                          |
| Low                                      | 0.1761           | 3086           | 5.0                    | 0.095                    |
| Mid                                      | 0.2322           | 4070           | 9.2                    | 0.169                    |
| High                                     | 0.2935           | 5143           | 15.5                   | 0.277                    |
| <b>SLA 3%</b>                            |                  |                |                        |                          |
| Low                                      | 0.1767           | 3087           | 4.6                    | 0.096                    |
| Mid                                      | 0.2320           | 4053           | 8.7                    | 0.174                    |
| High                                     | 0.2917           | 5096           | 14.6                   | 0.284                    |
| <b>SLA 3% - tripped</b>                  |                  |                |                        |                          |
| Low                                      | 0.1760           | 3055           | 4.4                    | 0.098                    |
| Mid                                      | 0.2313           | 4016           | 8.0                    | 0.173                    |
| High                                     | 0.2900           | 5034           | 13.0                   | 0.282                    |
| <b>SLS</b>                               |                  |                |                        |                          |
| Low                                      | 0.1755           | 3062           | 4.7                    | 0.101                    |
| Mid                                      | 0.2318           | 4043           | 8.1                    | 0.183                    |
| High                                     | 0.2872           | 5009           | 12.6                   | 0.292                    |
| <b>FormLabs</b>                          |                  |                |                        |                          |
| Low                                      | 0.1761           | 3066           | 4.5                    | 0.089                    |
| Mid                                      | 0.2314           | 4028           | 8.1                    | 0.150                    |
| High                                     | 0.2922           | 5086           | 13.2                   | 0.24                     |
| <b>FormLabs-partial trip<sup>2</sup></b> |                  |                |                        |                          |
| Low                                      | 0.1755           | 3045           | 4.1                    | 0.08                     |
| Mid                                      | 0.2319           | 4024           | 7.0                    | 0.14                     |
| High                                     | 0.2941           | 5103           | 11.5                   | 0.228                    |
| <b>FormLabs-partial trip<sup>3</sup></b> |                  |                |                        |                          |
| Low                                      | 0.1753           | 3045           | 4.0                    | 0.082                    |
| Mid                                      | 0.2316           | 4022           | 6.9                    | 0.142                    |
| High                                     | 0.2920           | 5070           | 11.2                   | 0.23                     |
| <b>FormLabs-tripped<sup>4</sup></b>      |                  |                |                        |                          |
| Low                                      | 0.1763           | 3067           | 4.2                    | 0.088                    |
| Mid                                      | 0.2317           | 4030           | 7.2                    | 0.150                    |
| High                                     | 0.2935           | 5103           | 11.5                   | 0.245                    |
| <b>COTS</b>                              |                  |                |                        |                          |
| Low                                      | 0.1766           | 3057           | 5.0                    | 0.098                    |
| Mid                                      | 0.2312           | 4002           | 8.8                    | 0.168                    |
| High                                     | 0.2900           | 5021           | 13.9                   | 0.263                    |
| <b>COTS-tripped</b>                      |                  |                |                        |                          |
| Low                                      | 0.1753           | 3036           | 4.9                    | 0.095                    |
| Mid                                      | 0.2311           | 4002           | 8.5                    | 0.163                    |
| High                                     | 0.2935           | 5083           | 13.7                   | 0.263                    |

<sup>1</sup>Corrected with density

<sup>2</sup>Tripped from 50 to 100% span

<sup>3</sup>Tripped from 60 to 100% span

<sup>4</sup>Fully tripped from 20 to 100% span



## 5 Acoustic Results

This section describes acoustic results from testing the various rotors. First, the acoustic processing methods and their limitations are described. Next, spectral characteristics common to small rotors tested in a hover chamber are highlighted, building upon observations made in Ref. [8] for a subset of these rotors. The spectral trends of all the rotors (test conditions listed in Appendix A) are presented to illustrate how varying tip speed influences the total raw noise signal. An examination of how physical trips affect rotor noise is presented for specified tip speed conditions, (which are listed in Table 3), expanding on the findings of Ref. [9]. Finally, amplitude and frequency scaling are introduced and applied to the broadband portion of the noise data across different tip speeds.

While some physics are discussed, this report takes an empirical approach, a point reiterated in Section 6. Previous publications (Refs. [8] and [9]) have identified potential sources of self-noise. This report expands on that research by providing a wider range of tip speed conditions, by providing additional rotors (SLA 1%, all FormLabs and COTS-tripped rotors), and by providing a more detailed analysis of specific test configurations.

For the purposes of this report, presented acoustic spectra will correspond to an observer located  $35^\circ$  below the plane of the rotor, because an out-of-plane observer is where broadband noise is expected to be loudest. This corresponds to microphone 6 (M6) in the facility diagram illustrated in Fig. 4.

### 5.1 Acoustic Processing

Acoustic measurements were processed by treating the microphone data as random datasets and computing a raw narrowband acoustic spectrum using a Fast Fourier Transform (FFT), resulting in a raw signal. Since the facility was enclosed, spectra were only computed for data without the onset of recirculation effects. For more information on accounting for recirculation effects for small rotors in this facility see Refs. [5] and [15]. Periodic averaging was used to separate the tonal and broadband noise contributions for a given observer. First, a mean rotor revolution time history was computed and subtracted from the entire time record to retain the residual components. Then, using an FFT, it was possible to compute the periodic and residual spectra using the mean rotor revolution time series and residual time series, respectively. The blade passage frequency (BPF) tones were calculated by filtering the entire time series to retain only harmonics of the BPF. More information on these acoustic processing techniques are found in Refs. [16] and [17]. Figure 8 demonstrates the results of acoustic post-processing methods utilized to separate the noise into raw, periodic, broadband and tonal components.

Some peaks remain in the residual, or broadband signal, denoted with the subscript “bb”. Remaining peaks left in the broadband signal are removed to clearly see the broadband noise floor, with this broadband signal denoted with with subscript “bb,pr”. Figure 9 shows the results of this peak removal. More details on the approach and techniques for this experiment are found in Ref. [10].

Generally, for these small rotors in hover, periodic noise extraction works well for the first two blade passage frequency harmonics, after which residual harmonics are left in the signal. In Fig. 8, these residual harmonics are seen at frequencies between 400 Hz and 4 kHz. These residual harmonics can be due to several sources, the most likely being related to turbulence ingestion. The three most likely sources of turbulence ingestion in a facility such as SHAC are incident turbulence from the inlet of the facility, perpendicular blade vortex interactions, and flow recirculation generated by the wake of the rotor. Per the data interrogation methods discussed in Ref. [5], it is believed that the first two of these sources are the most likely culprits. It is further assumed that the peak removal process detailed in Fig. 9 provides a reasonable approximation of the rotor trailing edge

self-noise to serve as a basis for comparison between the different rotors and tripping conditions. More information on the common spectral content of these small rotors tested in the SHAC can be found in Ref. [5].

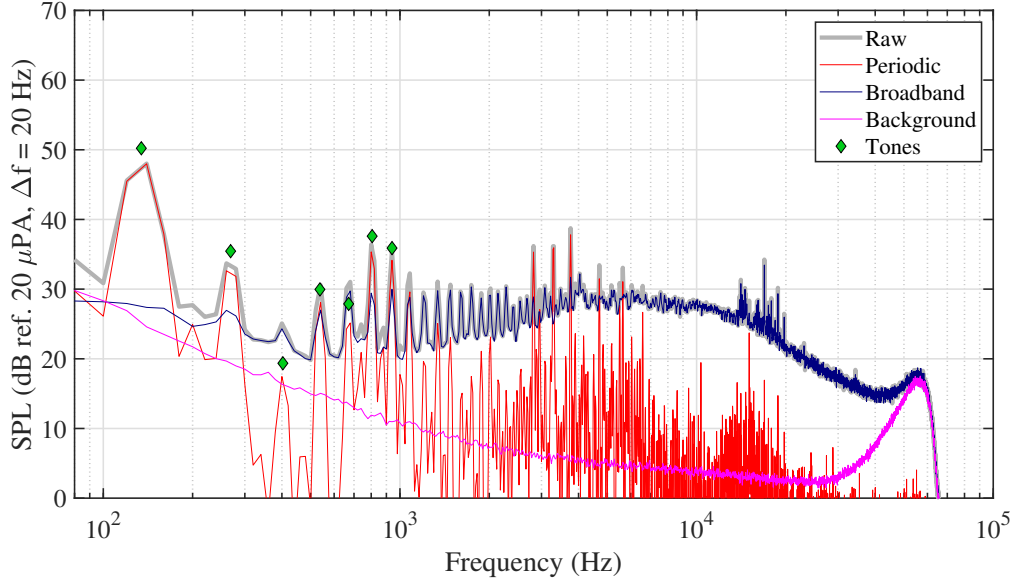


Figure 8. Acoustic post-processing applied to the FormLabs-tripped rotor ( $M_{\text{tip}} = 0.2317$ ,  $\theta_o = -35$  deg.).

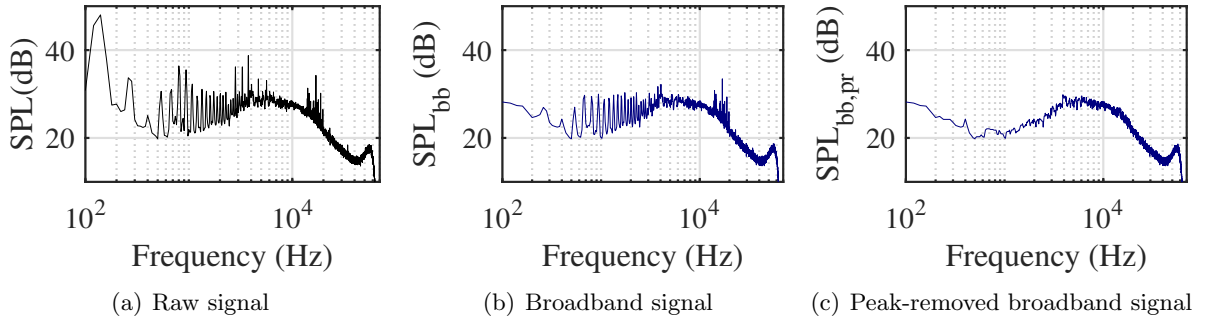


Figure 9. Illustration of broadband residual noise extraction post-processing.

## 5.2 Spectral Trends

To identify transitional acoustic behavior in different rotor blade tip speeds, the isolated rotor acoustic measurements are examined at various Mach numbers ranging from  $0.1463 \leq M_{\text{tip}} \leq 0.2935$ , for an observer located at  $\theta = -35$  degrees below the plane of the rotor. Figures 10, 11, and 12 contain raw spectral trends for all 10 rotors tested in this study: Fig. 10 shows spectral trends for the SLA and SLS rotors, Fig. 11 shows spectral trends for the FormLabs rotors, and Fig. 12 shows spectral trends for the COTS rotors. The hover chamber background noise spectrum is also plotted to show its contribution to noise at low (below approximately 400 Hz) and high (above approximately 30 kHz) frequencies, which affects lower tip speed measurements.

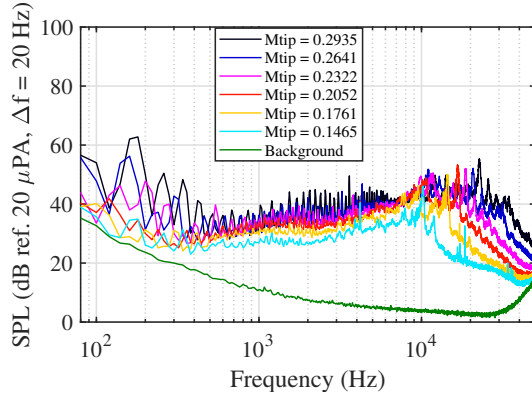
Figure 10 shows the spectra for the SLA and SLS OPT2 rotors. In Fig. 10(a) and 10(b), at the lowest tip speed, a noise hump appears at around 3 kHz and drops off between 10 and 13 kHz. As tip speed increases, this noise source increases in amplitude and frequency, although after a tip speed of  $M_{\text{tip}} = 0.2322$  this noise source starts to dissipate. This behavior is similar to that of the ideally twisted rotor in Reference [5], which identified this type of Reynolds-limited behavior to be due to LBLVS. Additionally, Ref [9] identified the presence of LBLVS in the same SLA 3% OPT2 rotor for a design tip speed of  $M_{\text{tip}} = 0.2313$ .

Figure 11 shows the spectra for the FormLabs rotors. Figure 11(a) shows the noise an untripped FormLabs blade produces, and at mid-frequencies of between 2 and 8 kHz, the lowest tip speed produces noise levels that are comparable to the highest speed, producing a “pinching” effect of the various tip speed spectra together. This is attributed to the same LBLVS mechanism shown in the the SLA blades in Fig. 10(b). This pinching effect is not present in Figs. 11(b), 11(c), and 11(d), although in Fig. 11(c) a small hump is present in between 3 and 6 kHz for lower tip speeds, indicating that the LBLVS noise source could be returning. At first glance, Fig. 11(b) and Fig. 11(d) look nearly identical, with noise increasing in amplitude with tip speed in a similar manner, indicating that the partial 50% to 100% trip impacts noise similar full-span trip. However, when a trip is only applied to 60% to 100% of rotor blade span, such as in Fig. 11(c), behavior starts to change, indicating that the trip dependent noise mechanism of LBLVS is starting to occur between 50% and 60% of the blade span. A direct comparison of particular cases will be presented in Section 5.4.

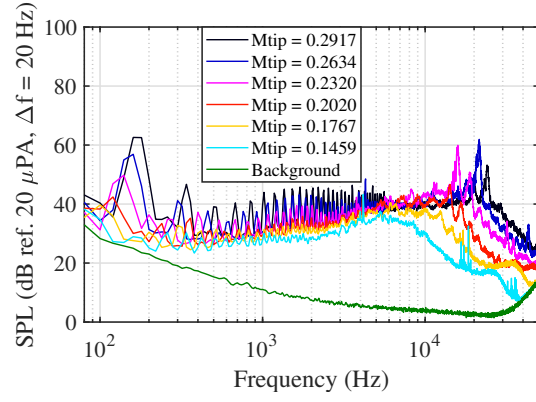
Figure 12 shows the spectra for the COTS rotors. One observation of both the untripped COTS and tripped COTS is that there are many tones (especially for the COTS tripped rotors). The COTS rotors exhibit a flatter behavior than the OPT2 rotors, and increasing tip speed has less of an effect on the amplitudes so the curves are closer together than those of the OPT2 rotors. In other words, the spectra of different tip speeds are more closely pinched together across various frequencies, in the untripped COTS rotor in Fig. 12(a), than in untripped OPT2 rotors in Fig. 11(a), 10(a) and 10(b).

Motor noise tones are found between frequencies of 3 kHz and 6 kHz, as well as between frequencies of 15 and 20 kHz, for all cases. In low tip speed cases or cases where broadband noise levels are low enough, this can be seen in the spectra, for example in the FormLabs-tripped blades in Figs. 11(b), 11(c), and 11(d). However, for untripped OPT2 blades such as the SLA 1%, SLA 3% and FormLabs rotors in Figs. 10(a), 10(b), 11(a), respectively, the motor noise levels are drowned out by additional noise sources. The COTS rotors did have higher levels of motor noise. The rotors may have different loading properties due to their different geometry and weight when compared to the OPT2 rotors.

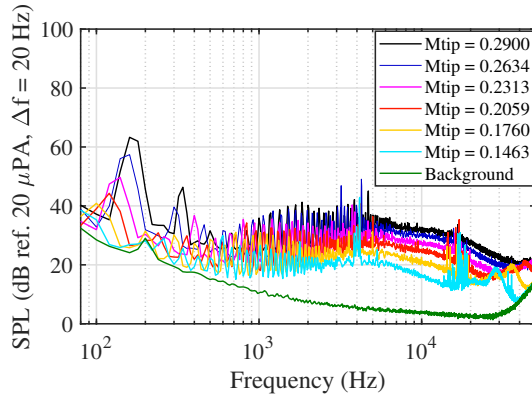
It is important to note that at tip speed of  $M_{\text{tip}} = 0.2500$ , a resonance condition exists in the rig that amplifies motor noise, creating sharp tones at around 3100 Hz and 4100 Hz. This tip speed is not tested for all rotor sets, but is present in Figs. 10(c), 11(a), 11(b), 11(c), 11(d) and 12(a).



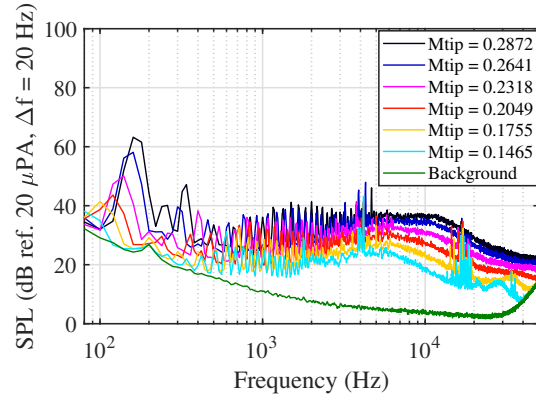
(a) SLA 1 %



(b) SLA 3 %

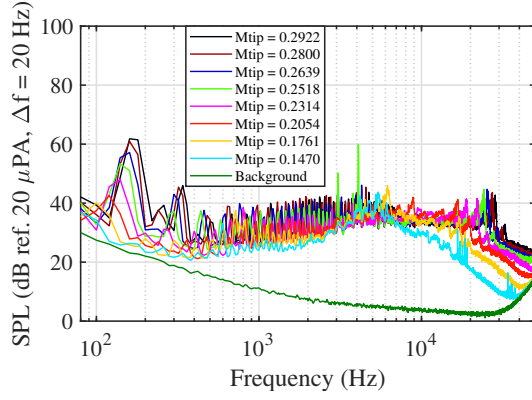


(c) SLA 3 % - tripped

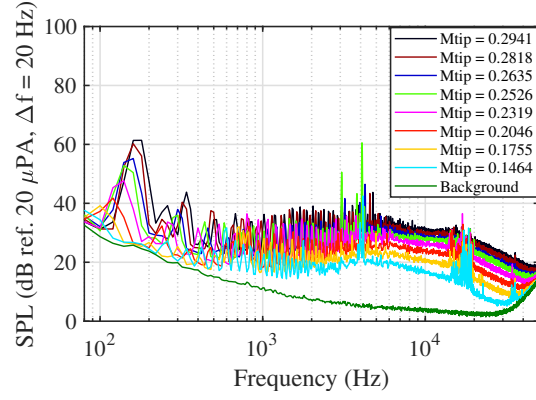


(d) SLS

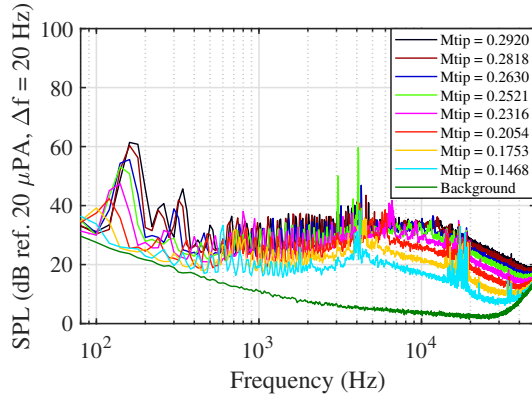
Figure 10. Isolated raw acoustic spectra in hover for SLA and SLS rotors.



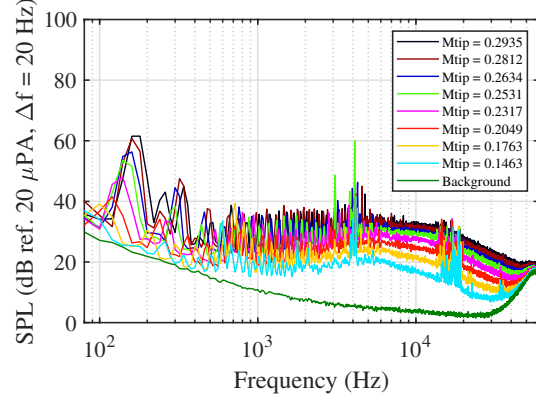
(a) FormLabs



(b) FormLabs 50 to 100 % tripped

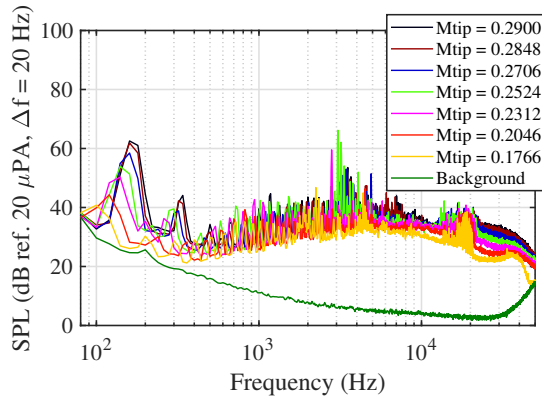


(c) FormLabs 60 to 100 % tripped

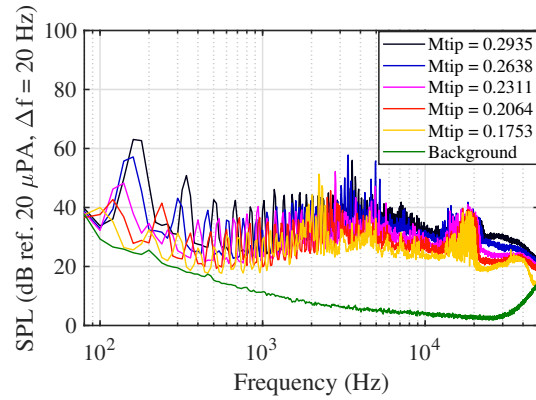


(d) FormLabs 100 % tripped

Figure 11. Isolated raw acoustic spectra in hover for FormLabs rotors.



(a) COTS



(b) Fully Tripped COTS

Figure 12. Isolated raw acoustic spectra in hover for COTS rotors.

### 5.3 Periodic and Broadband Noise Results

Figures 13 through 16 show the spectra and integrated levels for the FormLabs, FormLabs-tripped, SLA 3%, and COTS rotors, for the low, medium, and high conditions defined in Table 3. A more extensive set of measurements is included in Appendix B, which includes additional rotor sets. The raw (total) spectra are plotted, along with periodic and broadband components of the total signal. The first 7 blade passage frequency (BPF) tones are plotted. Background noise spectra are plotted to illustrate the frequencies at which they affect noise levels. The integrated sound pressure levels (L) are plotted for all observers between frequencies of 100 Hz and 40 kHz and have been corrected to a common radius of 1.9156 m. The spectra have no correction. These acoustic measurements have some common behavior. Using the mid tip speed condition FormLabs-tripped in Fig. 13(c) as an example, (the same case presented in Fig. 8), tonal noise initially dominates from frequencies between 100 Hz and 1000 kHz. Broadband noise then starts to dominate the spectra at a frequency at around 1 kHz. This broadband noise is attributed to self-noise sources, which depend on both the tip speed and type of rotor. In this example, self-noise is attributed to turbulent boundary layer trailing edge (TBLTE) behavior on the suction side of the rotor.

The FormLabs-tripped acoustic measurements are plotted in Fig. 13. The directivity plots show that for the  $\theta = -35$  deg. observer plotted in Figs. 13(b), 13(d) and 13(f), the overall sound pressure levels are 54 dB, 60 dB and 68 dB for the low, mid, and high tip speed conditions, respectively. For the baseline case at  $M_{\text{tip}} = 0.2317$  in Fig. 13(c), the first BPF is at 134 Hz and has an amplitude of 50.2 dB. The corresponding observer ( $\theta = -35$  deg.) in the directivity plot in Fig. 13(d), shows the total noise level is 60 dB, with broadband noise levels being at 59 dB and the 1st BPF contributing 52 dB. Thus, broadband noise levels match or are greater than the tonal components, hence the emphasis on broadband noise investigation in this report. There are exceptions at some observers at the high tip speed condition ( $M_{\text{tip}} = 0.2935$ ) for the FormLabs-tripped case shown in Figs. 13(c), due to the levels of the first BPF being high enough (in this case 65 dB).

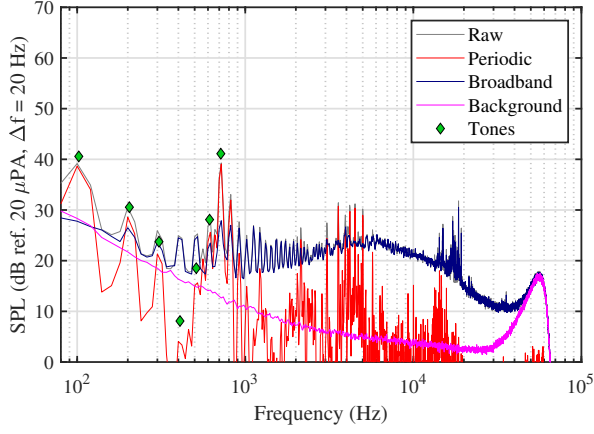
The FormLabs acoustic measurements are plotted in Fig. 14. The directivity plots show that for the  $\theta = -35$  deg. observer plotted in Figs. 14(b), 14(d) and 14(f), the overall sound pressure levels are 66 dB, 68 dB and 70 dB for the low, mid, and high tip speed conditions, respectively. At the lowest tip speed, ( $M_{\text{tip}} = 0.1761$ ), between 2 kHz and 30 kHz, a noise source attributed to laminar boundary layer vortex shedding is present, which peaks at an amplitude level of 46 dB at 6.2 kHz. At the mid tip speed condition, ( $M_{\text{tip}} = 0.2314$ ), there is still a presence of LBLVS noise, including the ladder-type tones described in Ref. [9] for the SLA 3% rotor (which will be pointed out in Fig. 15). These ladder-like tones have amplitudes of 42 and 41 dB at 18.9 kHz and 22 kHz, respectively.

The SLA 3% acoustic measurements are plotted in Fig. 15. The directivity plots show that for the  $\theta = -35$  deg. observer plotted in Figs. 15(b), 15(d) and 15(f), the overall sound pressure levels are 66 dB, 78 dB and 76 dB for the low, mid, and high tip speed conditions, respectively. The mid tip speed condition ( $M_{\text{tip}} = 0.2320$ ) produces the highest noise, and as seen in Fig. 15(c), at around 3 kHz a noticeable hump develops, with high frequency peaks developing at around 15 kHz and 20 kHz, then dropping off at 40 kHz. This noise source is the aforementioned (LBLVS) described in Ref. [6], with the ladder-like tones. This noise source is significant enough that the mid tip speed condition generates more noise than the high tip speed condition. Finally, while tripped rotors at high tip speeds like the ones in Fig. 13(f) have periodic noise dominate directivity levels due to the significantly high BPF, this untripped rotor like the one in 15(f) has broadband noise dominate the directivity levels due to the presence of LBLVS.

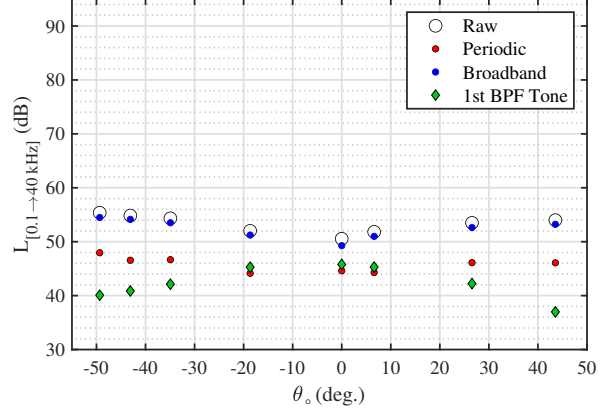
The COTS acoustic measurements are plotted in Fig. 16. The directivity plots show that for the  $\theta = -35$  deg. observer plotted in Figs. 16(b), 16(d) and 16(f), the overall sound pressure levels are 64 dB, 68 dB, and 71 dB for the low, mid, and high tip speed conditions, respectively. While

these noise levels are very similar to those of the untripped FormLabs rotor in Fig. 14, the spectra differ. The untripped COTS rotors in Fig. 16 show a flatter spectral behavior than the OPT2 rotors in Figs. 14 and 15. Additionally, many tones are present in these data, especially in the low tip speed condition ( $M_{\text{tip}} = 0.1766$ ) in Fig. 16(a). While motor noise has been identified as the noise source between 3 and 6 kHz, between 1.7 and 2.5 kHz there are significant tones that are not present in other rotor sets. In Fig. 16(c) there is also a tone at 2.8 kHz. The source of these additional tones is not known, though they may be related to motor noise.

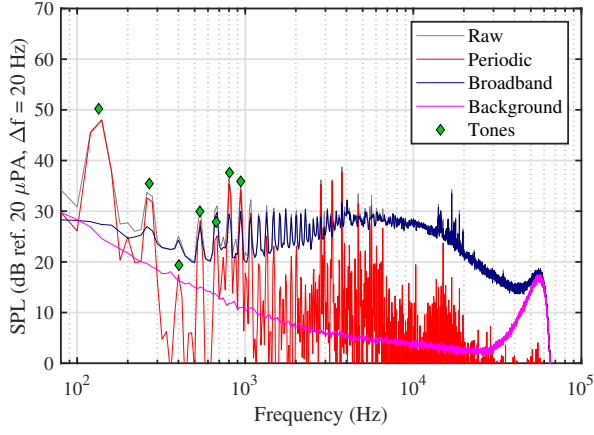
There is a presence of a noise source between 20 and 40 kHz, which is most visible in the lowest tip speed case in Fig. 16(a), which is due to the grid caps being accidentally left on microphones. For two rotor datasets, the COTS untripped and tripped configurations, the protective grid caps were unintentionally left on the facility microphones. Because of this, the COTS data have contamination across a frequency range between 20 and 40 kHz. This can be verified in Fig. 17, with some legacy data that are available for the COTS at the same operating condition ( $M_{\text{tip}} = 0.1747$ ). The measurements with grid cap on will still be presented in this report as frequencies of interest are between 100 Hz and 40 kHz, so the contamination only affects a portion of the measurements.



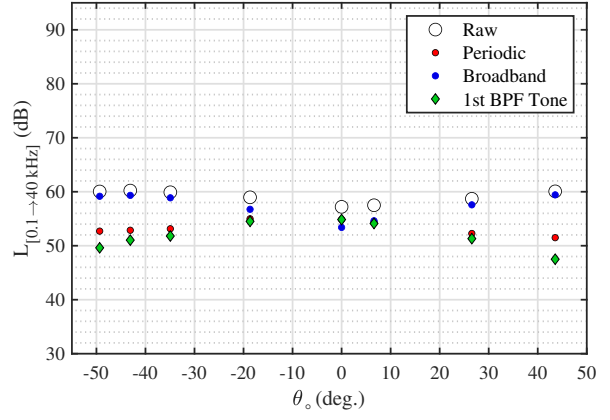
(a)  $M_{\text{tip}} 0.1763$



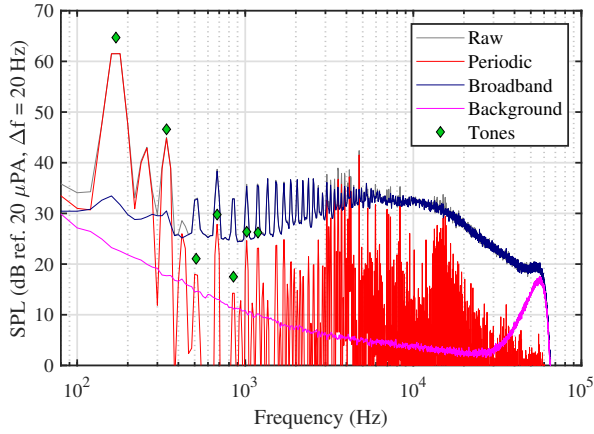
(b)  $M_{\text{tip}} 0.1763$



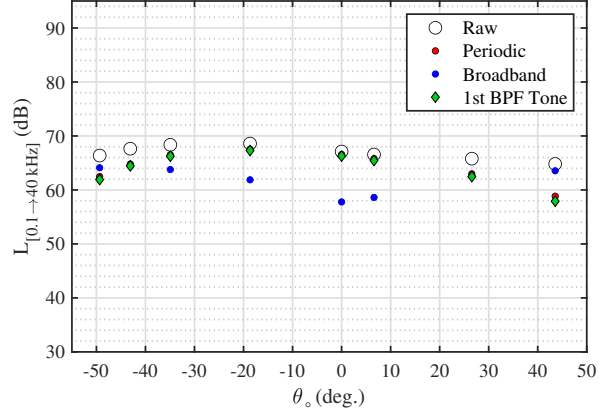
(c)  $M_{\text{tip}} 0.2317$



(d)  $M_{\text{tip}} 0.2317$



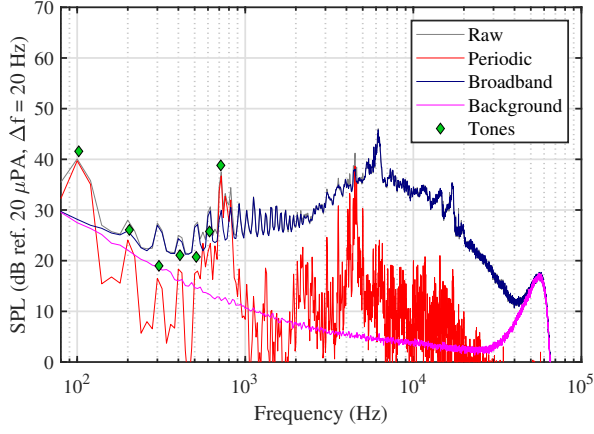
(e)  $M_{\text{tip}} 0.2935$



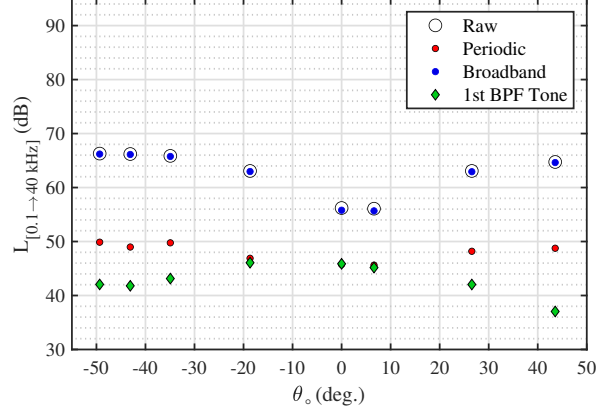
(f)  $M_{\text{tip}} 0.2935$

Figure 13. FormLabs-tripped acoustic measurements.

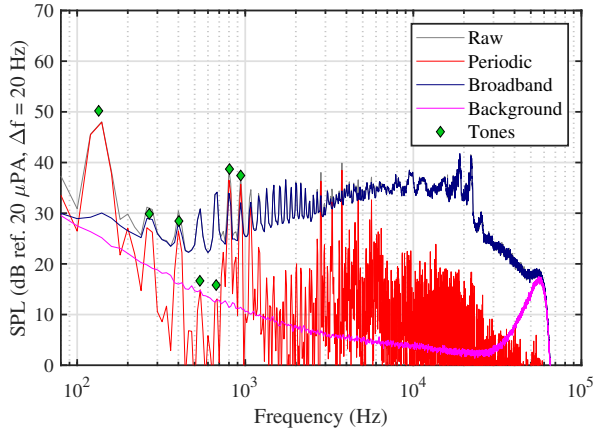




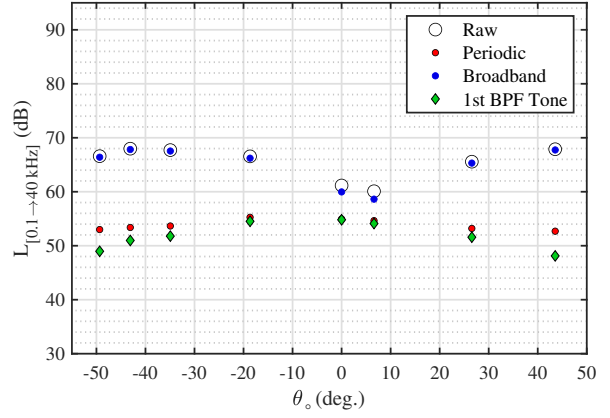
(a)  $M_{\text{tip}} 0.1761$



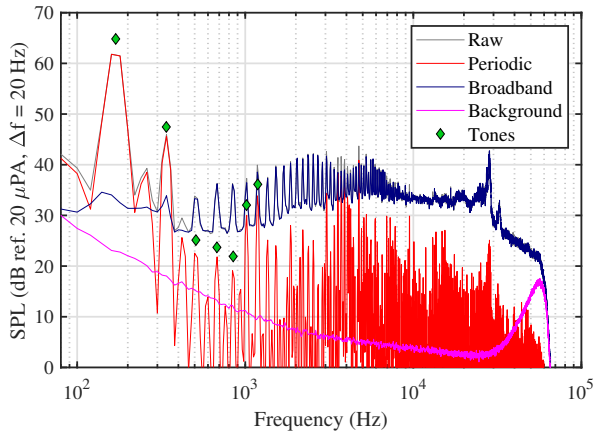
(b)  $M_{\text{tip}} 0.1761$



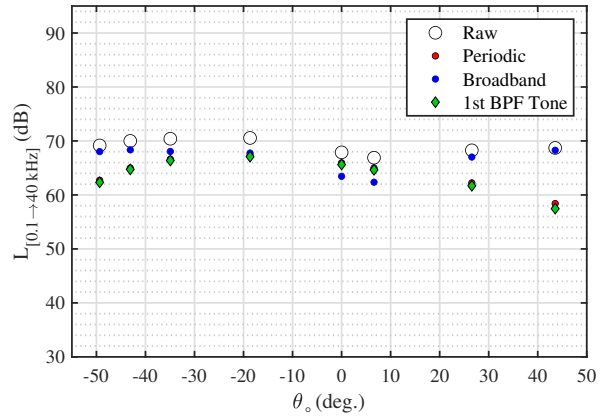
(c)  $M_{\text{tip}} 0.2314$



(d)  $M_{\text{tip}} 0.2314$

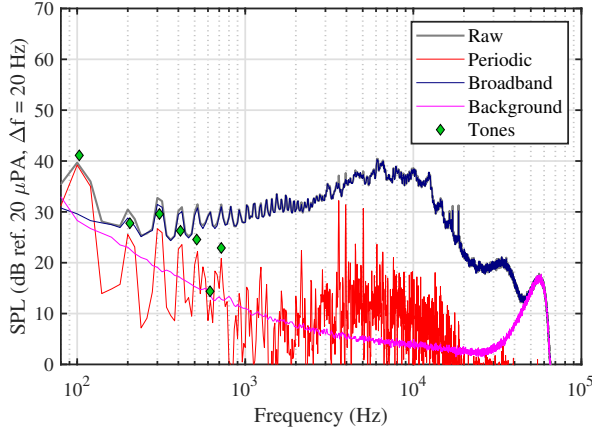


(e)  $M_{\text{tip}} 0.2922$

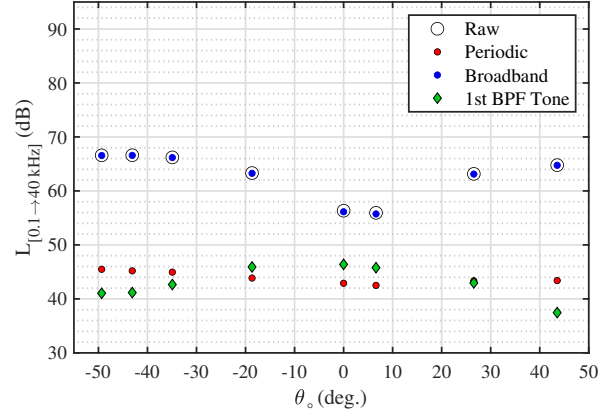


(f)  $M_{\text{tip}} 0.2922$

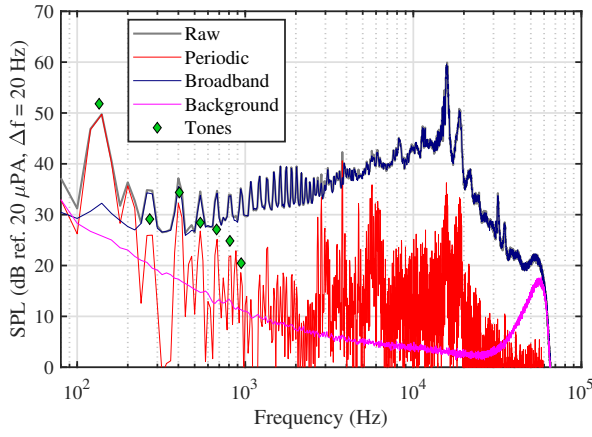
Figure 14. FormLabs acoustic measurements.



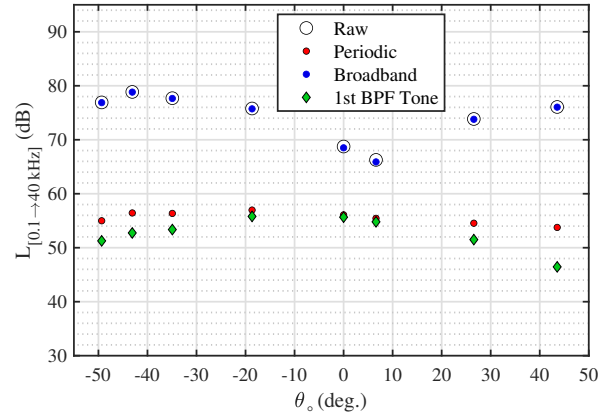
(a)  $M_{\text{tip}} 0.1767$



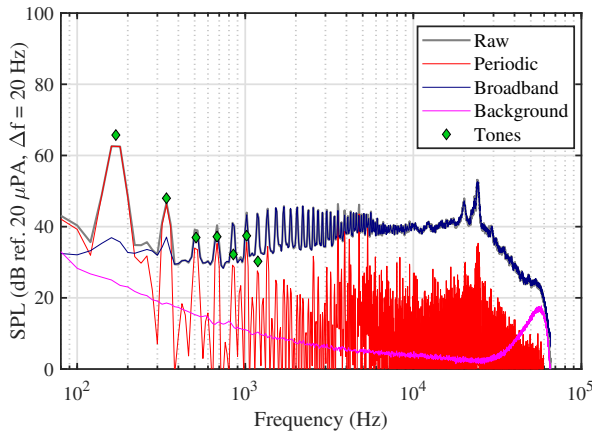
(b)  $M_{\text{tip}} 0.1767$



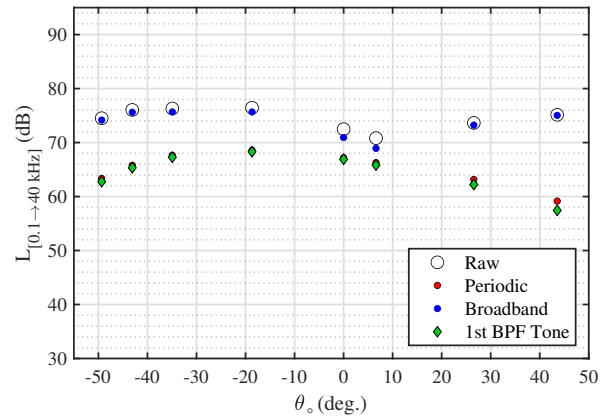
(c)  $M_{\text{tip}} 0.2320$



(d)  $M_{\text{tip}} 0.2320$

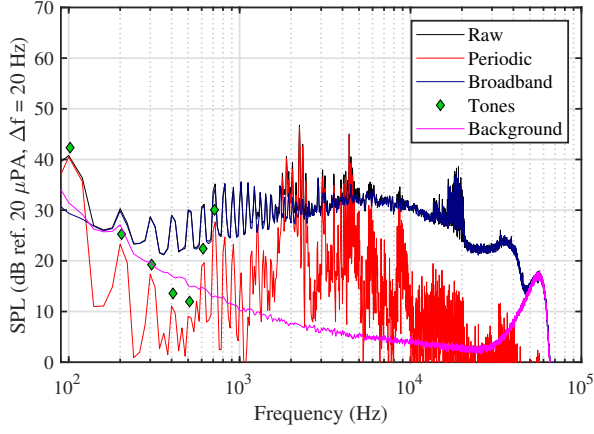


(e)  $M_{\text{tip}} 0.2917$

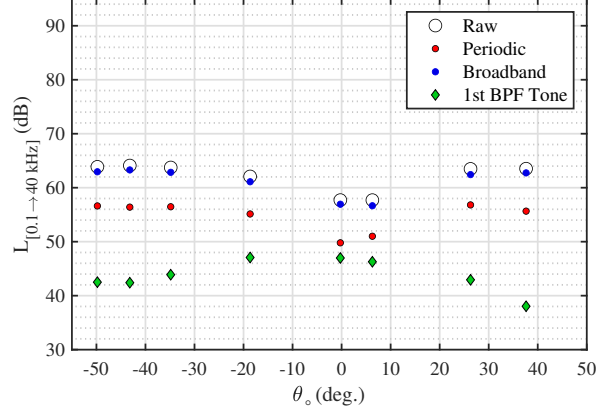


(f)  $M_{\text{tip}} 0.2917$

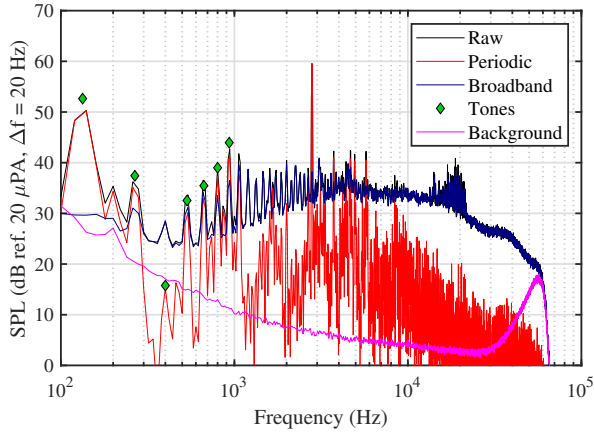
Figure 15. SLA 3% acoustic measurements.



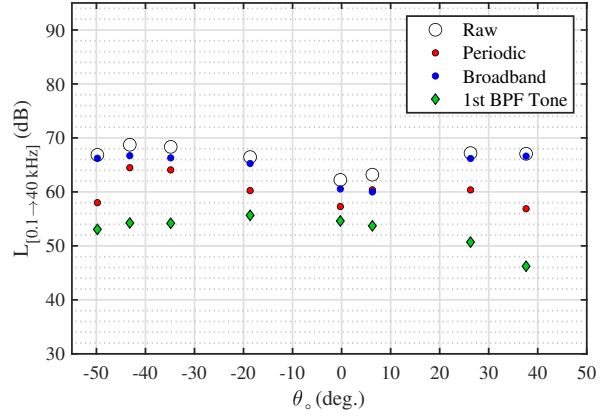
(a)  $M_{\text{tip}} 0.1766$



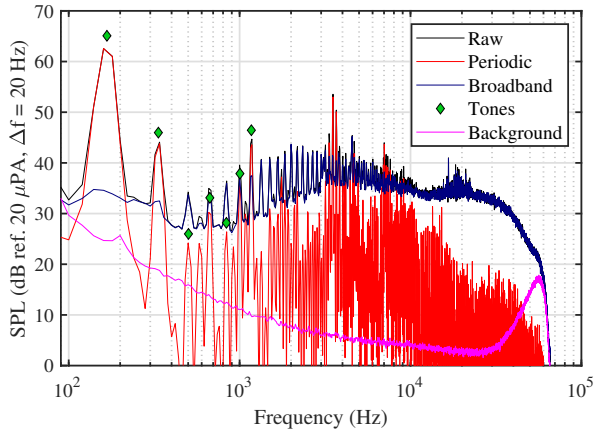
(b)  $M_{\text{tip}} 0.1766$



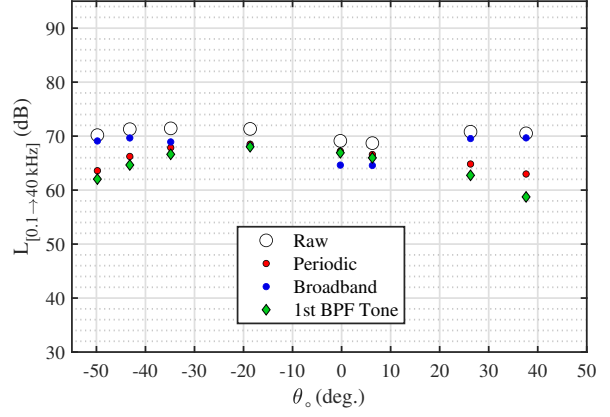
(c)  $M_{\text{tip}} 0.2312$



(d)  $M_{\text{tip}} 0.2312$



(e)  $M_{\text{tip}} 0.2900$



(f)  $M_{\text{tip}} 0.2900$

Figure 16. COTS acoustic measurements.

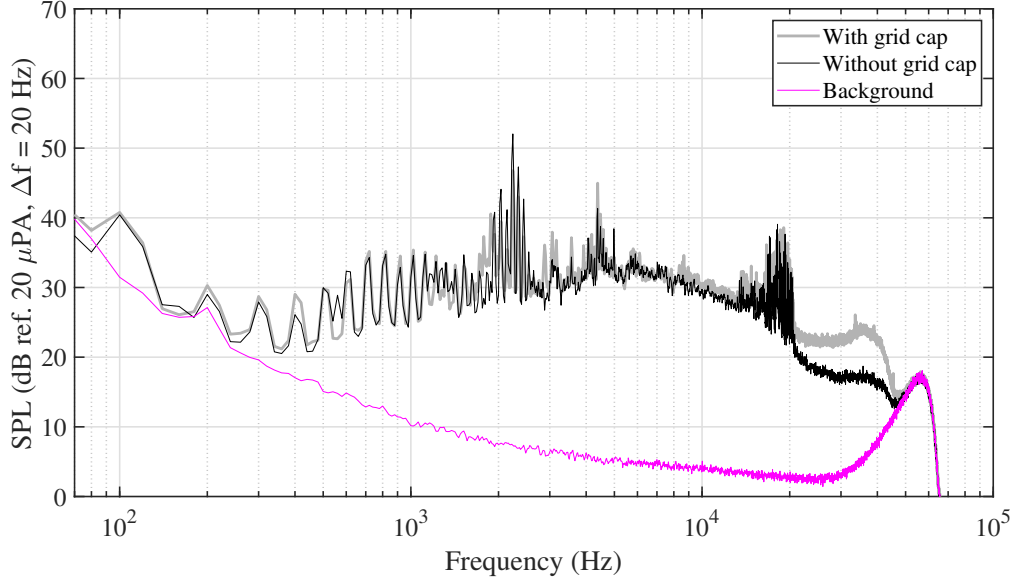


Figure 17. The effects of the presence of grid caps accidentally left on microphones during the COTS rotor noise measurements.

#### 5.4 Tripping Rotors

This section examines the acoustics effects of boundary layer trips on rotor noise. Raw narrowband spectra and unweighted sound pressure levels (averaged from 0.1 to 40 kHz), are compared for all the rotors in Figs. 18 through 20. The peak-removed broadband noise signals and unweighted sound pressure levels (averaged from 300 Hz to 40 kHz) are also presented in Figs. 21 and 22.

Figure 18 compares the narrowband spectra and unweighted sound pressure levels for low, mid, and high tip speed conditions for the FormLabs, FormLabs-partial trip (50 to 100%), FormLabs-partial trip (60 to 100%) and FormLabs-tripped rotors. Figure 18 shows the decrease in higher-frequency noise in all conditions when any trip is applied. The lowest tip speed condition shows the largest reduction in noise, at frequencies between 1 kHz and 30 kHz. Refs. [8] and [9] have identified these high frequency noise sources as the self-noise source LBLVS. At low and mid frequencies, it can be seen that when the rotor is only gritted from 60 to 100%, some of the peaks return (but go away when you grit up 50 to 100%). There is negligible difference from the FormLabs-partial trip (50 to 100%) to FormLabs-tripped. This indicates that LBLVS starts to occur at around the 50% spanwise location, and any part of the blade inwards from that point does not experience LBLVS.

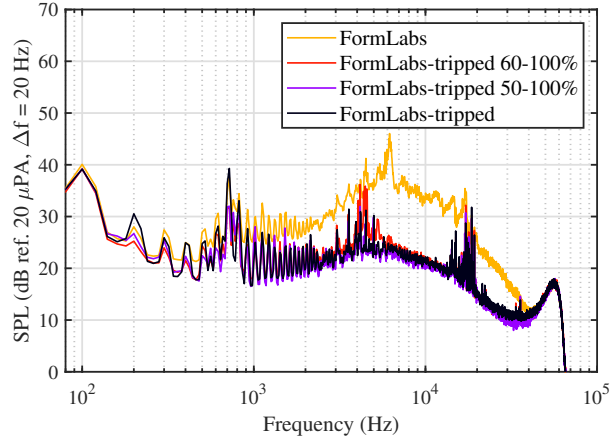
Figure 19 compares the narrowband spectra and unweighted sound pressure levels for low, mid, and high tip speed conditions for the SLA 3%, SLA 3%-tripped and SLS rotors. The SLS rotors, as described in Section 2.1, have a rough texture that trips the flow. In all three tip speed conditions and for all observers, the SLA 3% - tripped and SLS rotors produce less overall noise than the SLA 3% rotors. This noise reduction is attributed to LBLVS no longer being present due to the tripping of the flow. The SLA/SLS rotors have similar geometry to FormLabs rotors, so the effects of applying a trip strip are similar. The SLS rotors, whose material has a homogeneous rough surface, generate more noise than the SLA 3% - tripped at frequencies between 3 and 40 kHz for the baseline condition in Fig. 19(c), and at similar frequencies for the low and high tip speed conditions in Figs. 19(a) and Figs. 19(e). In Ref. [9], this was attributed to the surface roughness tripping flow on both the suction and pressure side of the rotor blade, contrasting with the grit strip on the SLA-gritted rotor tripping only the suction side of the rotor.

Figure 20 compares the narrowband spectra and unweighted sound pressure levels for low, mid, and high tip speed conditions for the COTS and COTS-tripped rotors. The effects of tripping the rotor are minimal, although benefits are seen for the low tip speed condition. This happens at frequencies between 3 and 15 kHz.

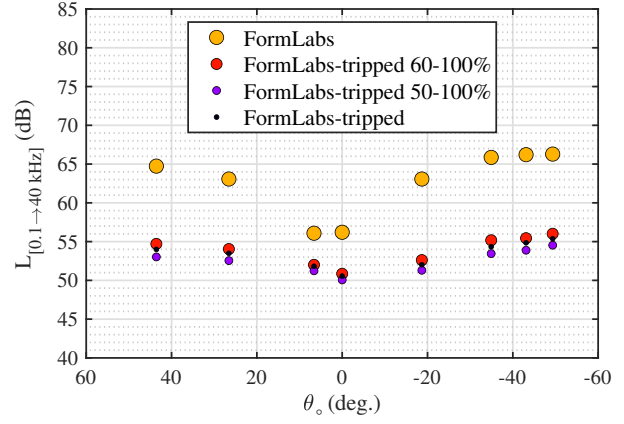
Peak-removed broadband noise spectra for the FormLabs and COTS rotors in Fig. 21 show noise reductions for tripping the rotors at all tip speeds. The lowest tip speed shows significant broadband noise reduction across all frequencies for both the FormLabs rotors in Figs. 21(a) and the COTS rotors in Figs. 21(b). Maximum reductions in noise when comparing fully tripped to untripped rotors at the low tip speeds reach 21 dB (at 6100 Hz) and 9 dB (at 5700 Hz) for the FormLabs and COTS rotors, respectively. For the FormLabs rotors at low and mid tip speed conditions (Figs. 21(a) and 21(c)), the high levels of mid-frequency LBLVS are present for the untripped FormLabs rotor, and only start to reappear when the rotors are only tripped from 60-100%. At the high tip speed in Fig. 21(e) the FormLabs-tripped 60-100% behaves similar to the FormLabs-tripped 50-100% and full span trip. At higher tip speeds, shown in Figs. 21(e) and 21(f), tripping effects become minimal over most frequency ranges, however, FormLabs tripped rotors don't have the "ladder-like" peaks that the untripped rotors produce between 17 and 34 kHz in Fig. 21(e).

Overall sound pressure levels, averaged from 300 Hz to 30 kHz, are compared in Fig. 22 for the FormLabs rotor and COTS rotors. For the FormLabs rotors, measured at  $\theta_o = -35^\circ$ , tripped rotors are 12.7 dB, 8.87 dB and 3.87 dB quieter than the untripped rotors for the low, mid, and high tip speed conditions, respectively. For the COTS rotors, measured at  $\theta_o = -35^\circ$ , tripped rotors are 4.42 dB, 3.87 dB and 2.54 dB quieter than the untripped rotors for the low, mid, and high tip speed conditions, respectively. It is important to remember that these acoustic benefits come with the tradeoff of performance reduction pointed out in Section 4.

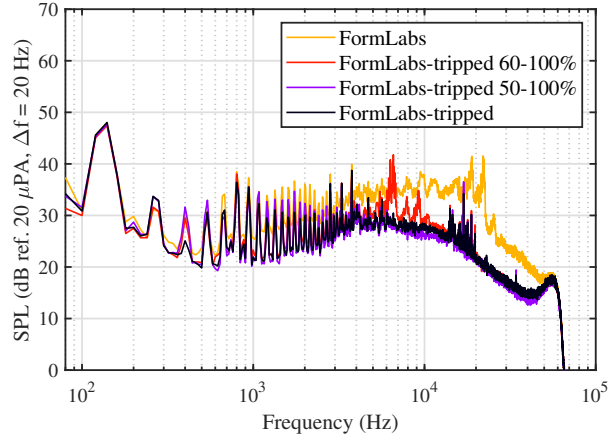
Tripping consistently reduces noise across most frequencies and all observers, with maximum benefit at lower tip speeds. For the FormLabs rotors it is shown that the full noise reduction can be achieved with tripping 50% of the span of the blade, as it is somewhere between 50% and 60% where broadband noise starts to develop on the untripped portion of the blade.



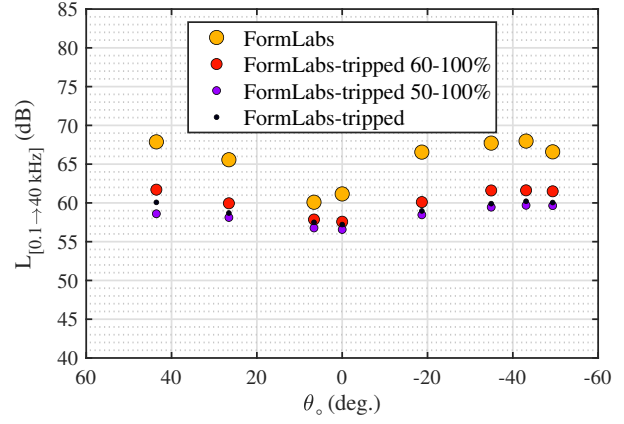
(a) low



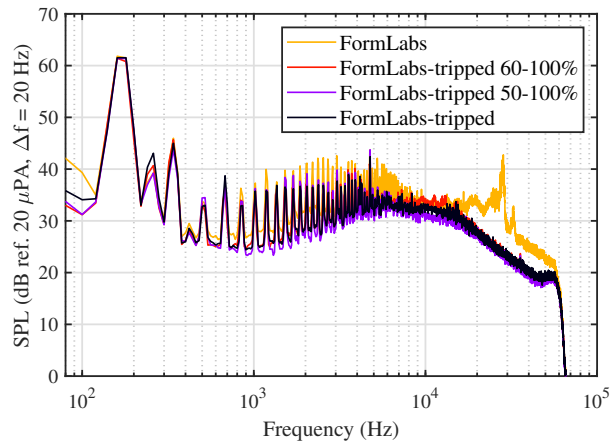
(b) low



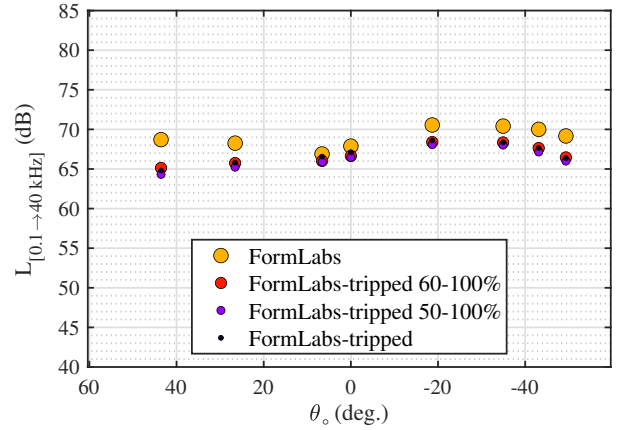
(c) mid



(d) mid

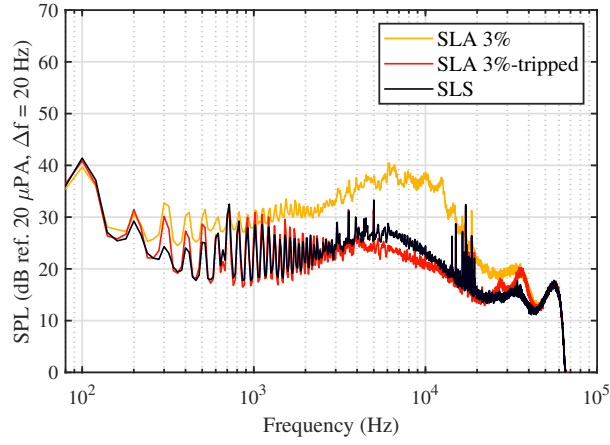


(e) high

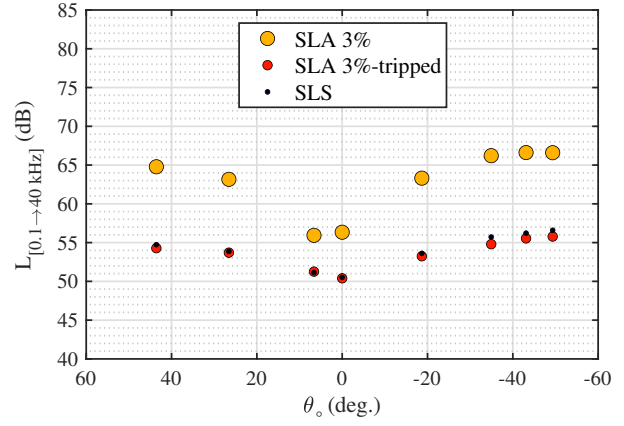


(f) high

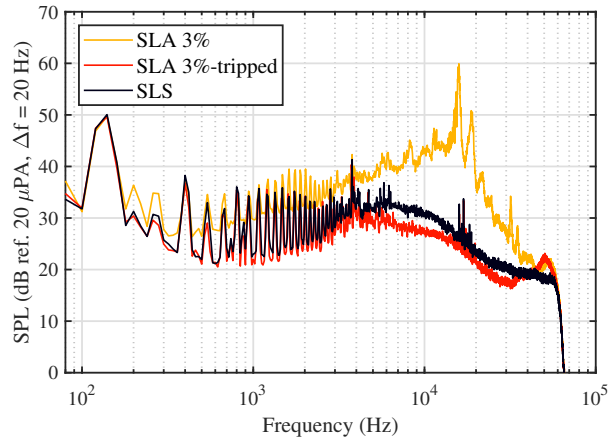
Figure 18. Tripping FormLabs rotor.



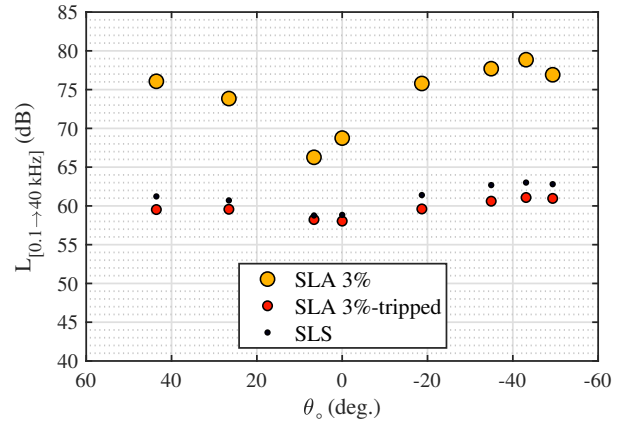
(a) low



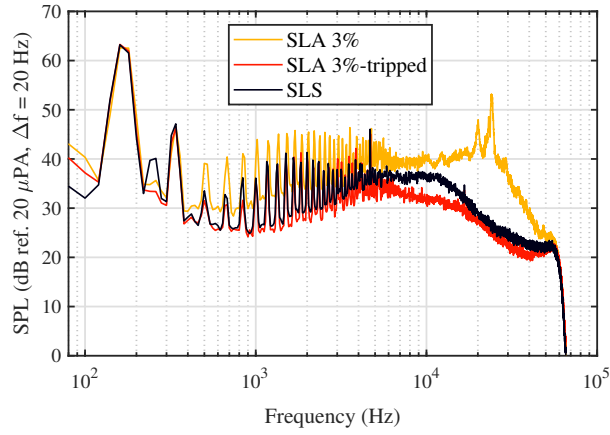
(b) low



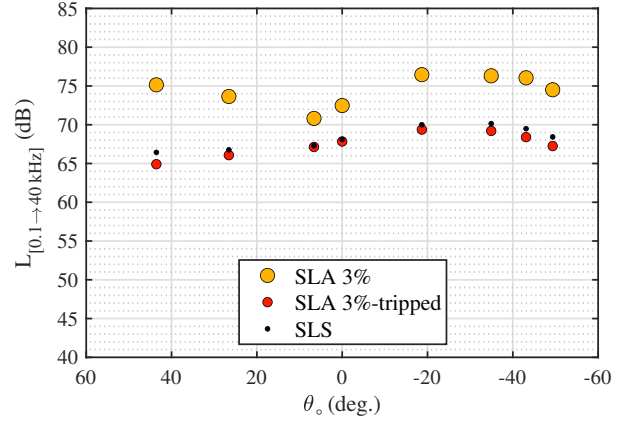
(c) mid



(d) mid



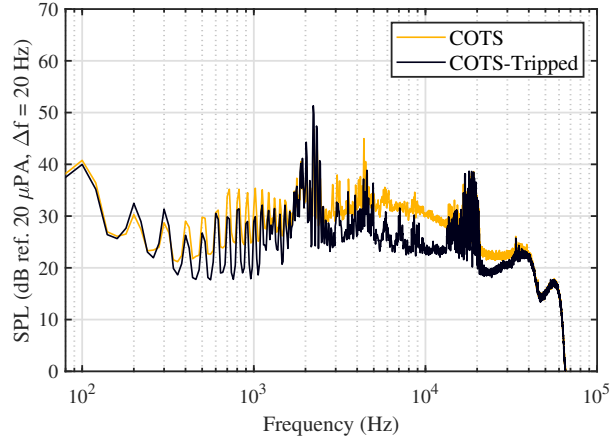
(e) high



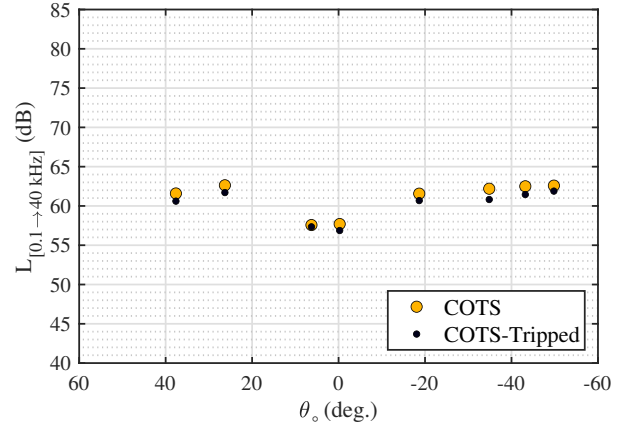
(f) high

Figure 19. Tripping SLA rotor.

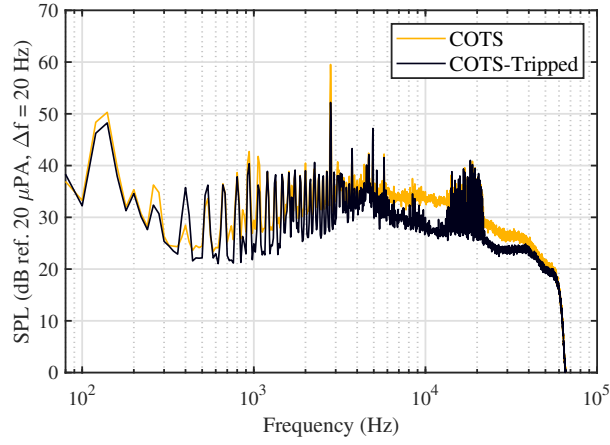




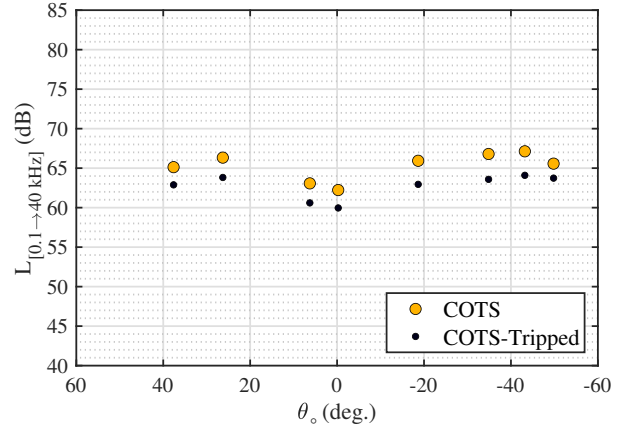
(a) low



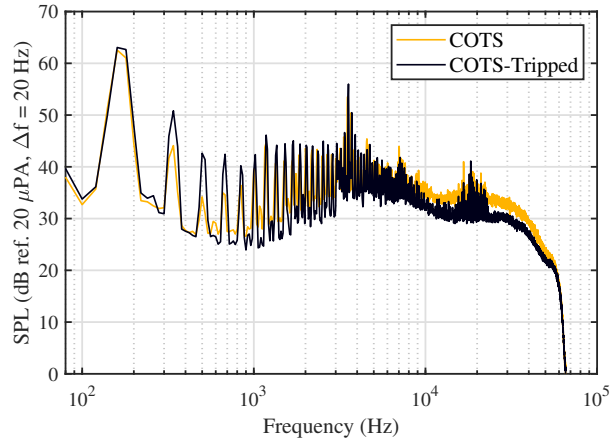
(b) low



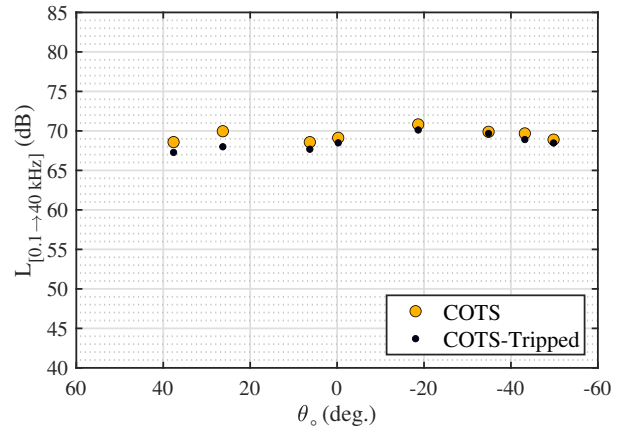
(c) mid



(d) mid



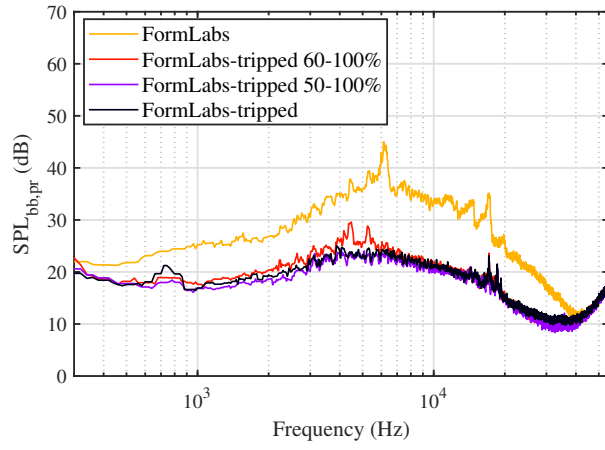
(e) high



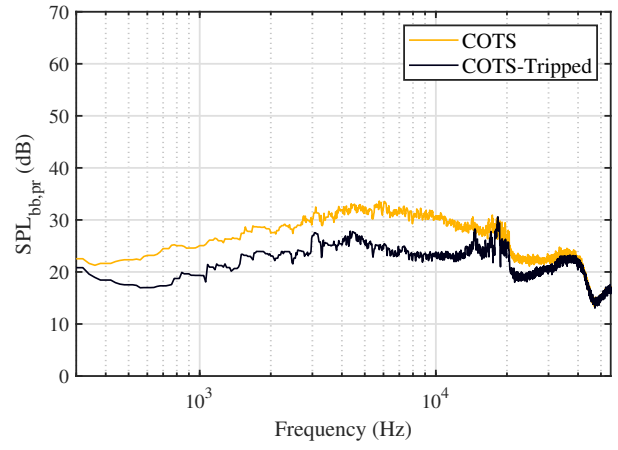
(f) high

Figure 20. Tripping COTS rotor.

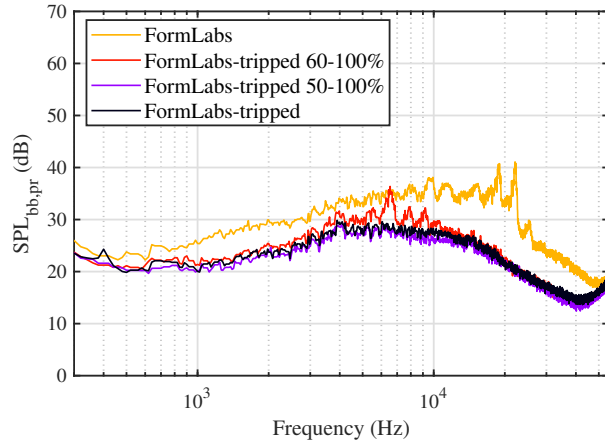




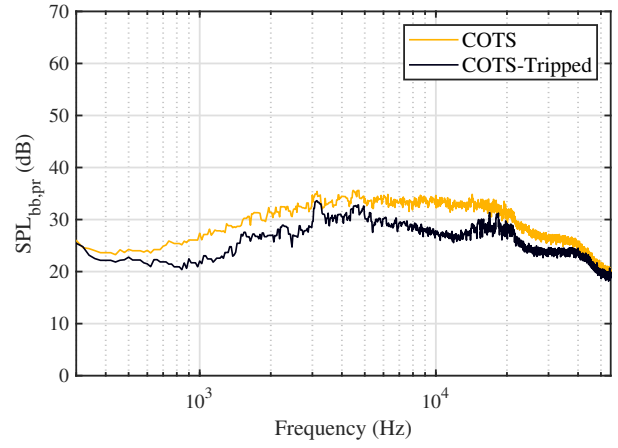
(a) low - FormLabs



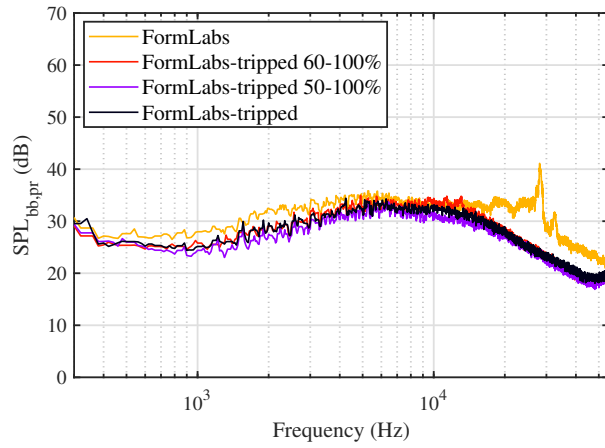
(b) low - COTS



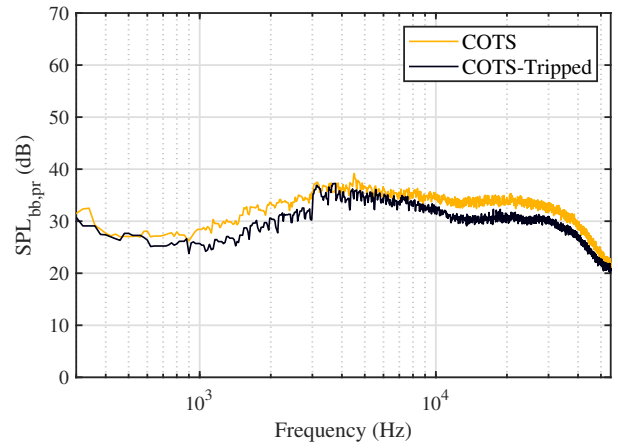
(c) mid - FormLabs



(d) mid - COTS

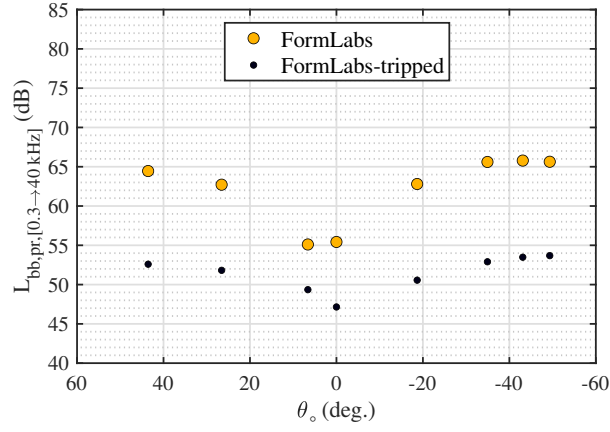


(e) high - FormLabs

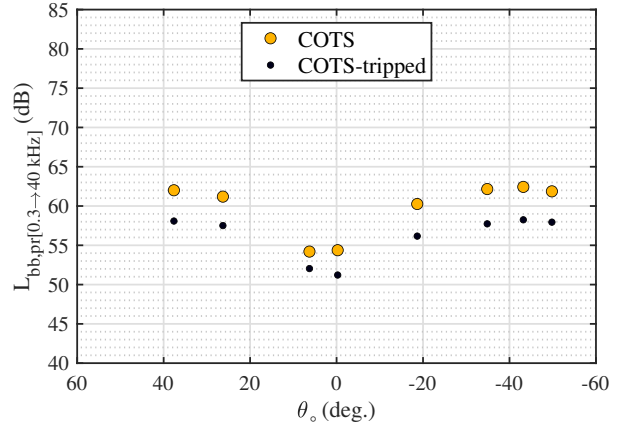


(f) high - COTS

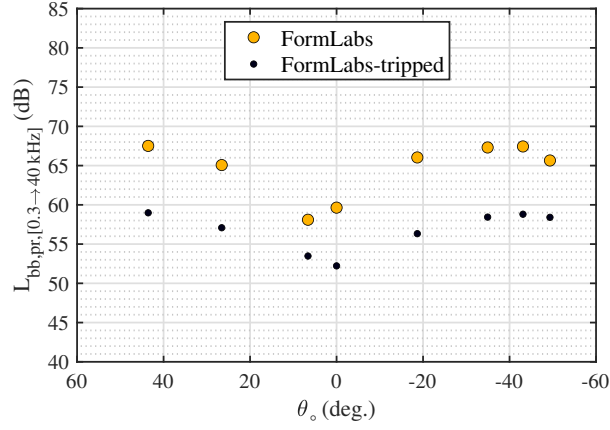
Figure 21. Peak-removed broadband noise comparisons for FormLabs and COTS rotors.



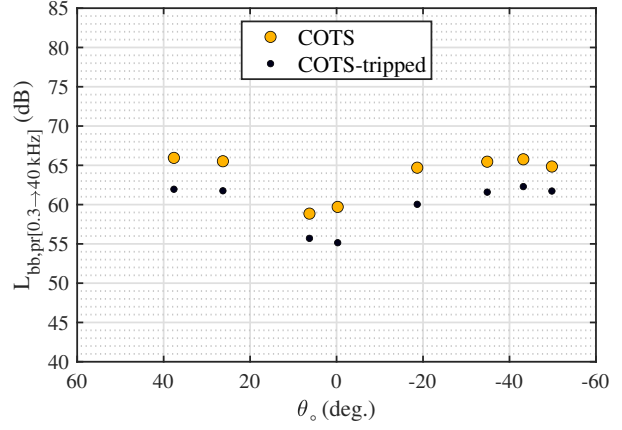
(a) low - FormLabs



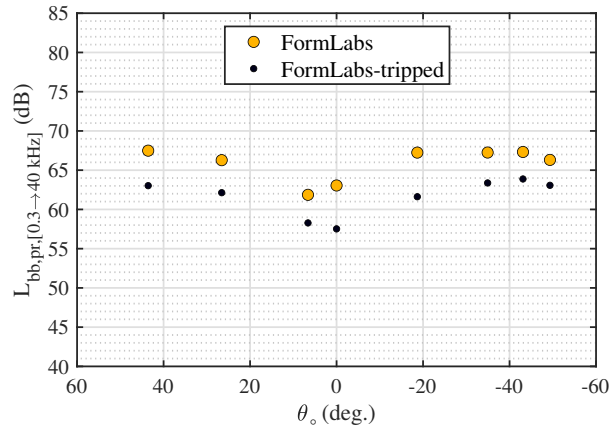
(b) low - COTS



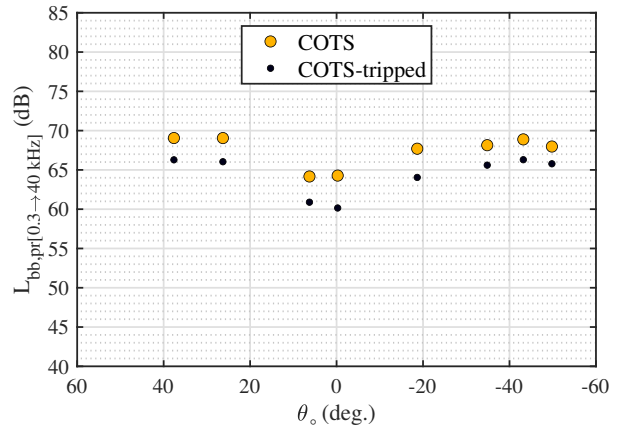
(c) mid - FormLabs



(d) mid - COTS



(e) high - FormLabs



(f) high - COTS

Figure 22. Broadband noise directivity levels.

## 6 Spectral Scaling

In Section 5.2, the raw spectra of various tip speeds were examined to display transitional acoustic behavior of the entire raw noise signal (including periodic and broadband components); this section will examine the broadband portion of the signal. Broadband self-generated noise sources are expected to scale in amplitude and frequency based on their respective scaling laws described in Ref. [4]. Reference [5] scaled hover chamber data for an ideally twisted rotor using parameters related to the spectral functions defined in Refs. [4, 18]. In this section, scaling techniques will be described, and the broadband noise spectra at various tip speeds are examined to identify transitional acoustic behavior between various rotor blade tip speed operating conditions. To scale the data, both amplitude and frequency scaling methods are employed. This analysis adopts a primarily empirical approach, focusing on evaluating the effectiveness of various scaling parameters. While acknowledging the underlying fluid dynamics, a comprehensive theoretical explanation is beyond the scope of this report.

### 6.1 Amplitude Scaling

To investigate the relationship between tip speed and the amplitude of the broadband noise levels, the following definitions are used to calculate scaled amplitudes:

The scaled sound pressure level is calculated as:

$$\text{SPL}_{\text{scaled}} = \text{SPL} + 10\log_{10} \left( \frac{M_{\text{tip,ref}}}{M_{\text{tip}}} \right)^n \quad (4)$$

and similarly, for the overall sound pressure levels,

$$L_{\text{scaled}} = L + 10\log_{10} \left( \frac{M_{\text{tip,ref}}}{M_{\text{tip}}} \right)^n \quad (5)$$

Where  $M_{\text{tip,ref}}$  is a reference tip speed, and  $n$  is a power scaling factor. This is a simplified and general approach to the techniques used in Ref. [4]. For example, a noise source such as TBLTE noise was found to have a relationship in amplitude to a 5th power of a characteristic Mach number ( $n = 5$ ) in Ref. [4] for noise attributed to this mechanism. In this present study, variations in boundary layer parameters such as displacement thickness are unavailable due to measurement limitations, so only Mach number scaling from the reference is included.

## 6.2 Frequency Scaling

In addition to finding relationships between the broadband acoustic amplitudes and tip speed conditions, it is possible to see if there are relationships between the broadband frequency content and tip speed conditions.

For the purposes of this report, Strouhal and Helmholtz are the known nondimensional numbers that will be utilized. The Strouhal number is a dimensionless parameter that is used to characterize the unsteady, oscillatory nature of aerodynamic flow. In terms of vortex shedding, higher Strouhal numbers indicated oscillations dominate the flow while at lower Strouhal numbers the steady flow dominates the oscillations. The Helmholtz number is traditionally a description of acoustic compactness, as it describes the wavelength in terms of a length scale. Small Helmholtz number indicates that a source is small compared to the sound wavelength.

The Helmholtz number is a number calculated as

$$He = 2\pi \frac{fL}{c_o}. \quad (6)$$

The Strouhal number is a number calculated as

$$St = \frac{fL}{U_{\text{tip}}}. \quad (7)$$

Here, the length scale can be represented by a range of parameters. For the purposes of this and similar studies, it is taken to be the trailing edge bluntness thickness at 70% of the blade-span. However, another suitable selection could be the boundary layer or displacement thickness near the trailing edge at that spanwise location, which would account for the changing boundary layer behaviors between tip conditions. Ideally, nondimensionalization should incorporate a length scale that relates to the boundary layer thicknesses, however direct measurement of this was not available for this study. Therefore, the trailing edge bluntness was chosen to represent this length scale. It is important to remember that broadband self-generated noise consists of several noise mechanisms, dependent on different boundary layer characteristics. These noise mechanisms are dependent on the spanwise variability of conditions along the blade, so finding a length scale that encompasses all noise mechanisms is challenging; however, a possible correlation between tip speeds and boundary layer thickness can result in spectra collapsing for a given trailing edge bluntness.

Table 4 shows the three nondimensional parameters that are used: the Helmholtz number, the Strouhal number, and an undefined number that combines Strouhal and Helmholtz, in the primary frequency scaling method denoted as M.1. These parameters were chosen after identifying a pattern using a simple blade passage frequency approach, which incorporated a Mach tip speed to a power of  $m = 1, 0.5$  or  $0$ . This second approach, denoted as M.2, is described and applied in Appendix C of the report. The values of  $m = 1, 0.5$  and  $0$  will be used to track frequency scaling in this report and correspond to  $He$ ,  $HeSt$ , and  $St$ , respectively.

Table 4. Frequency scaling methods and parameters.

| Method ↓, m → | a. $m = 1$                            | b. $m = 0.5$                                | c. $m = 0$             |
|---------------|---------------------------------------|---------------------------------------------|------------------------|
| M.1           | $He$                                  | $HeSt$                                      | $St$                   |
| M.2           | $\frac{f}{\text{BPF}} M_{\text{tip}}$ | $\frac{f}{\text{BPF}} M_{\text{tip}}^{0.5}$ | $\frac{f}{\text{BPF}}$ |

### 6.3 Application of Scaling Methods

The extracted broadband signals for the FormLabs and COTS rotor are shown in Fig. 23 as narrowband spectra with peaks removed ( $SPL_{bb,pr}$ ). This peak removal is necessary in order to better see the trends in broadband noise, as hover residual broadband measurements retain a considerable amount of harmonic tonal energy (see Section 5.1 for more details).

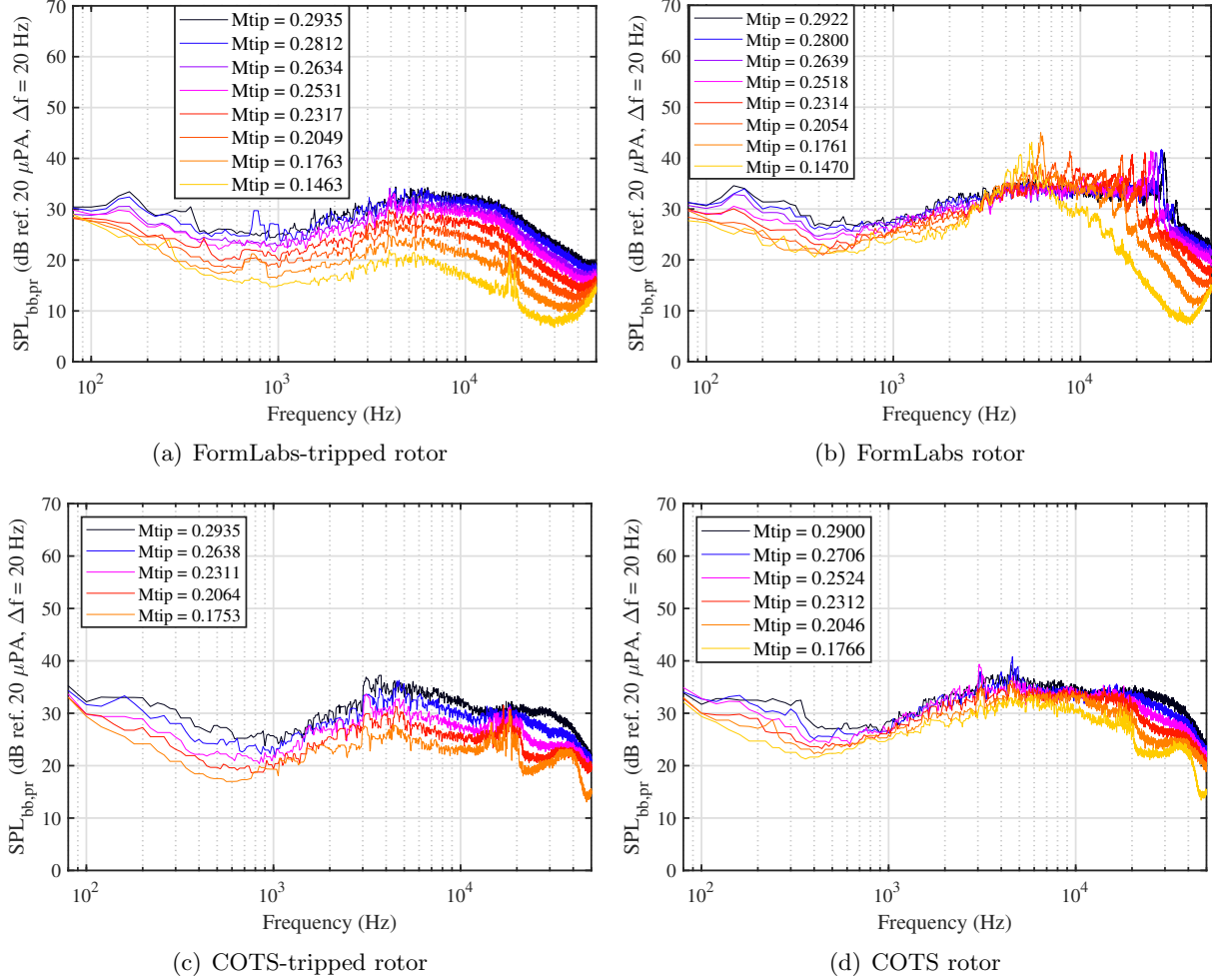


Figure 23. Dimensional broadband noise.

The application of the amplitude and frequency scaling methods are applied in Figs. 24, 25, 26, and 27, as referenced to the respective baseline conditions of  $M_{tip,ref} = 0.2317, 0.2314, 0.2311, 0.2312$ , for the FormLabs tripped, FormLabs, COTS tripped, and COTS rotors respectively. The dimensional broadband noise spectra are once again shown in Figs. 24(a), 25(a), 26(a), 27(a), with the reference condition colored black to make it easier for the reader to reference the scaled spectra to one condition. It is important to note that the baseline data have a frequency resolution of 20 Hz, and thus the levels after scaling result higher than if the original narrowband were processed at a frequency resolution of 1 Hz. The  $n$  amplitude values were chosen based on visual observation (4.5, 2, 4 and 2), of which collapsed the curves onto each other. Extensive results for additional rotors and amplitude values ( $n = 3$  and  $n = 5.5$ ) are included in the Appendices C and D.

Frequency scaling using Helmholtz number ( $He$ , or  $m = 1$ ) is represented in Figs. 24(b), 25(b), 26(b), and 27(b). A Helmholtz frequency scaling nondimensionalizes frequency, however

it is independent of tip speed, thus all tip speeds are shifted equally. This is a representation of acoustic compactness as well.

Frequency scaling using the “weighted” scaling combining Helmholtz and Strouhal ( $HeSt$ , or  $m = 0.5$ ) is shown in Figs. 24(c), 25(c), 26(c), and 27(c). This  $HeSt$  number takes into account the presence of oscillatory forces, however it also factors in that some speed dependent inertial forces might be in play. The physics associated with this parameter need to be investigated more in future publications.

Frequency scaling using Strouhal number ( $St$ , or  $m = 0$ ) is represented in Figs. 24(d), 25(d), 26(d), and 27(d). The Strouhal number is the representation of how the vortex shedding frequency is related to tip speed, with the assumption that bluntness or boundary layer length scales are not changing.

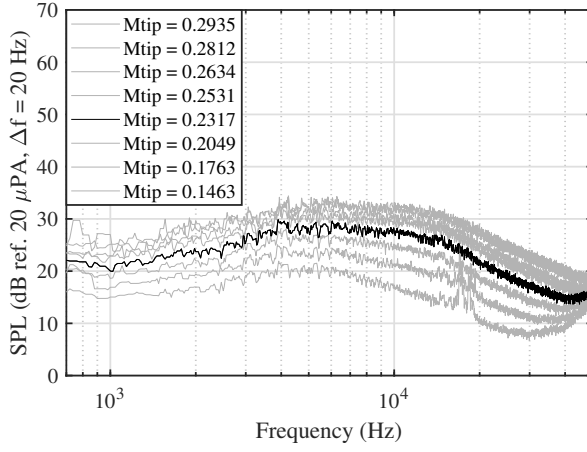
For the FormLabs-tripped rotor results in Fig. 24, an amplitude scaling factor of  $n = 4.5$  was applied. This 4.5 value was decided on based on visual observation of successful amplitude collapse of the data, though it should be noted that an  $n = 5$  would be a more traditional value for TBLTE noise. The broadband noise in the dimensional Fig. 24(a) resembles a flat hump that peaks between 4 and 6 kHz and starts to drop off at around 15 kHz, when looking at the baseline condition ( $M_{\text{tip,ref}} = 0.2317$ ). The other two scaling numbers of  $He$  and  $St$  in Figs. 24(b) and 24(d), respectively, do a decent job in collapsing data, but not at all nondimensional x-values. The  $HeSt$  scaling in Fig. 24(c), collapses the data nicely at nearly all nondimensional x-axis values. The exception of this is the presence of motor noise between  $HeSt$  values of  $7\text{e-}3$  and  $1.4\text{e-}2$ , which does not collapse.

For the FormLabs rotor results in Fig. 25, an amplitude scaling factor of  $n = 2$  was applied. The noise attributed to LBLVS is present at lower tip speeds; for example, it is present at the  $M_{\text{tip}} = 0.1470$  condition at frequencies between 2 and 10 kHz in Fig. 25(a). This noise source does not scale in amplitude due to its Reynolds-limited nature, meaning the source goes away at higher tip speeds, for any of the scaled plots in Figs. 25. However, the stair-like peaks, present for the  $M_{\text{tip}}$  condition of 0.2314 in Fig. 25(a) at frequencies of 19 and 23 kHz, scale nicely in *amplitude* in Figs. 25(b), 25(c), and 25(d). These peaks scale particularly nicely in *frequency* for the Strouhal scaling in Fig. 25(d).

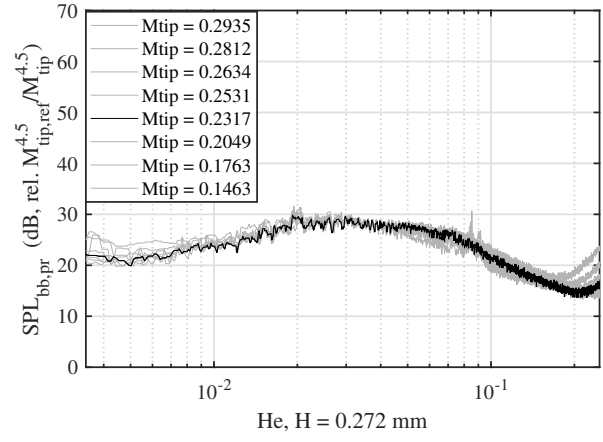
For the COTS-tripped rotor results in Fig. 26, an amplitude scaling factor of  $n = 4$  was applied. There is very little difference between the  $He$ ,  $HeSt$  and  $St$  scaling shown in Figs. 26(b), 26(c) 26(d) at all nondimensional x-axis values, with the exception of the higher nondimensional x-axis values. In the dimensional Fig. 26(a), this corresponds to frequencies above 13 kHz, and for the nondimensional values of  $He$ ,  $HeSt$  and  $St$  this corresponds to values of 0.18, 0.034, and 0.18, respectively.

For the COTS rotor results in Fig. 27, an amplitude scaling factor of  $n = 2$  was applied. There is little difference between the  $He$ ,  $HeSt$  and  $St$  scaling shown in Figs. 27(b), 27(c) and 27(d), with the exception of high and low nondimensional x-axis values. For instance, at the Strouhal value of  $St = 0.2$  and higher, the collapse is different than the corresponding values in the  $He$  (0.19) and  $HeSt$  (0.039) values.

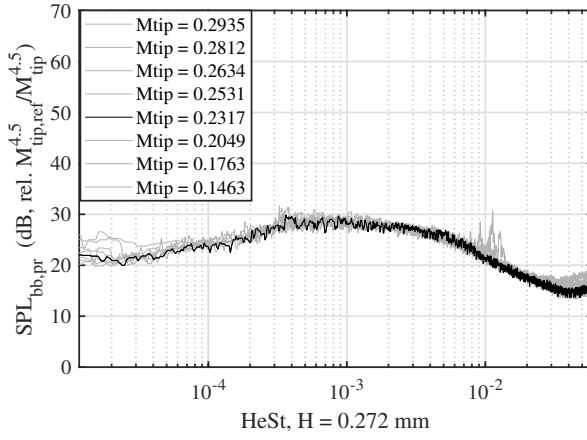
Frequency nondimensionalization works well once the flow is turbulent and low-Reynolds number effects are gone, although it does work well for the stair-like peaks. Low-Reynolds number effects would not be present in larger rotor tests, so the tripped rotors and associated collapse could be more representative of full-scale and possibly indicate these data could be scaled up to full-size.



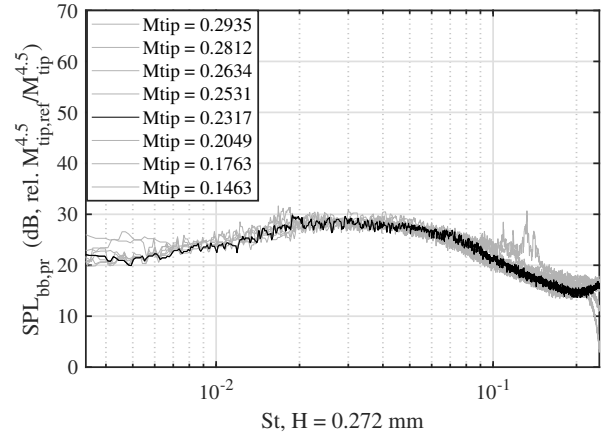
(a) Dimensional



(b)  $n = 4.5, m = 0$



(c)  $n = 4.5, m = 0.5$



(d)  $n = 4.5, m = 1$

Figure 24. Scaling FormLabs-tripped rotors ( $M_{\text{tip,ref}} = 0.2317$ ).

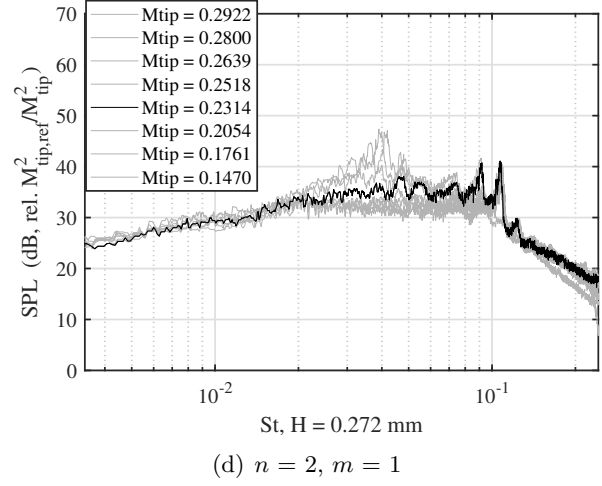
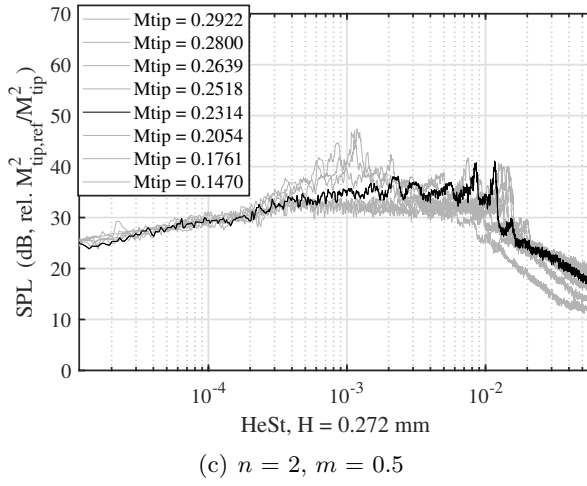
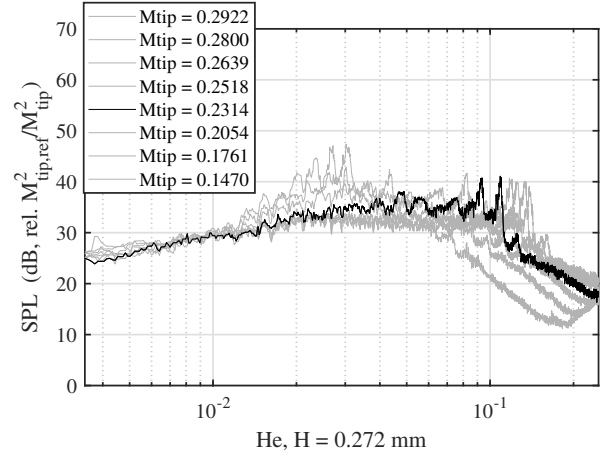
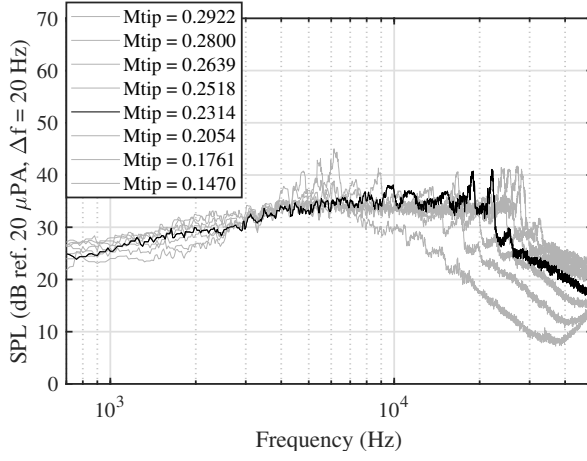
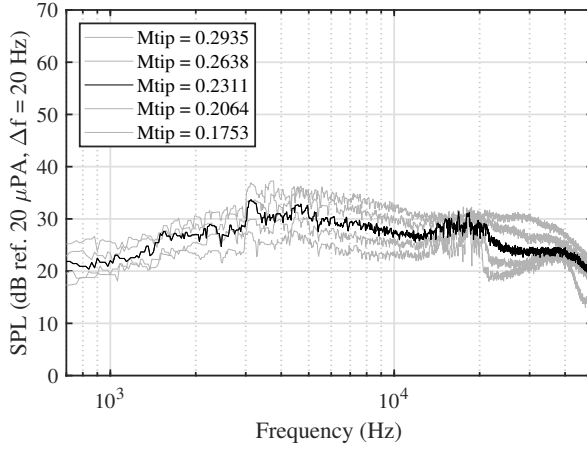
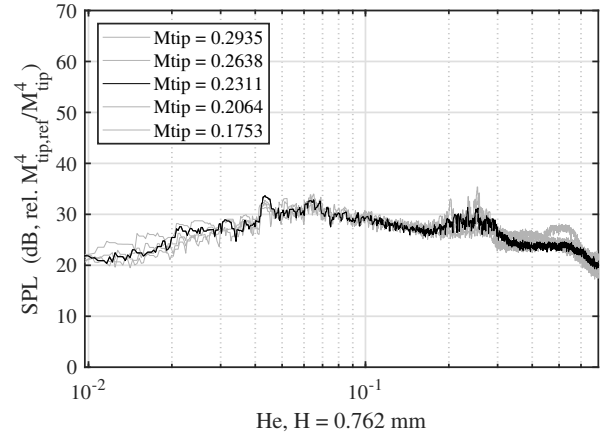


Figure 25. Scaling FormLabs rotors, ( $M_{\text{tip,ref}} = 0.2314$ ).

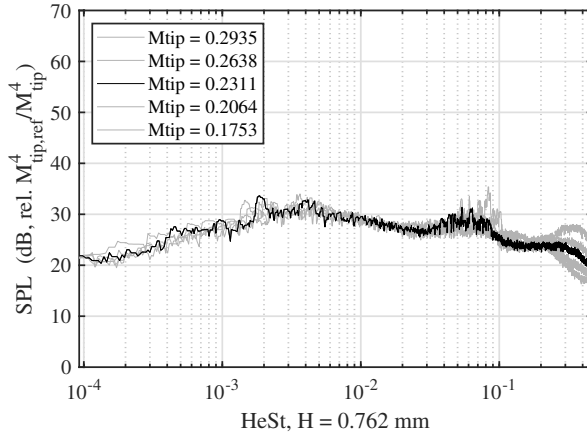




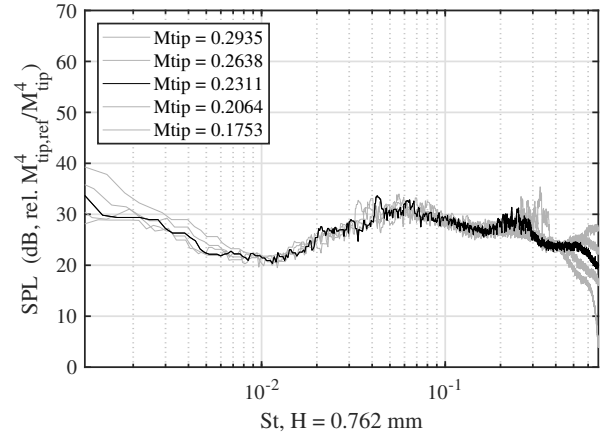
(a) Dimensional



(b)  $n = 4, m = 0$

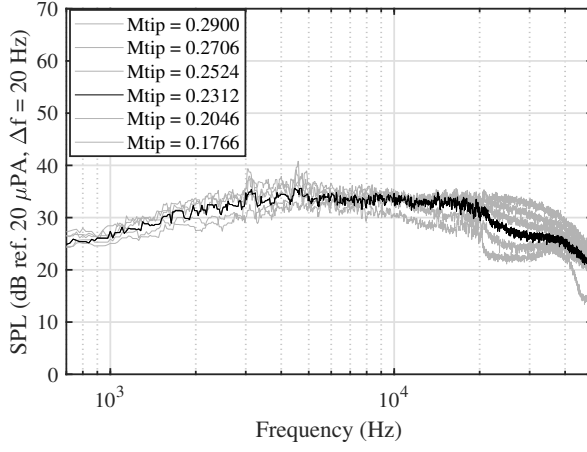


(c)  $n = 4, m = 0.5$

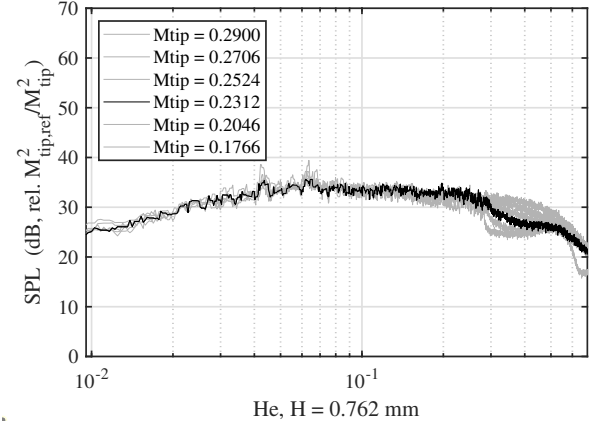


(d)  $n = 4, m = 1$

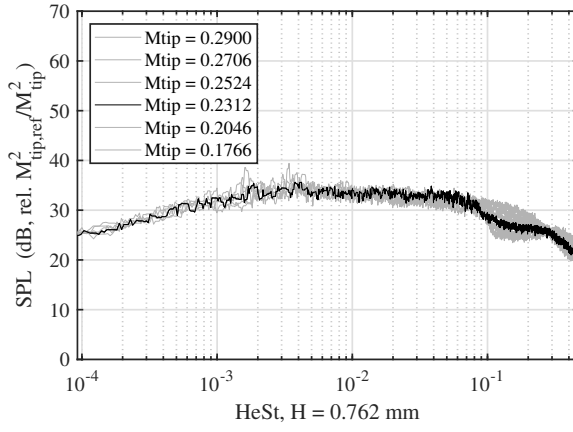
Figure 26. Scaling COTS-tripped rotor ( $M_{\text{tip,ref}} = 0.2311$ ).



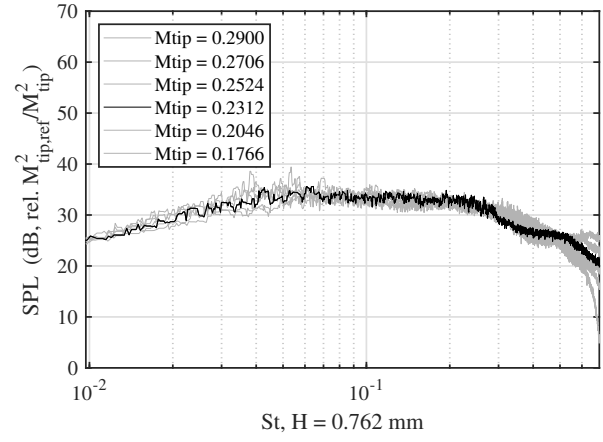
(a) Dimensional



(b)  $n = 2, m = 0$



(c)  $n = 2, m = 0.5$



(d)  $n = 2, m = 1$

Figure 27. Scaling COTS rotor ( $M_{\text{tip,ref}} = 0.2312$ ).

## 7 Conclusions and Future Work

Static performance and acoustic measurements of the COTS rotors and the various optimum hovering rotors were acquired in the SHAC and presented in this report. Through extensive testing of optimum hovering rotors (OPT2) fabricated using different additive manufacturing methods (SLA, FormLabs, and SLS) and COTS rotors with various boundary layer trip configurations, this report provides the research community with valuable acoustic results.

The rotors were tripped by applying either a narrow strip of sand grit or trip dots at the quarter-chord location along the blade span. The performance results demonstrated that boundary layer tripping reduces thrust by 3-11% depending on the rotor type, with the OPT2 rotors showing more sensitivity to tripping than COTS rotors. This performance reduction is accompanied by substantial acoustic benefits, particularly in broadband noise reduction. At the baseline operating conditions ( $M_{\text{tip}} = 0.2300$ ), tripping reduced broadband noise levels by 8.87 dB for the FormLabs OPT2 rotor and 3.87 dB for the COTS rotor for an observer located out of the plane of the rotor. The noise reduction was most dramatic at lower tip speeds and high frequencies, confirming the effectiveness of boundary layer tripping for mitigating laminar boundary layer vortex shedding (LBLVS) noise.

By taking isolated rotor measurements at various tip speeds and applying scaling techniques, it was possible to find a relationship between broadband noise and tip speed. For tripped rotors, where turbulent boundary layer trailing edge (TBLTE) noise dominates, amplitude scaling using Mach number to higher powers ( $n = 4-5.5$ ) effectively collapsed the spectral data, while untripped rotors with significant LBLVS content scaled better with lower powers ( $n = 2$ ). The frequency scaling analyses using Helmholtz number, Strouhal number, and their combination revealed that boundary layer characteristics influence how noise scales with operating conditions.

These findings have important practical implications for UAM vehicle design. The optimum hovering rotor tested in this investigation provides the acoustic community with a valuable experimental dataset for a rotor whose geometry is analytically simpler to model than commercial designs. The proven effectiveness of boundary layer tripping for noise reduction, particularly for the OPT2 rotors, offers a promising path for quieter rotor design.

Future work should focus on developing more sophisticated boundary layer models that can better predict the transition phenomena observed in these experiments, along with investigating more comprehensive scaling parameters that incorporate boundary layer characteristics directly, and testing rotors of different sizes to investigate geometric scaling due to parameters in addition to just tip speed. A comprehensive theoretical investigation into the scaling behavior should be done, as this report adopts a primarily empirical approach. Scaling relationships could result in prediction of full-scale acoustic behavior from subscale test data. Extended testing at higher Reynolds numbers would also help bridge the gap between these small-scale findings and full-scale UAM applications. This study has contributed to the understanding of small rotor aerodynamics and acoustics across various tip speeds.

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## Appendix A

### Hover Operating Conditions

| ID                    | $M_{\text{tip}}$ | $\Omega$ (RPM) | T (N) <sup>A1</sup> | Q (N-m) <sup>A1</sup> | $c_{\infty}$ (m/s) | $\rho_{\infty}$ (kg/m <sup>3</sup> ) |
|-----------------------|------------------|----------------|---------------------|-----------------------|--------------------|--------------------------------------|
| <b>SLA 1%</b>         |                  |                |                     |                       |                    |                                      |
| 123                   | 0.2935           | 5143           | 15.5                | 0.277                 | 349.6              | 1.172                                |
| 124                   | 0.2641           | 4626           | 12.2                | 0.220                 | 349.5              | 1.173                                |
| 125                   | 0.2322           | 4070           | 9.2                 | 0.169                 | 349.6              | 1.172                                |
| 126                   | 0.2052           | 3595           | 7.0                 | 0.130                 | 349.6              | 1.172                                |
| 127                   | 0.1761           | 3086           | 5.0                 | 0.095                 | 349.6              | 1.172                                |
| 128                   | 0.1465           | 2568           | 3.3                 | 0.065                 | 349.6              | 1.172                                |
| <b>SLA 3%</b>         |                  |                |                     |                       |                    |                                      |
| 101                   | 0.2917           | 5096           | 14.6                | 0.284                 | 348.5              | 1.163                                |
| 102                   | 0.2634           | 4601           | 11.6                | 0.229                 | 348.4              | 1.163                                |
| 103                   | 0.2320           | 4053           | 8.7                 | 0.174                 | 348.4              | 1.163                                |
| 104                   | 0.2020           | 3529           | 6.2                 | 0.128                 | 348.5              | 1.162                                |
| 105                   | 0.1767           | 3087           | 4.6                 | 0.096                 | 348.5              | 1.162                                |
| 106                   | 0.1459           | 2549           | 3.0                 | 0.065                 | 348.5              | 1.162                                |
| <b>SLA 3%-tripped</b> |                  |                |                     |                       |                    |                                      |
| 222                   | 0.2900           | 5034           | 13.0                | 0.282                 | 346.3              | 1.188                                |
| 224                   | 0.2634           | 4572           | 10.4                | 0.229                 | 346.3              | 1.188                                |
| 228                   | 0.2313           | 4016           | 8.0                 | 0.173                 | 346.3              | 1.187                                |
| 229                   | 0.2059           | 3574           | 6.2                 | 0.136                 | 346.3              | 1.188                                |
| 230                   | 0.1760           | 3055           | 4.4                 | 0.098                 | 346.3              | 1.188                                |
| 231                   | 0.1463           | 2540           | 3.0                 | 0.067                 | 346.3              | 1.188                                |
| <b>SLS</b>            |                  |                |                     |                       |                    |                                      |
| 178                   | 0.2872           | 5009           | 12.6                | 0.292                 | 348.0              | 1.177                                |
| 180                   | 0.2641           | 4607           | 10.5                | 0.241                 | 348.0              | 1.177                                |
| 184                   | 0.2318           | 4043           | 8.1                 | 0.183                 | 348.0              | 1.177                                |
| 186                   | 0.2049           | 3574           | 6.3                 | 0.140                 | 348.0              | 1.177                                |
| 188                   | 0.1755           | 3062           | 4.7                 | 0.101                 | 348.0              | 1.177                                |
| 190                   | 0.1465           | 2556           | 3.2                 | 0.070                 | 348.0              | 1.177                                |

<sup>A1</sup>Corrected with density

| ID                                        | $M_{\text{tip}}$ | $\Omega$ (RPM) | T (N) <sup>A1</sup> | Q (N-m) <sup>A2</sup> | $c_{\infty}$ (m/s) | $\rho_{\infty}$ (kg/m <sup>3</sup> ) |
|-------------------------------------------|------------------|----------------|---------------------|-----------------------|--------------------|--------------------------------------|
| <b>FormLabs</b>                           |                  |                |                     |                       |                    |                                      |
| 294                                       | 0.2922           | 5086           | 13.2                | 0.240                 | 347.2              | 1.173                                |
| 295                                       | 0.2800           | 4872           | 12.1                | 0.220                 | 347.2              | 1.173                                |
| 296                                       | 0.2639           | 4593           | 10.8                | 0.196                 | 347.2              | 1.173                                |
| 297                                       | 0.2518           | 4383           | 9.6                 | 0.178                 | 347.2              | 1.173                                |
| 299                                       | 0.2314           | 4028           | 8.1                 | 0.150                 | 347.2              | 1.173                                |
| 300                                       | 0.2054           | 3576           | 6.3                 | 0.120                 | 347.3              | 1.173                                |
| 301                                       | 0.1761           | 3066           | 4.5                 | 0.089                 | 347.3              | 1.173                                |
| 302                                       | 0.1470           | 2560           | 3.0                 | 0.062                 | 347.3              | 1.172                                |
| <b>FormLabs-partial trip<sup>A2</sup></b> |                  |                |                     |                       |                    |                                      |
| 411                                       | 0.2941           | 5103           | 11.5                | 0.228                 | 346.1              | 1.185                                |
| 412                                       | 0.2818           | 4890           | 10.6                | 0.208                 | 346.1              | 1.185                                |
| 414                                       | 0.2635           | 4572           | 9.1                 | 0.182                 | 346.2              | 1.184                                |
| 415                                       | 0.2526           | 4383           | 8.2                 | 0.166                 | 346.2              | 1.184                                |
| 417                                       | 0.2319           | 4024           | 7.0                 | 0.140                 | 346.2              | 1.184                                |
| 418                                       | 0.2046           | 3550           | 5.4                 | 0.110                 | 346.2              | 1.184                                |
| 419                                       | 0.1755           | 3045           | 4.1                 | 0.080                 | 346.1              | 1.185                                |
| 420                                       | 0.1464           | 2539           | 2.7                 | 0.055                 | 346.1              | 1.185                                |
| <b>FormLabs-partial trip<sup>A3</sup></b> |                  |                |                     |                       |                    |                                      |
| 360                                       | 0.2920           | 5070           | 11.2                | 0.23                  | 346.4              | 1.185                                |
| 361                                       | 0.2818           | 4893           | 10.4                | 0.214                 | 346.4              | 1.185                                |
| 362                                       | 0.2630           | 4566           | 9.0                 | 0.186                 | 346.4              | 1.185                                |
| 363                                       | 0.2521           | 4378           | 8.2                 | 0.171                 | 346.4              | 1.185                                |
| 365                                       | 0.2316           | 4022           | 6.9                 | 0.142                 | 346.4              | 1.185                                |
| 366                                       | 0.2054           | 3566           | 5.3                 | 0.112                 | 346.4              | 1.185                                |
| 367                                       | 0.1753           | 3045           | 4.0                 | 0.082                 | 346.5              | 1.184                                |
| 368                                       | 0.1468           | 2550           | 2.7                 | 0.058                 | 346.4              | 1.185                                |
| <b>FormLabs-tripped<sup>A4</sup></b>      |                  |                |                     |                       |                    |                                      |
| 306                                       | 0.2935           | 5103           | 11.5                | 0.245                 | 346.9              | 1.180                                |
| 307                                       | 0.2812           | 4890           | 10.5                | 0.224                 | 346.9              | 1.180                                |
| 308                                       | 0.2634           | 4580           | 9.1                 | 0.196                 | 346.9              | 1.180                                |
| 309                                       | 0.2531           | 4400           | 8.3                 | 0.180                 | 346.9              | 1.180                                |
| 312                                       | 0.2317           | 4030           | 7.2                 | 0.150                 | 347.0              | 1.180                                |
| 313                                       | 0.2049           | 3563           | 5.6                 | 0.119                 | 347.0              | 1.179                                |
| 314                                       | 0.1763           | 3067           | 4.2                 | 0.088                 | 347.0              | 1.179                                |
| 315                                       | 0.1463           | 2545           | 2.9                 | 0.061                 | 347.0              | 1.179                                |

<sup>A1</sup>Corrected with density

<sup>A2</sup>Tripped from 50 to 100% span

<sup>A3</sup>Tripped from 60 to 100% span

<sup>A4</sup>Fully tripped from 20 to 100% span

| ID                  | $M_{\text{tip}}$ | $\Omega$ (RPM) | T (N) <sup>A1</sup> | Q (N-m) <sup>A2</sup> | $c_{\infty}$ (m/s) | $\rho_{\infty}$ (kg/m <sup>3</sup> ) |
|---------------------|------------------|----------------|---------------------|-----------------------|--------------------|--------------------------------------|
| <b>COTS</b>         |                  |                |                     |                       |                    |                                      |
| 28                  | 0.2900           | 5021           | 13.9                | 0.263                 | 345.3              | 1.185                                |
| 23                  | 0.2706           | 4683           | 12.1                | 0.229                 | 345.3              | 1.185                                |
| 24                  | 0.2524           | 4369           | 10.4                | 0.199                 | 345.3              | 1.185                                |
| 25                  | 0.2312           | 4002           | 8.8                 | 0.168                 | 345.3              | 1.185                                |
| 26                  | 0.2046           | 3542           | 6.8                 | 0.131                 | 345.3              | 1.185                                |
| 27                  | 0.1766           | 3057           | 5.0                 | 0.098                 | 345.3              | 1.185                                |
| <b>COTS-tripped</b> |                  |                |                     |                       |                    |                                      |
| 82                  | 0.2935           | 5083           | 13.7                | 0.263                 | 345.5              | 1.186                                |
| 83                  | 0.2638           | 4569           | 11.1                | 0.213                 | 345.5              | 1.186                                |
| 86                  | 0.2311           | 4002           | 8.5                 | 0.163                 | 345.5              | 1.186                                |
| 87                  | 0.2064           | 3574           | 6.7                 | 0.13                  | 345.5              | 1.186                                |
| 88                  | 0.1753           | 3036           | 4.9                 | 0.095                 | 345.5              | 1.186                                |

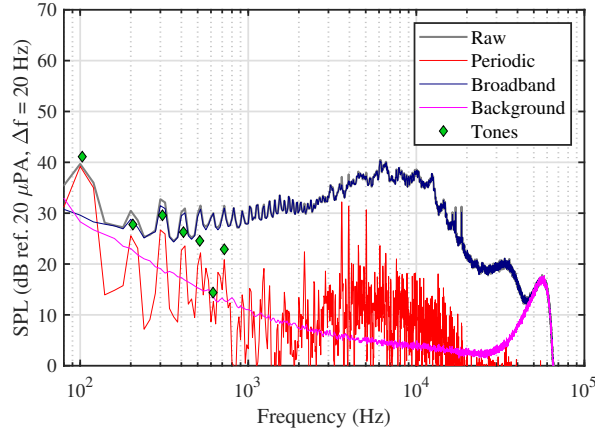
<sup>A1</sup>Corrected with density



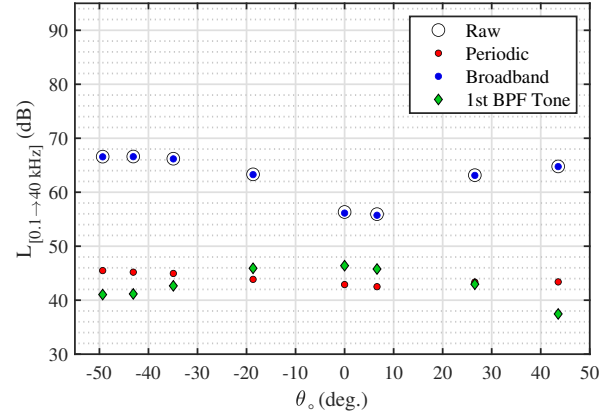
## Appendix B

### Acoustic Broadband and Periodic Noise Results

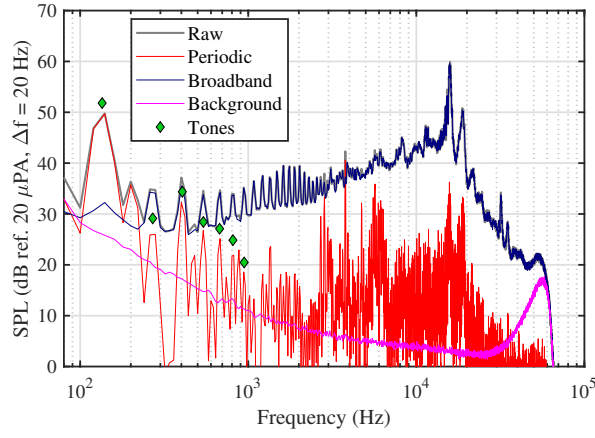
This appendix contains the periodic and broadband acoustics for low, mid, and high tip speed conditions defined in Table 3. Figures B28 through B34 show the spectra and integrated levels for the SLA 3%, SLA 3% - tripped, SLS, FormLabs, FormLabs-tripped, COTS smooth and COTS-tripped cases. Background noise spectra are plotted to illustrate where they affect noise levels. The integrated sound pressure levels (L) are plotted for all observers between frequencies of 100 Hz and 40 kHz and have been corrected to a common radius of 1.9156 m. The spectra have no correction.



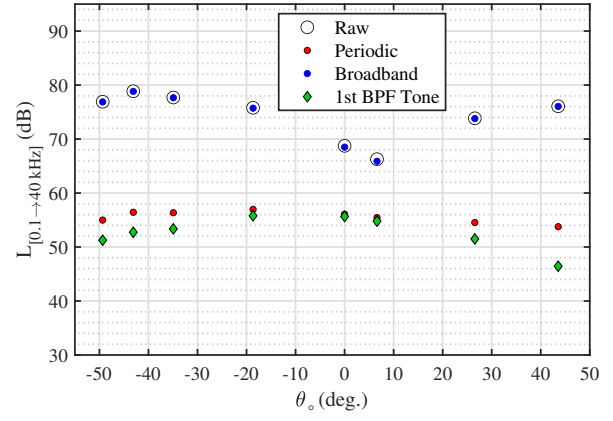
(a)  $M_{\text{tip}} 0.1767$



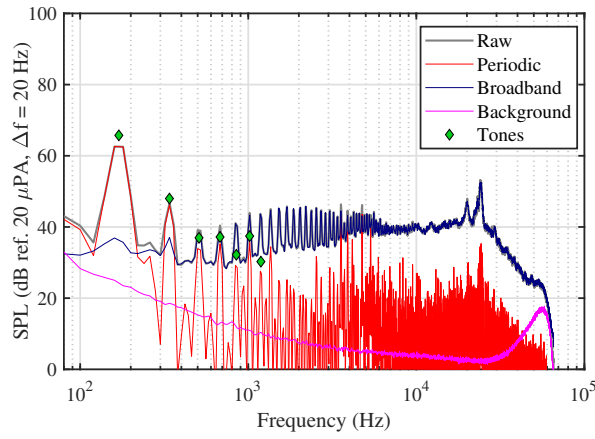
(b)  $M_{\text{tip}} 0.1767$



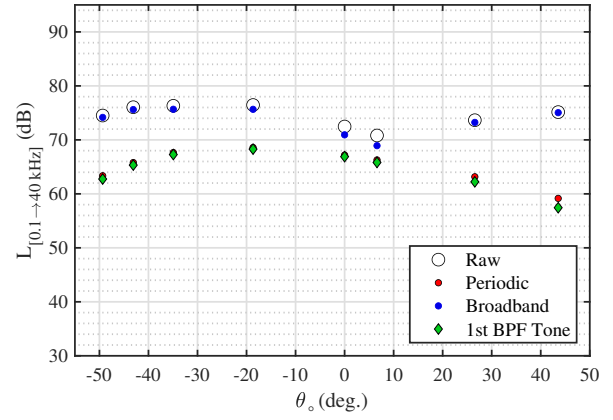
(c)  $M_{\text{tip}} 0.2320$



(d)  $M_{\text{tip}} 0.2320$

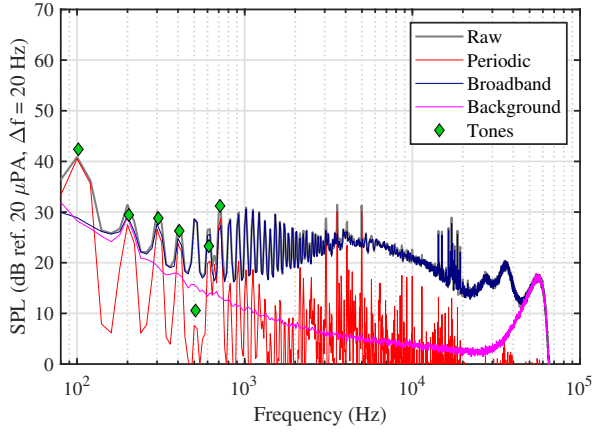


(e)  $M_{\text{tip}} 0.2917$

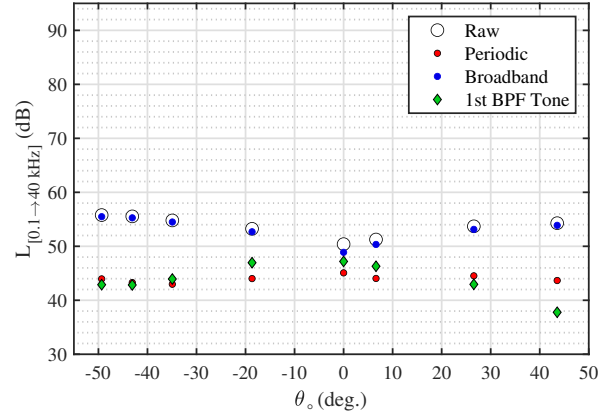


(f)  $M_{\text{tip}} 0.2917$

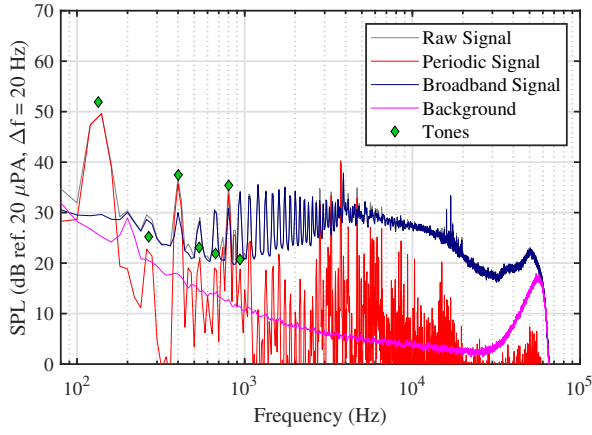
Figure B28. SLA 3% rotor.



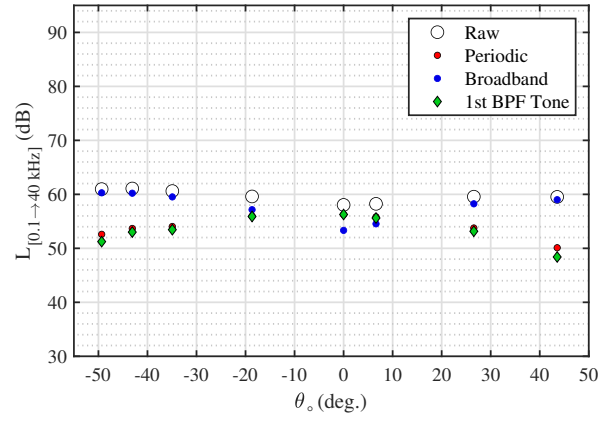
(a)  $M_{\text{tip}} 0.1760$



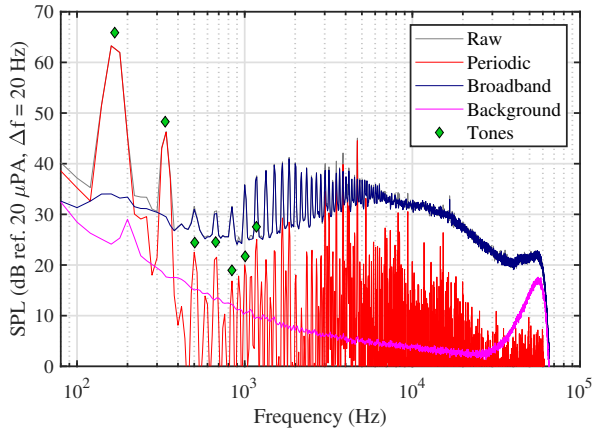
(b)  $M_{\text{tip}} 0.1760$



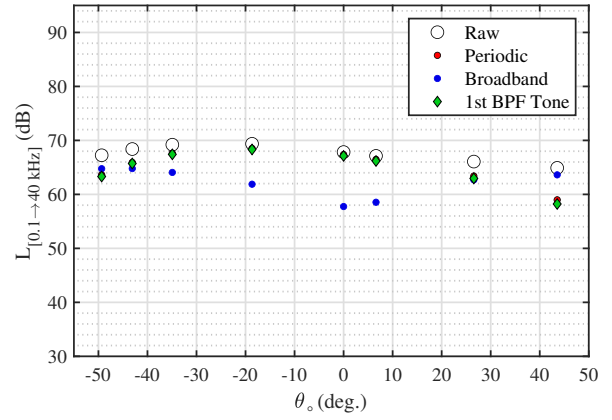
(c)  $M_{\text{tip}} 0.2313$



(d)  $M_{\text{tip}} 0.2313$

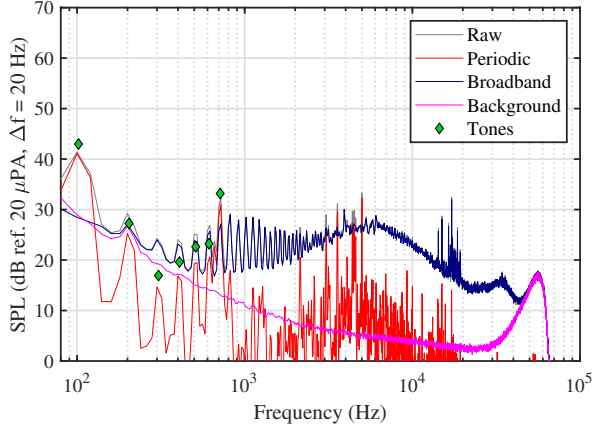


(e)  $M_{\text{tip}} 0.2900$

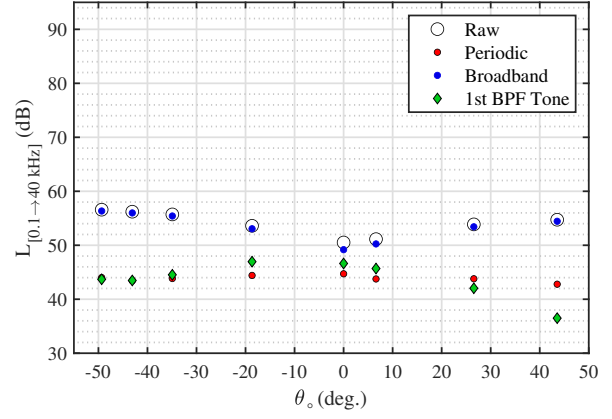


(f)  $M_{\text{tip}} 0.2900$

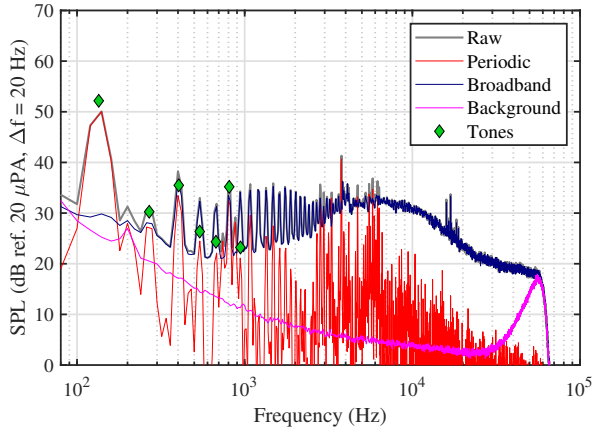
Figure B29. SLA 3% - tripped rotor.



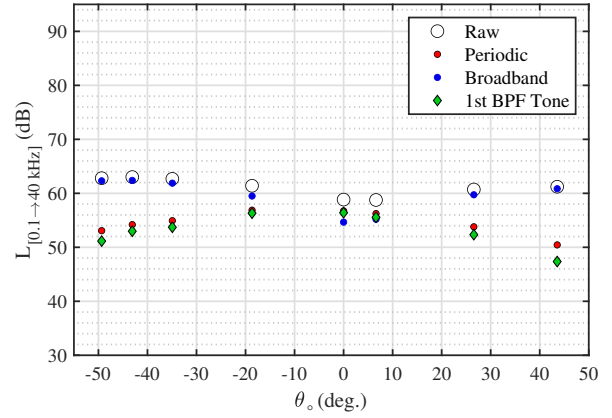
(a)  $M_{\text{tip}} 0.1755$



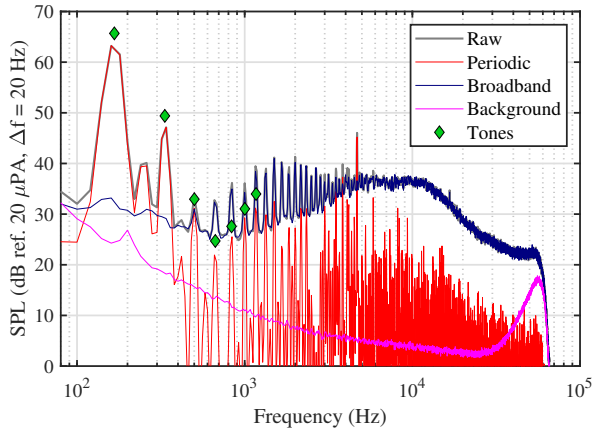
(b)  $M_{\text{tip}} 0.1755$



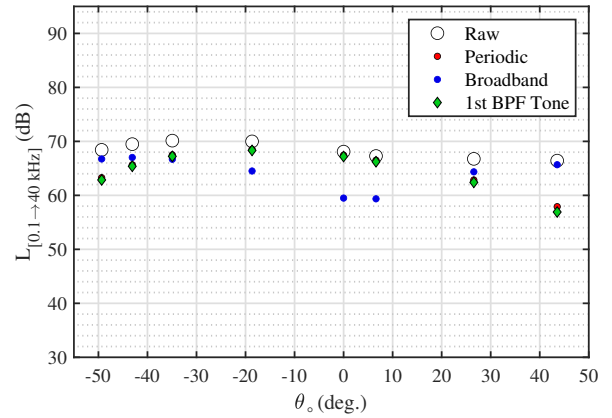
(c)  $M_{\text{tip}} 0.2318$



(d)  $M_{\text{tip}} 0.2318$

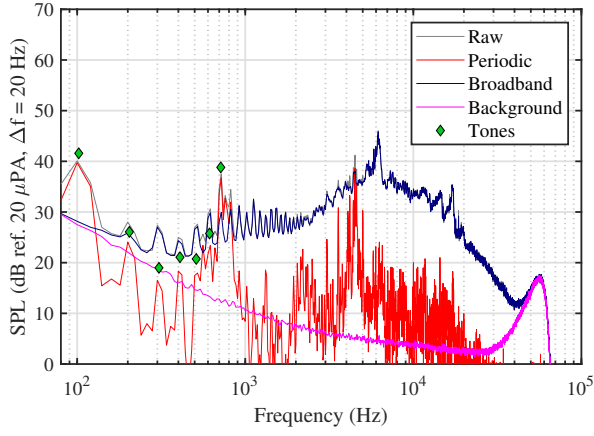


(e)  $M_{\text{tip}} 0.2872$

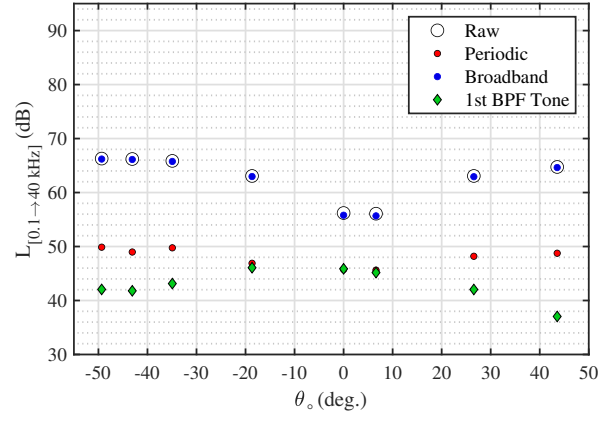


(f)  $M_{\text{tip}} 0.2872$

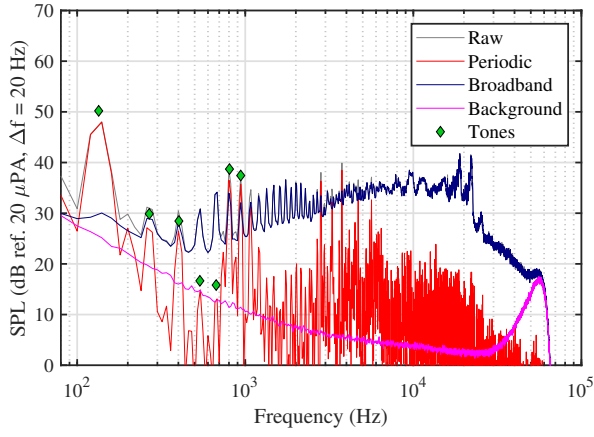
Figure B30. SLS rotor.



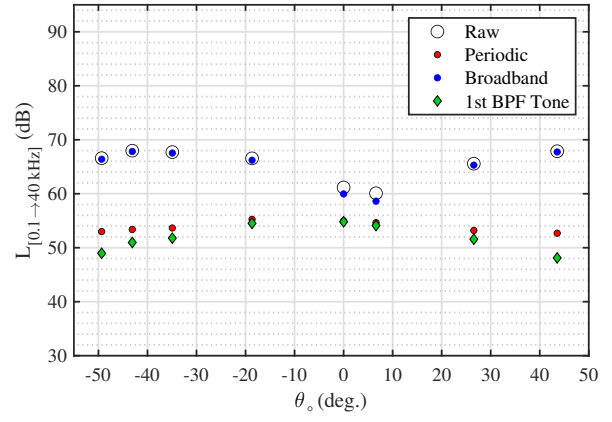
(a)  $M_{\text{tip}} 0.1761$



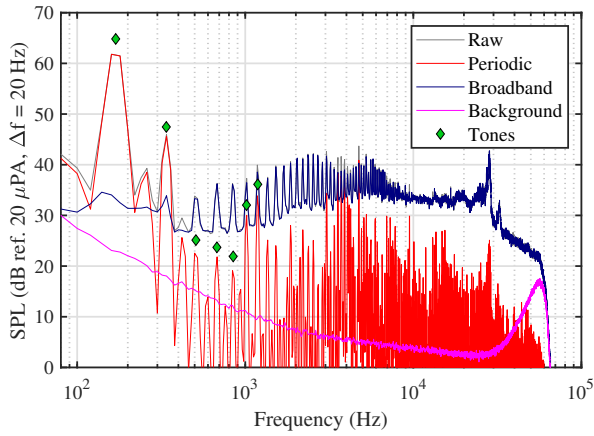
(b)  $M_{\text{tip}} 0.1761$



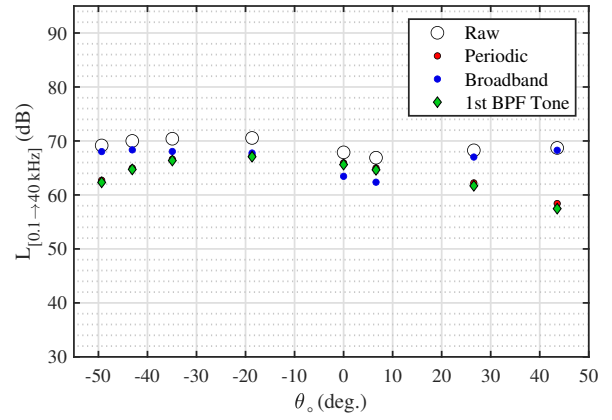
(c)  $M_{\text{tip}} 0.2314$



(d)  $M_{\text{tip}} 0.2314$

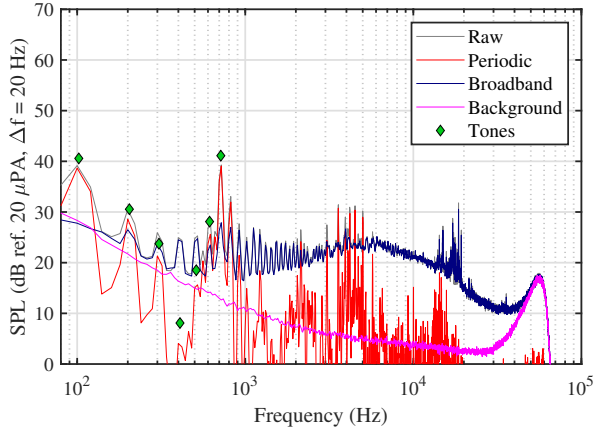


(e)  $M_{\text{tip}} 0.2922$

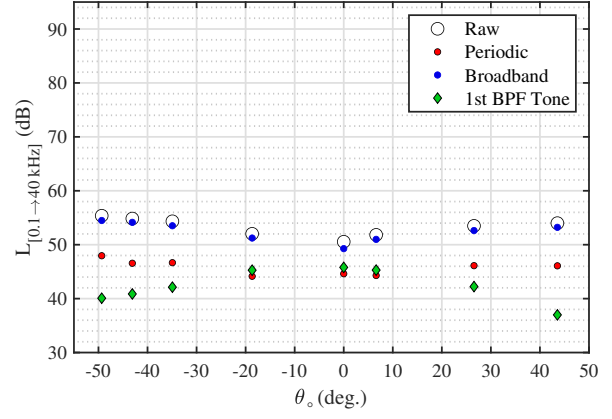


(f)  $M_{\text{tip}} 0.2922$

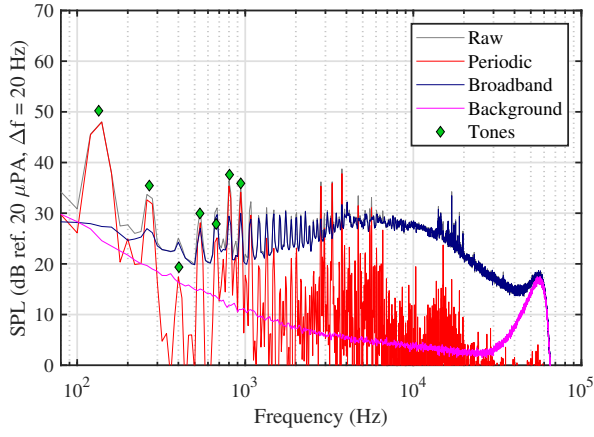
Figure B31. FormLabs rotor.



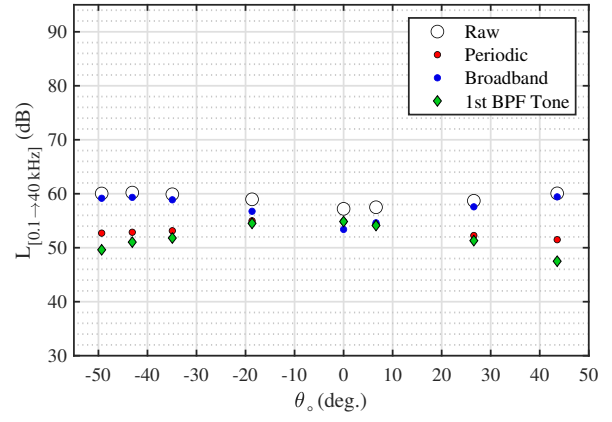
(a)  $M_{\text{tip}} 0.1763$



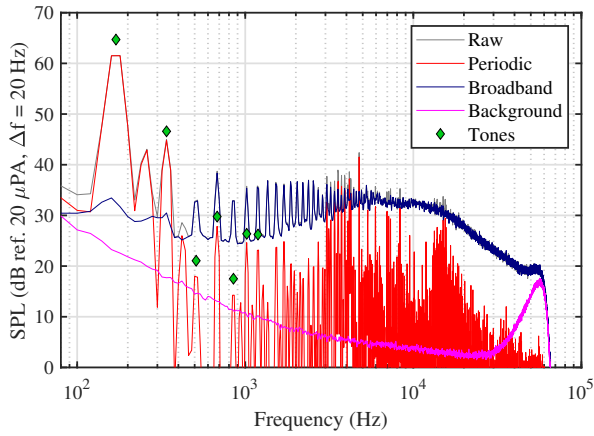
(b)  $M_{\text{tip}} 0.1763$



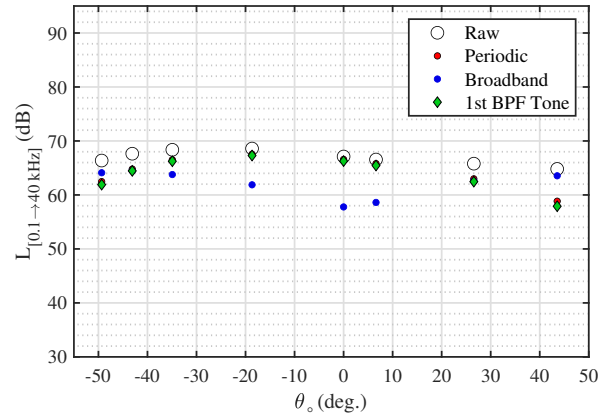
(c)  $M_{\text{tip}} 0.2317$



(d)  $M_{\text{tip}} 0.2317$

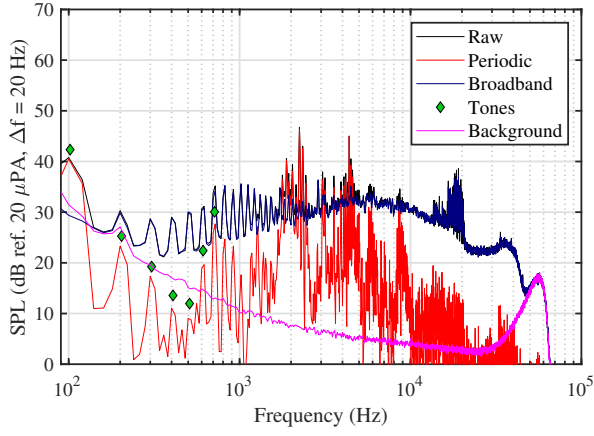


(e)  $M_{\text{tip}} 0.2935$

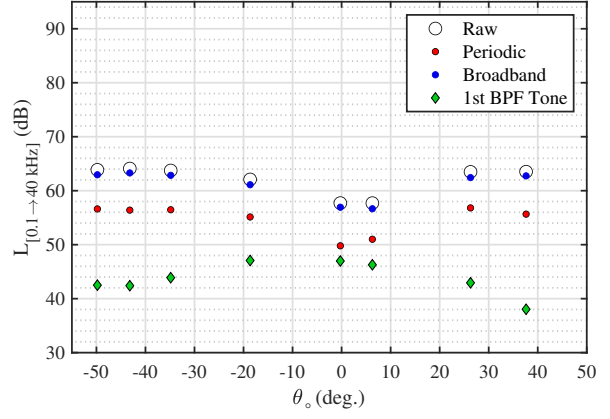


(f)  $M_{\text{tip}} 0.2935$

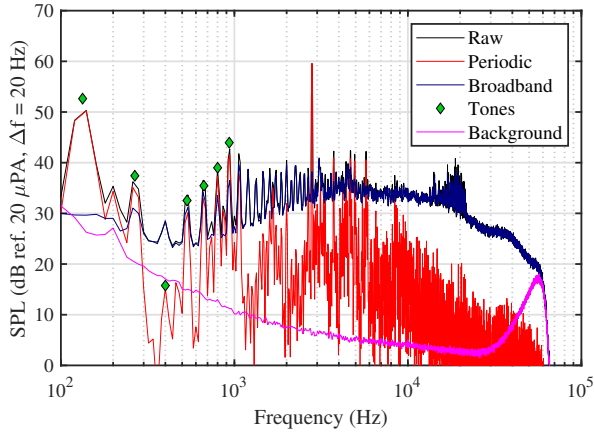
Figure B32. FormLabs-tripped rotor.



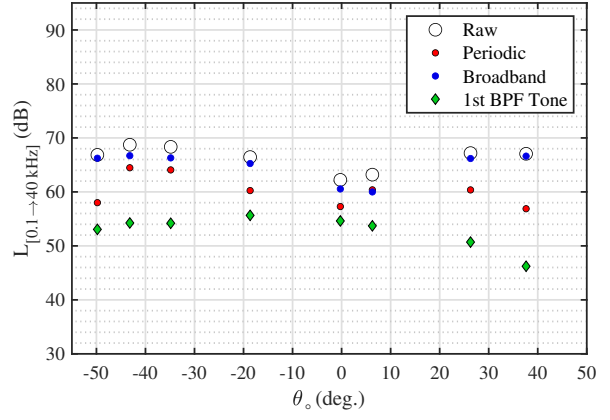
(a)  $M_{\text{tip}} 0.1766$



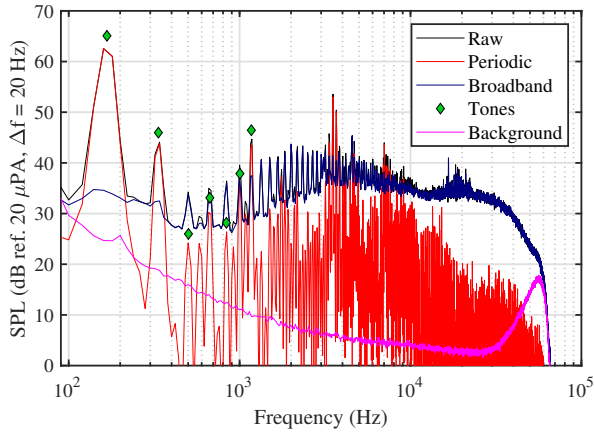
(b)  $M_{\text{tip}} 0.1766$



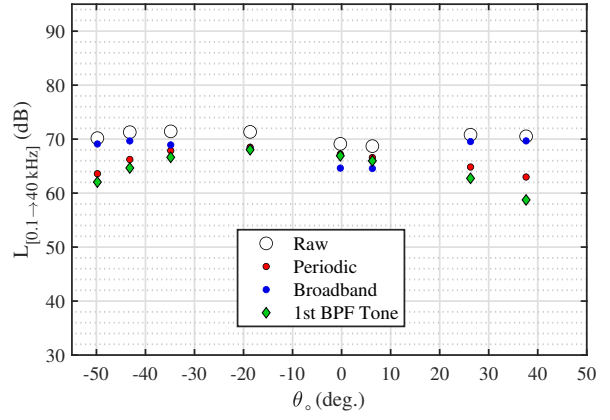
(c)  $M_{\text{tip}} 0.2312$



(d)  $M_{\text{tip}} 0.2312$

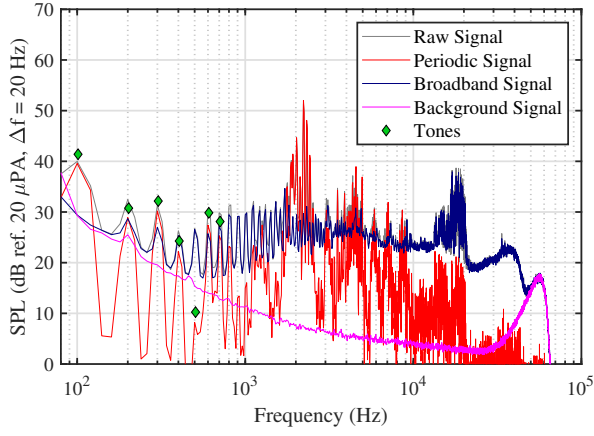


(e)  $M_{\text{tip}} 0.2900$

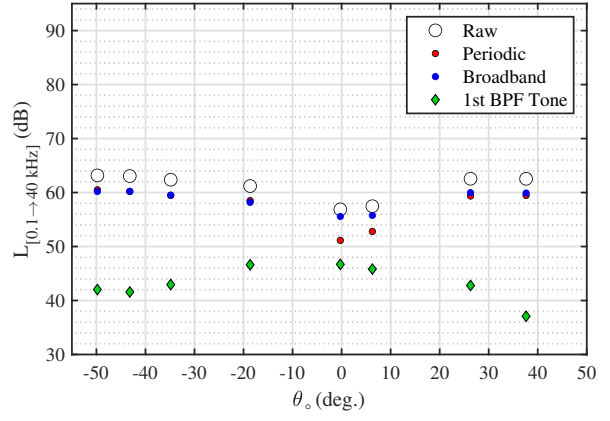


(f)  $M_{\text{tip}} 0.2900$

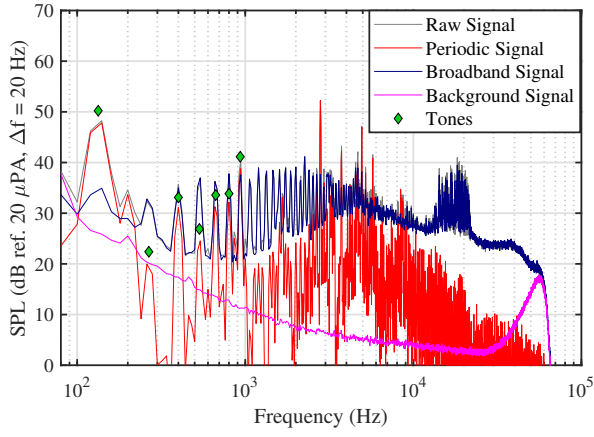
Figure B33. COTS rotor.



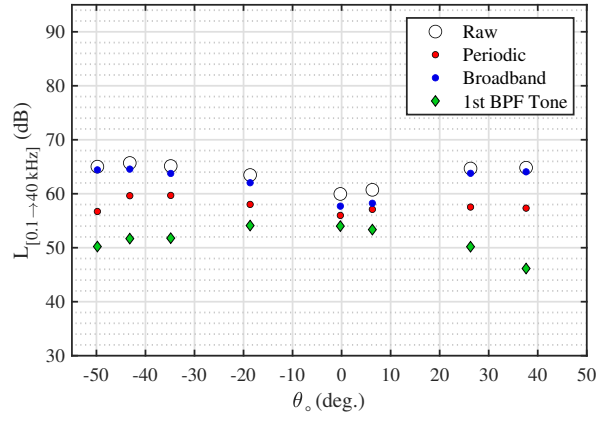
(a)  $M_{\text{tip}} 0.1753$



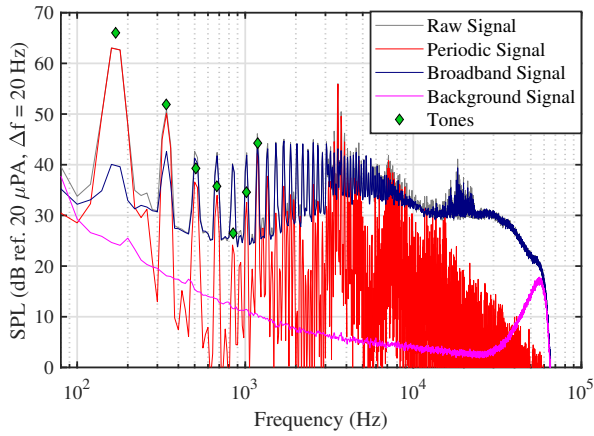
(b)  $M_{\text{tip}} 0.1753$



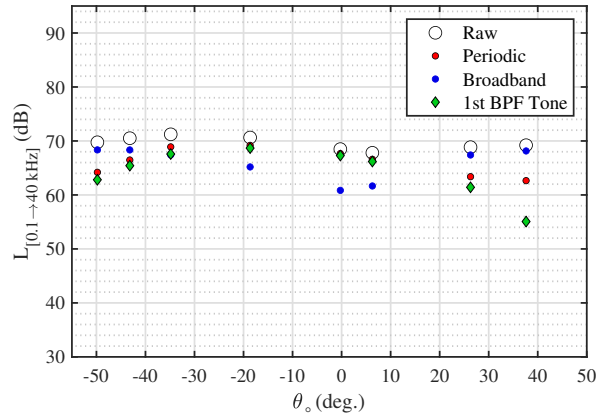
(c)  $M_{\text{tip}} 0.2311$



(d)  $M_{\text{tip}} 0.2311$



(e)  $M_{\text{tip}} 0.2935$



(f)  $M_{\text{tip}} 0.2935$

Figure B34. COTS-tripped rotor.



## Appendix C

### Illustrations of BPF Method Scaling

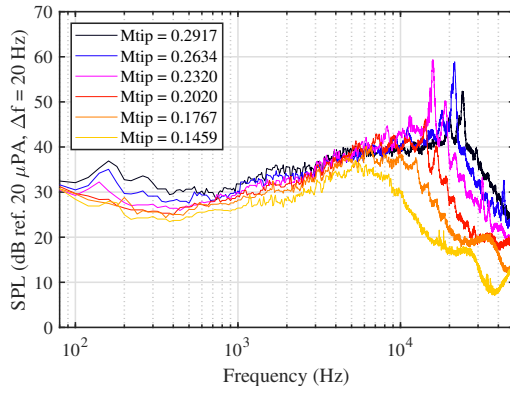
This approach uses a simple blade passage frequency (BPF) based approach. This method does not require using a length scale. Frequency is nondimensionalized by dividing out the blade passage frequency, and multiplied by tip speed to a power of  $m$ :

$$f^* = \frac{f}{\text{BPF}} M_{\text{tip}}^m, \quad (\text{C8})$$

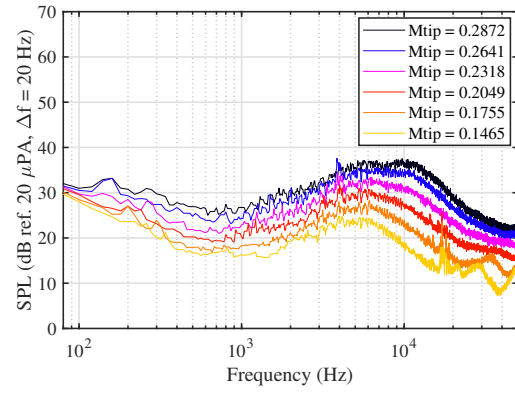
where  $M_{\text{tip}}^m$  is the tip speed of the rotor raised to a power  $m$  and the BPF is defined as:

$$\text{BPF} = \frac{\Omega N_b}{60}. \quad (\text{C9})$$

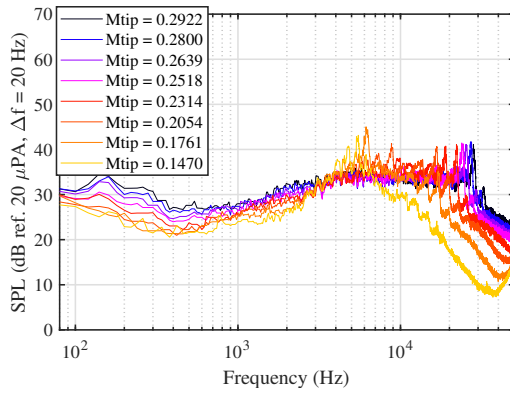
where  $\Omega$  is the rotation rate in RPM and  $N_b$  is the number of blades. This is more simplified than a Strouhal scaling approach. In addition to relating the frequency to the BPF, a tip speed factor  $M_{\text{tip}}^m$  is included. This tip speed factor makes it possible to explore variations of the exponent  $m$ .



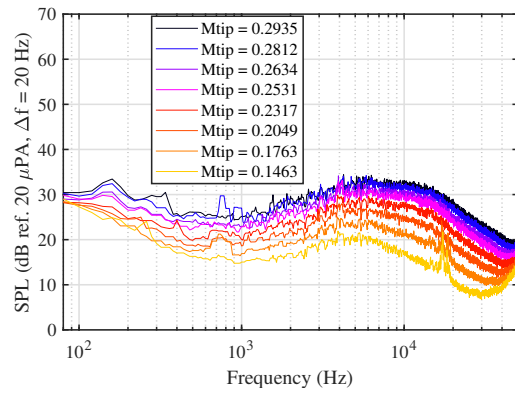
(a) SLA 3% Smooth



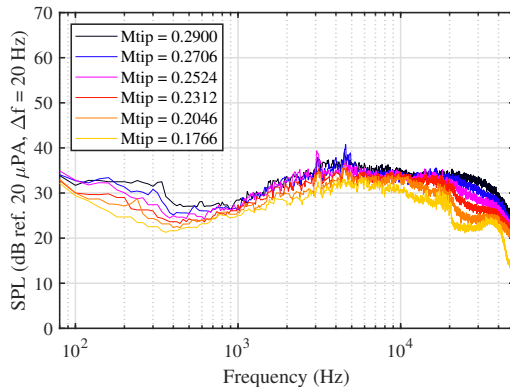
(b) SLS



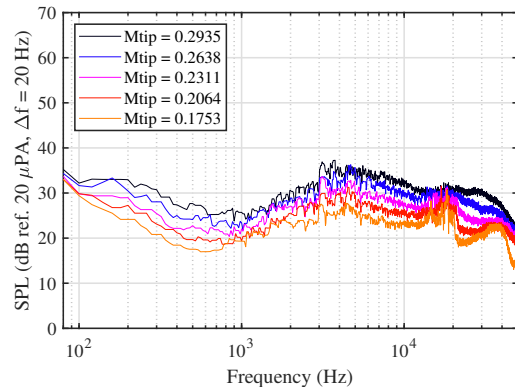
(c) FormLabs Smooth



(d) FormLabs-tripped

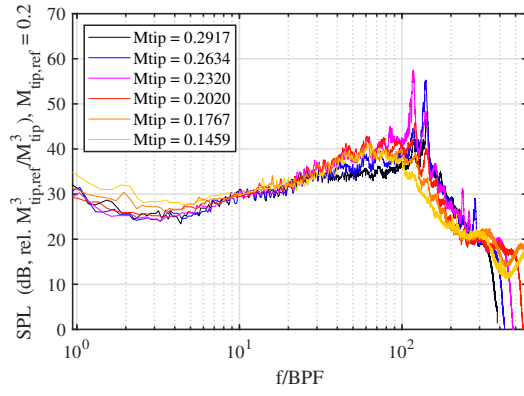


(e) COTS

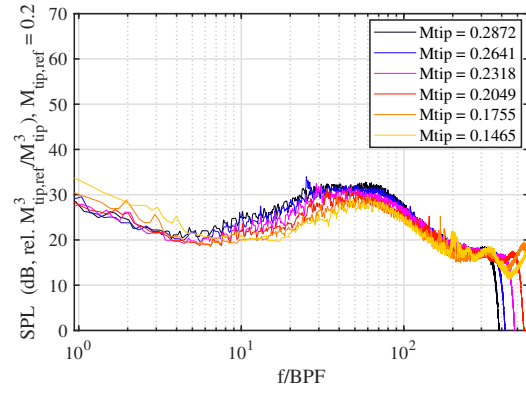


(f) COTS-tripped

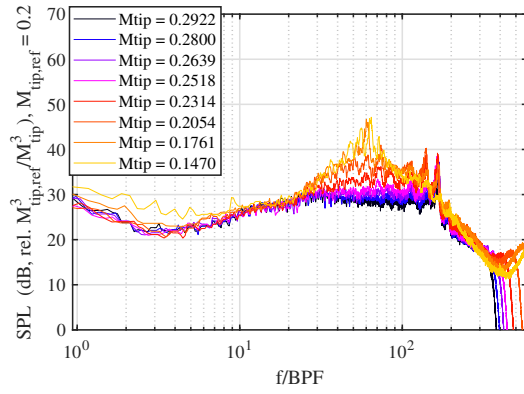
Figure C35. Broadband noise data baseline.



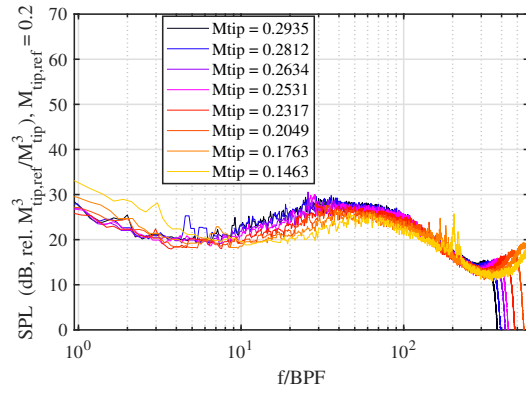
(a) SLA 3%



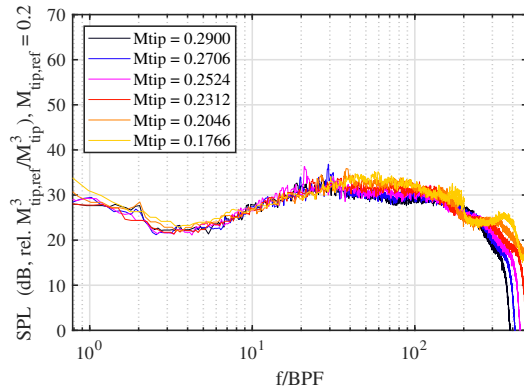
(b) SLS



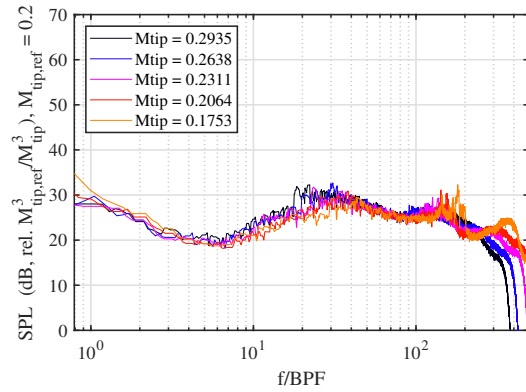
(c) FormLabs



(d) FormLabs-tripped

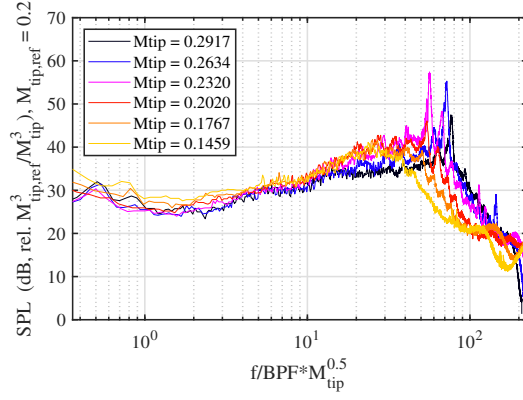


(e) COTS

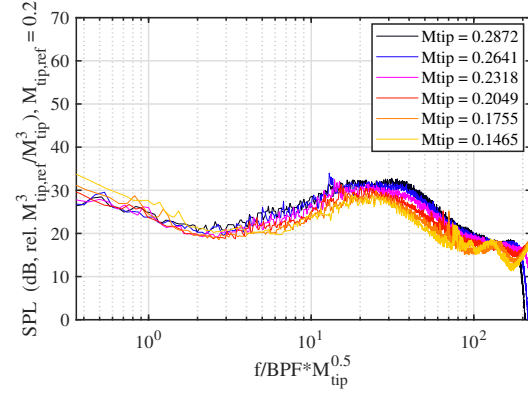


(f) COTS-tripped

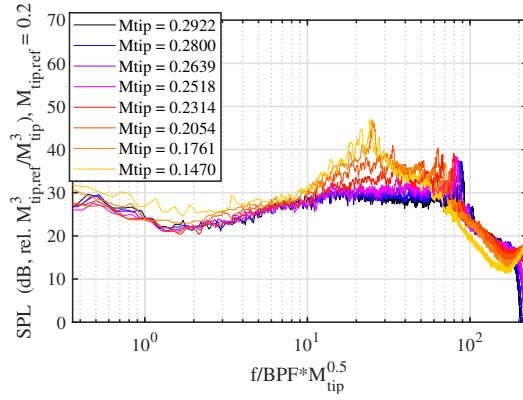
Figure C36. Scaling:  $m = 0$ ,  $n = 3$



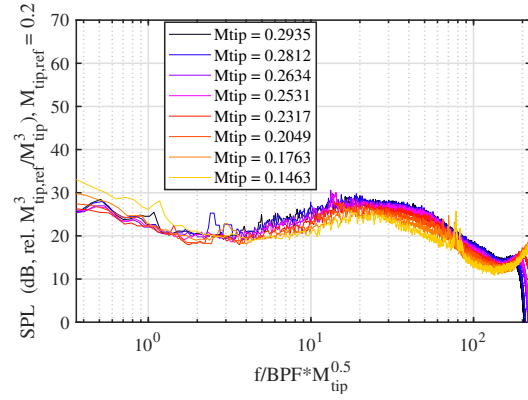
(a) SLA 3%



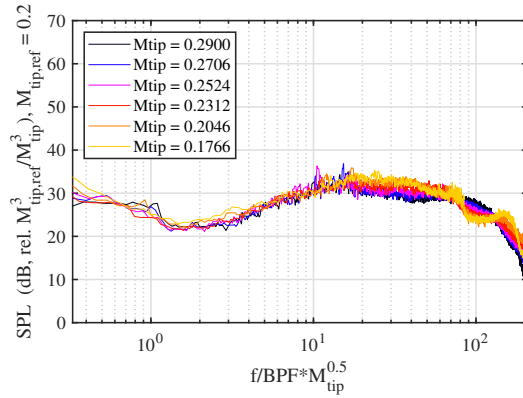
(b) SLS



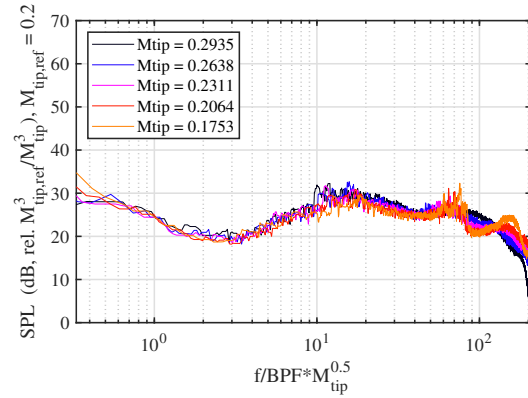
(c) FormLabs



(d) FormLabs-tripped

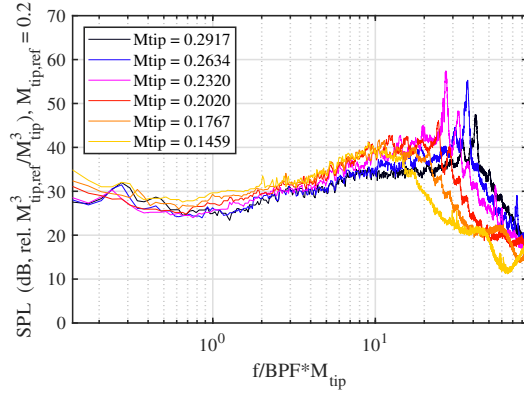


(e) COTS

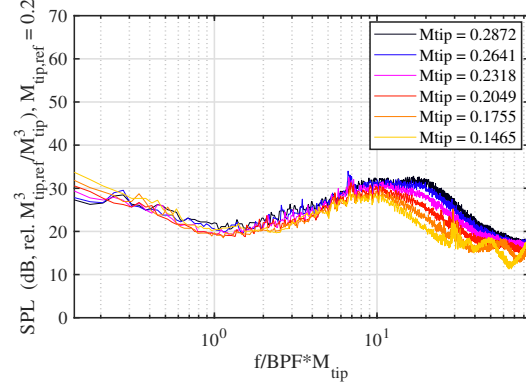


(f) COTS-tripped

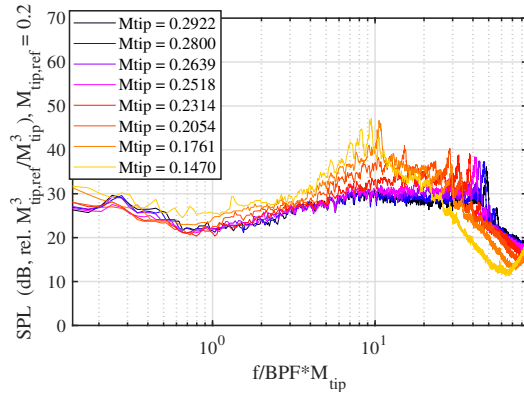
Figure C37. Scaling:  $m = 0.5$ ,  $n = 3$



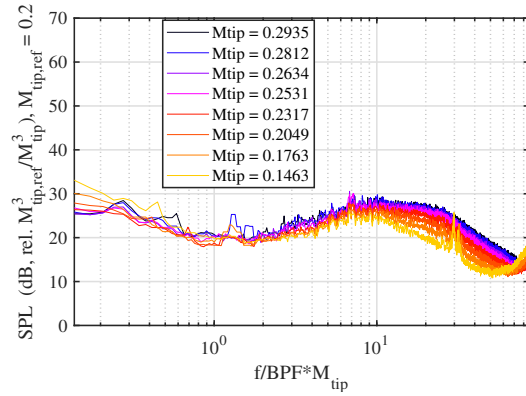
(a) SLA 3%



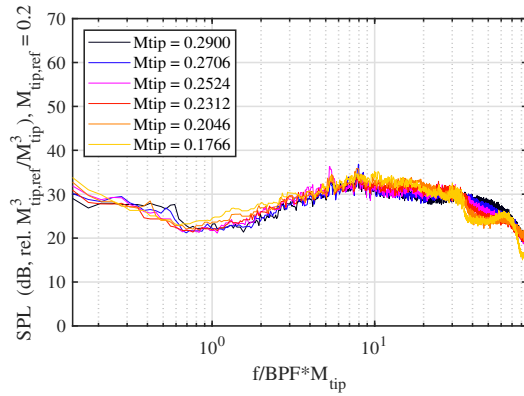
(b) SLS



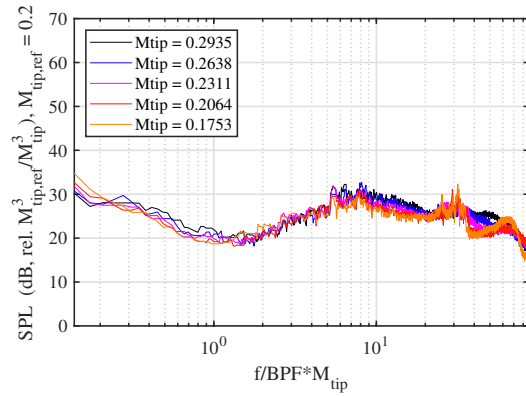
(c) FormLabs



(d) FormLabs-Tripped

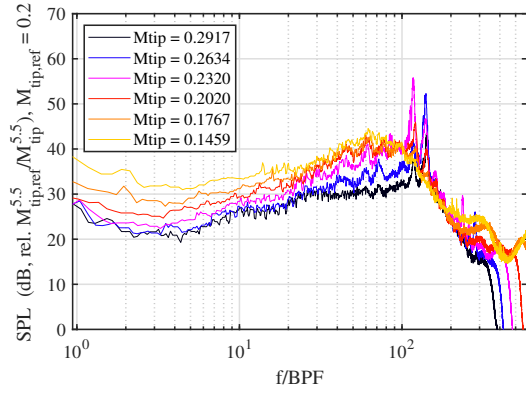


(e) COTS

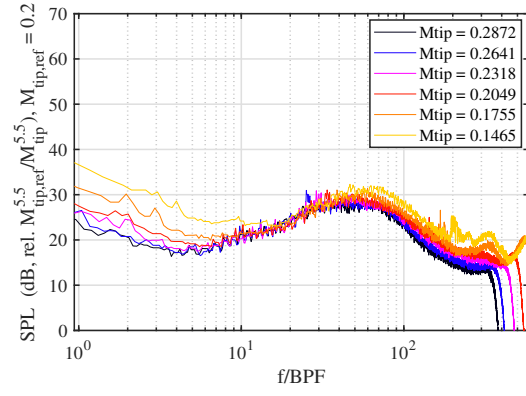


(f) COTS-Tripped

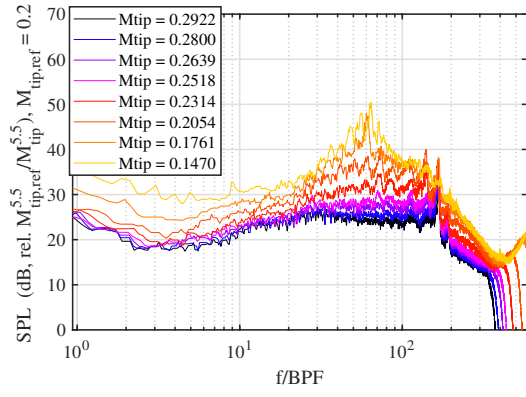
Figure C38. Scaling:  $m = 1$ ,  $n = 3$



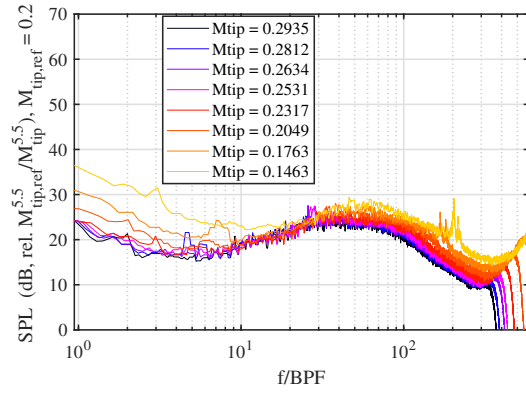
(a) SLA 3%



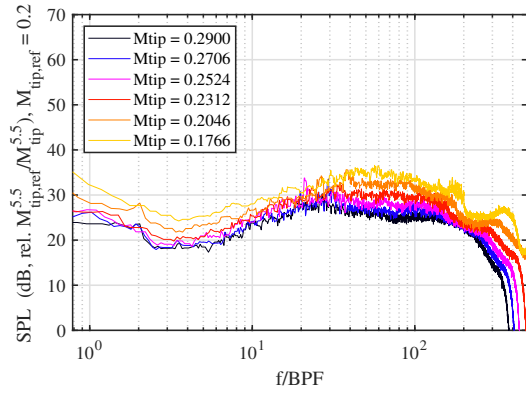
(b) SLS



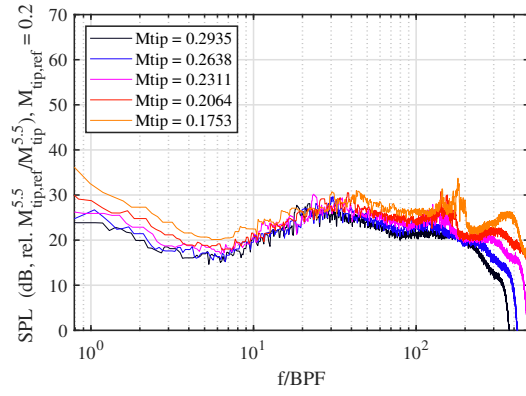
(c) FormLabs



(d) FormLabs-tripped

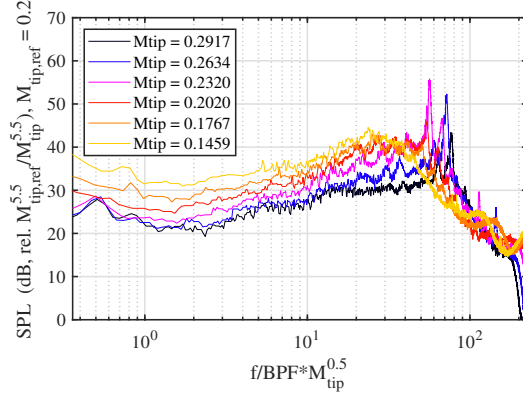


(e) COTS

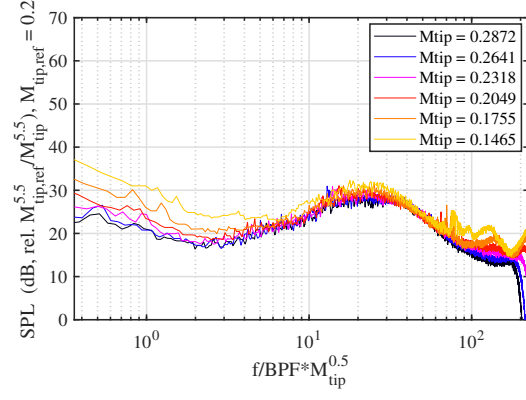


(f) COTS-tripped

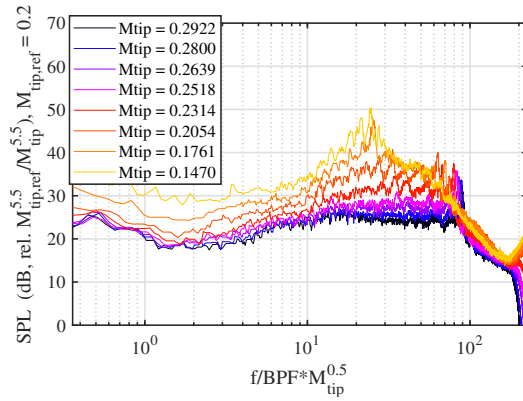
Figure C39. Scaling:  $m = 0$ ,  $n = 5.5$ .



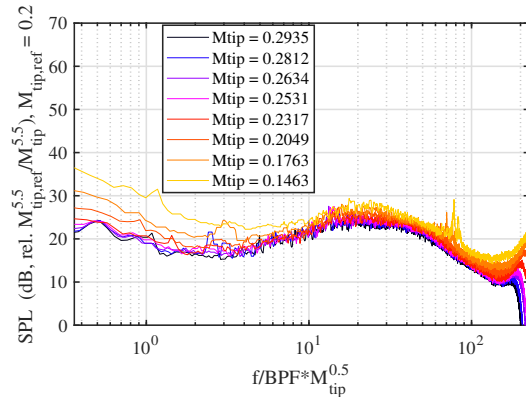
(a) SLA 3%



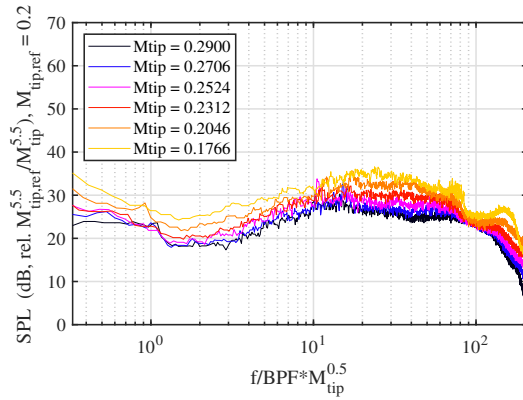
(b) SLS



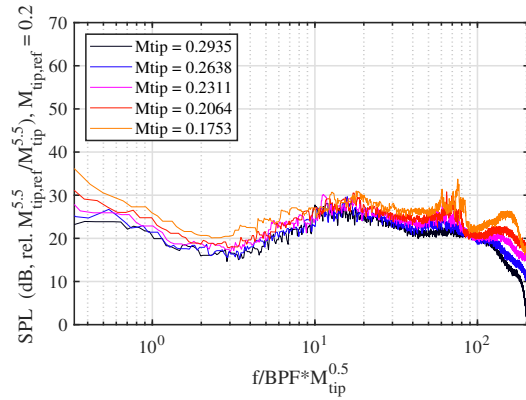
(c) FormLabs



(d) FormLabs-tripped

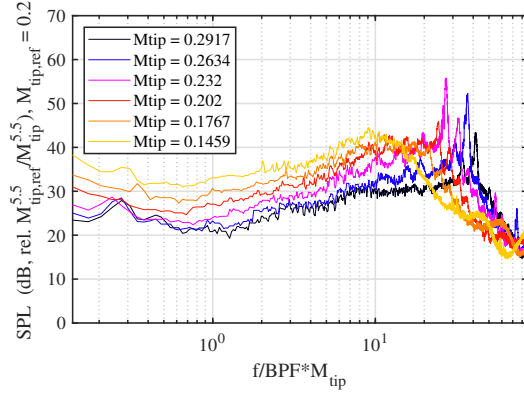


(e) COTS

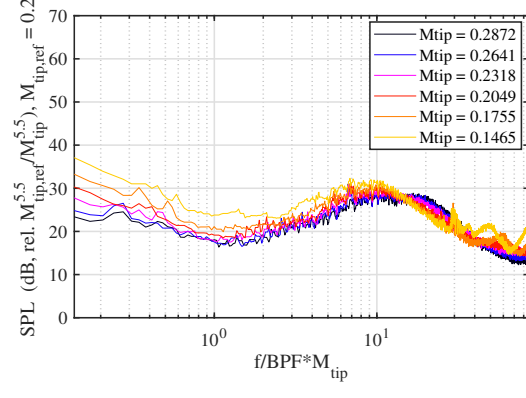


(f) COTS-tripped

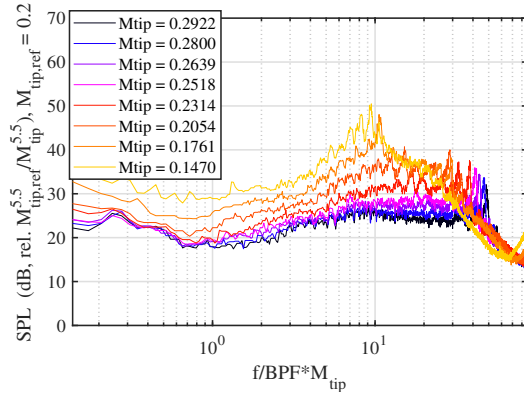
Figure C40. Scaling:  $m = 0.5$ ,  $n = 5.5$ .



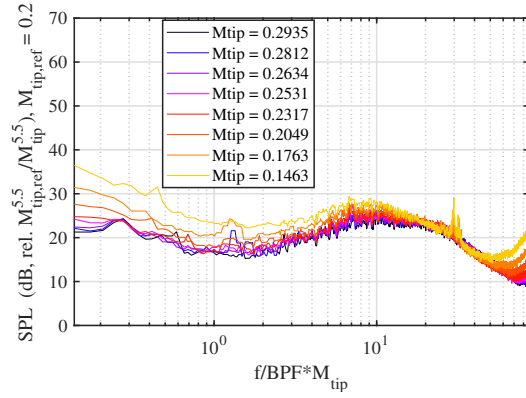
(a) SLA 3%



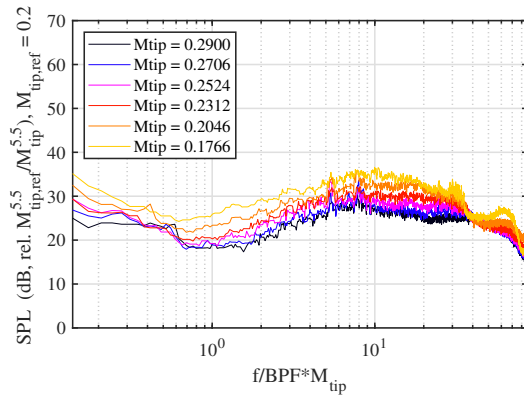
(b) SLS



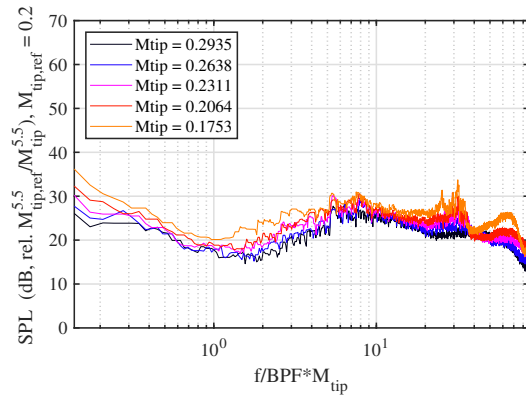
(c) FormLabs



(d) FormLabs-tripped



(e) COTS



(f) COTS Tripped

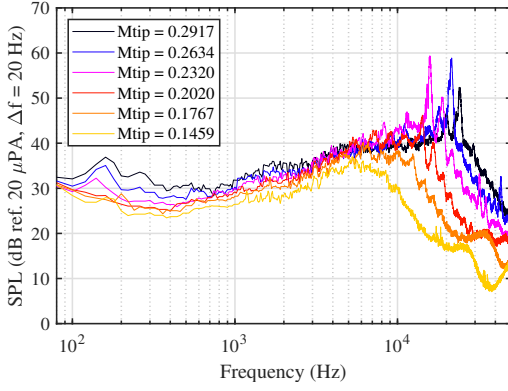
Figure C41. Scaling:  $m = 1$ ,  $n = 5.5$ .



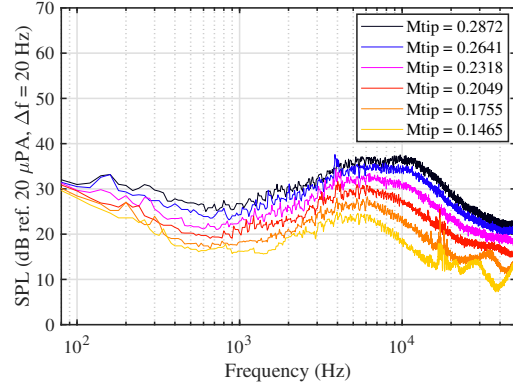
## Appendix D

### Illustrations of Method 1 Scaling

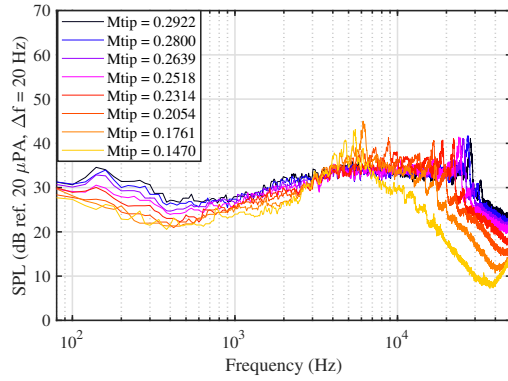
This appendix highlights the primary method described in Section 6. These figures use bluntness,  $H$ , as a length scale.



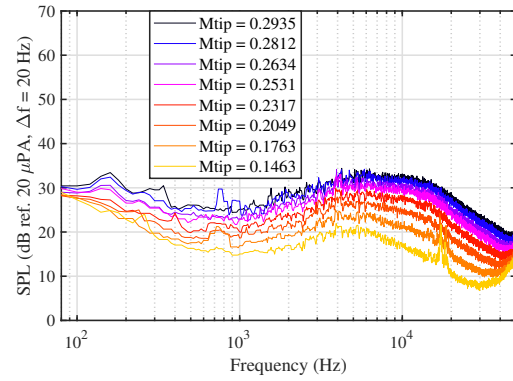
(a) SLA 3%



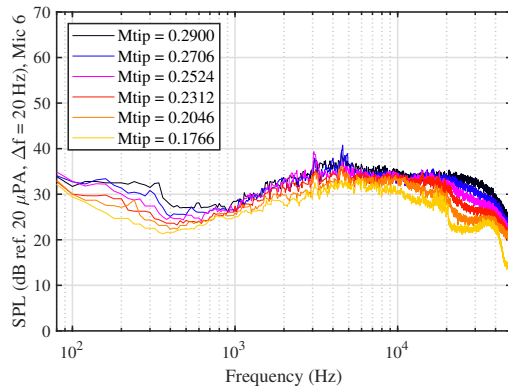
(b) SLS



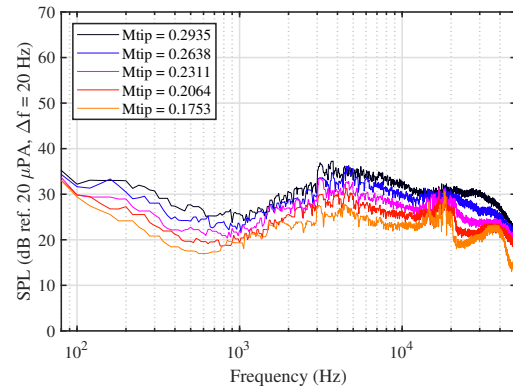
(c) FormLabs



(d) FormLabs-tripped

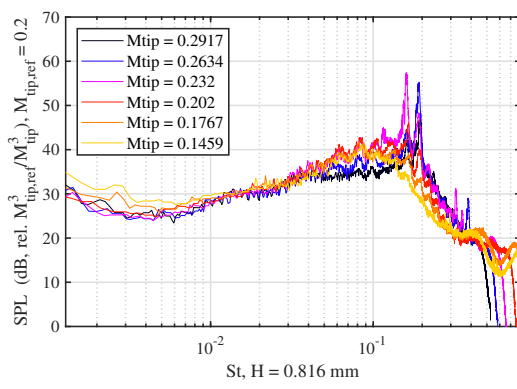


(e) COTS

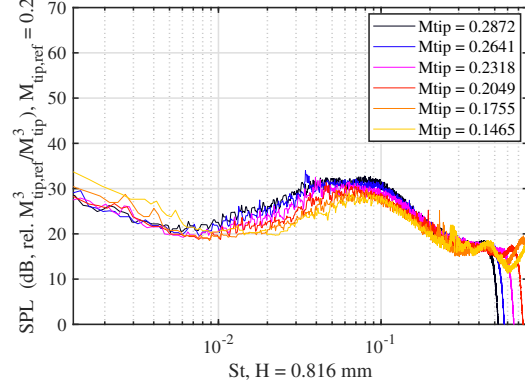


(f) COTS-tripped

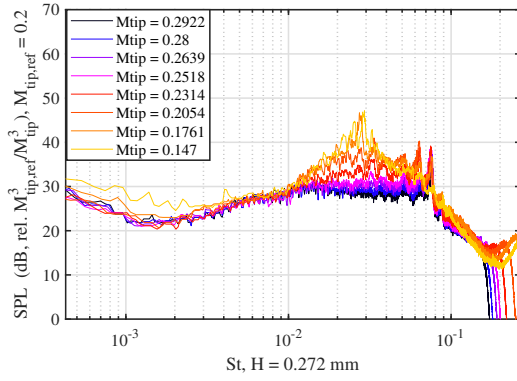
Figure D42. Broadband noise dimensional measurements.



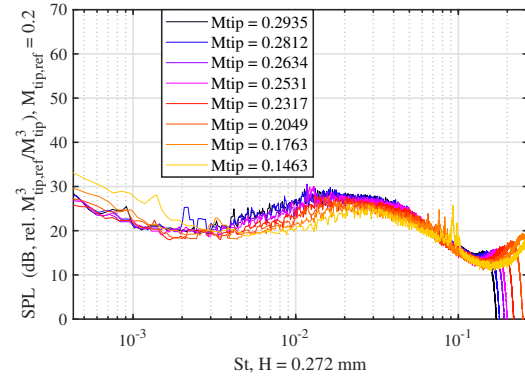
(a) SLA 3%



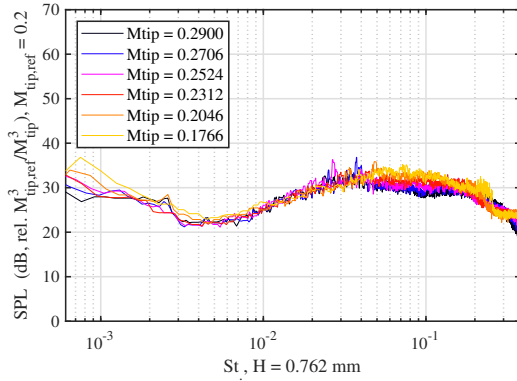
(b) SLS



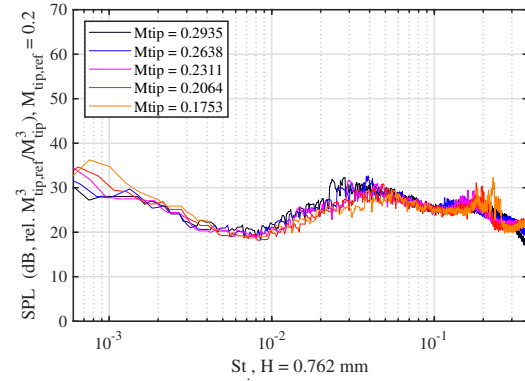
(c) FormLabs



(d) FormLabs-tripped

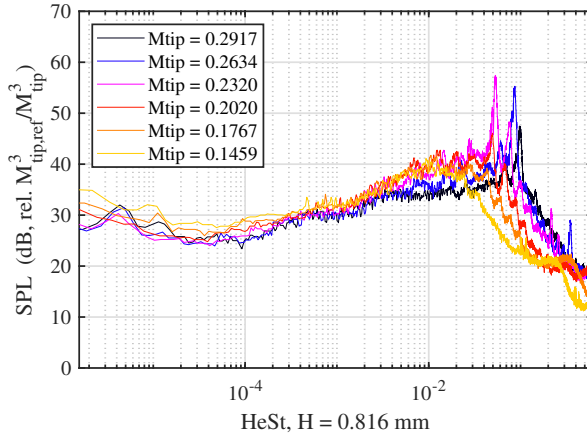


(e) COTS

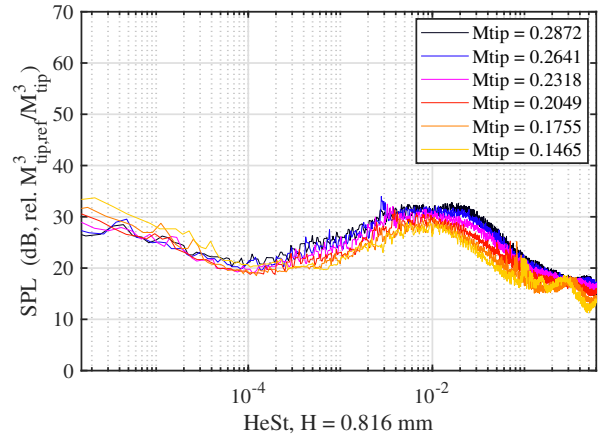


(f) COTS-tripped

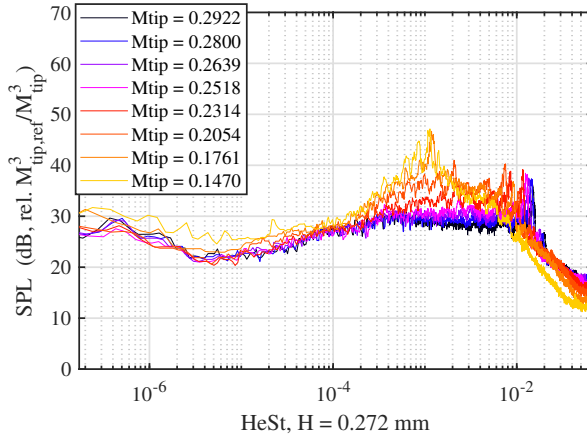
Figure D43. Scaling: Strouhal,  $n = 3$ .



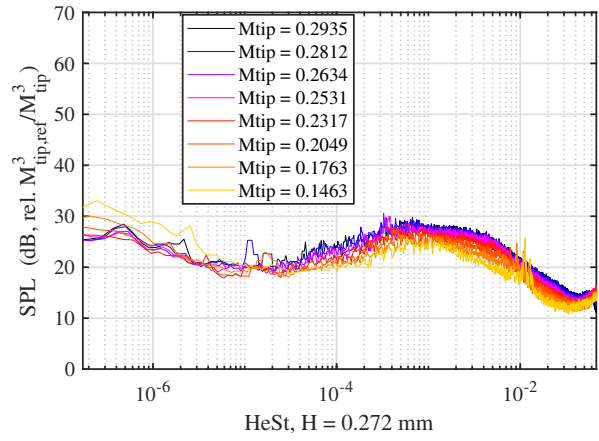
(a) SLA 3%



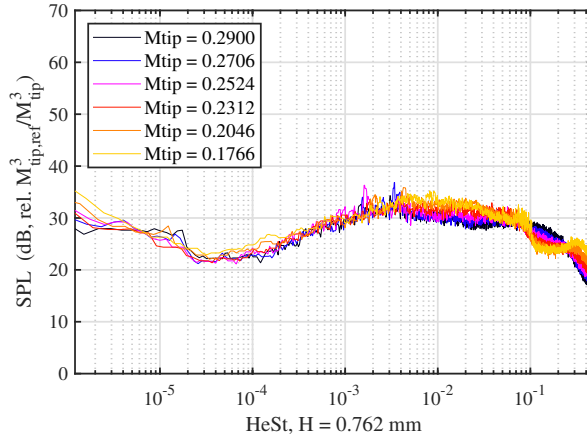
(b) SLS



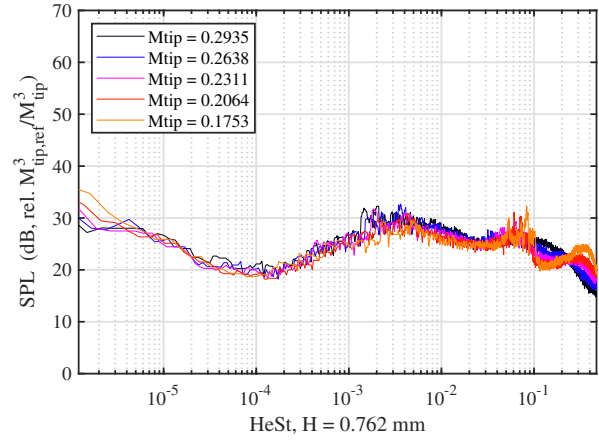
(c) FormLabs



(d) FormLabs-tripped

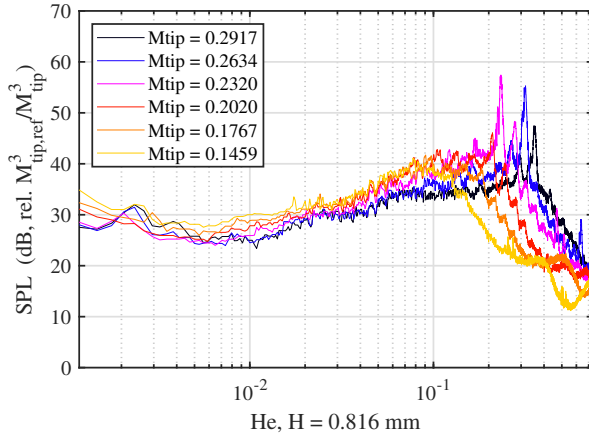


(e) COTS

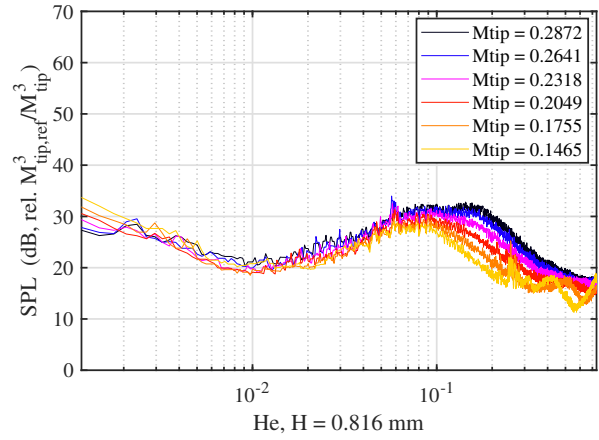


(f) COTS-tripped

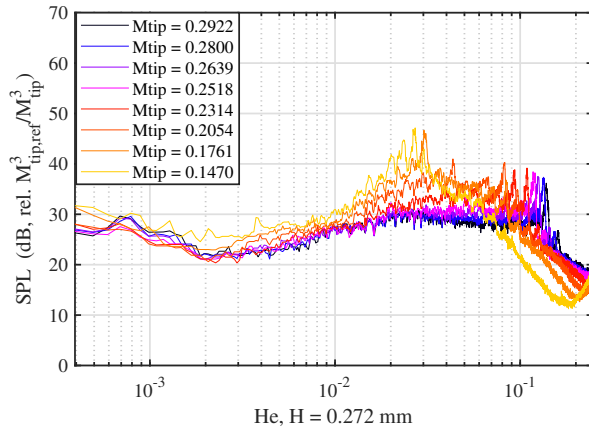
Figure D44. Scaling: Helmholtz Strouhal,  $n = 3$ ,  $M_{tip,ref} = 0.2$ .



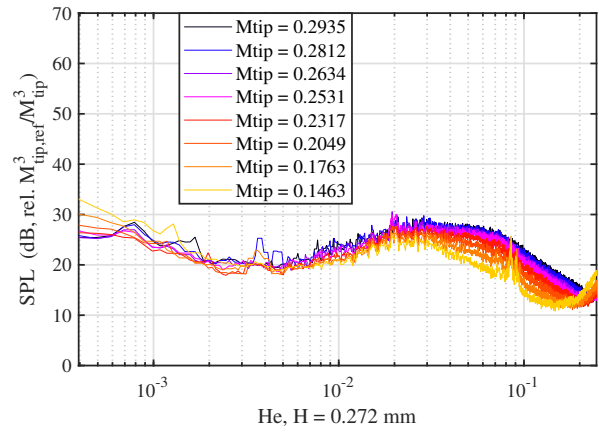
(a) SLA 3%



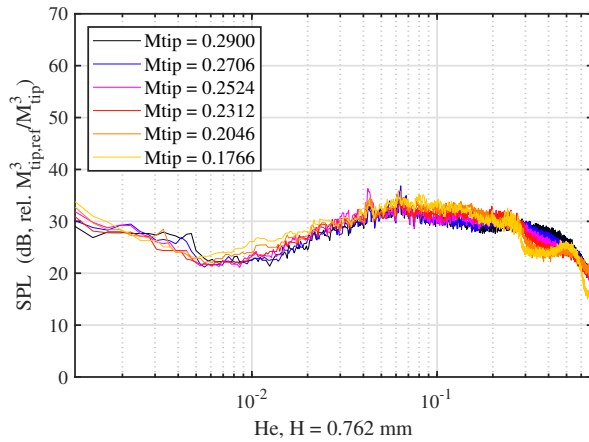
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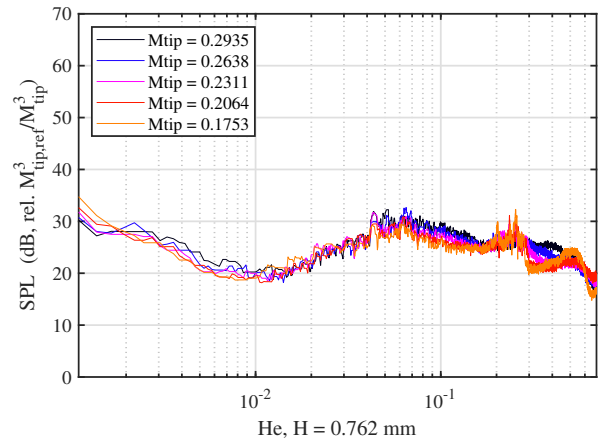
(c) FormLabs



(d) FormLabs-tripped

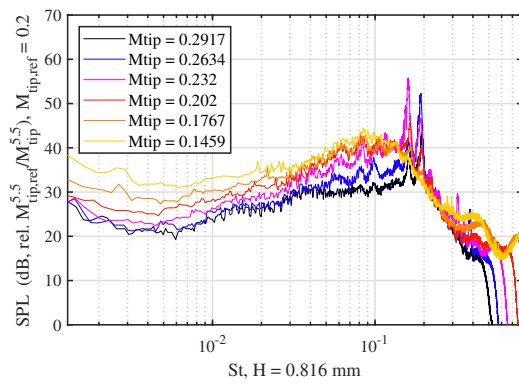


(e) COTS

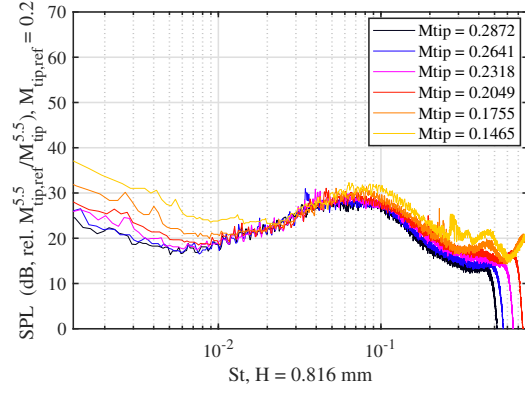


(f) COTS-tripped

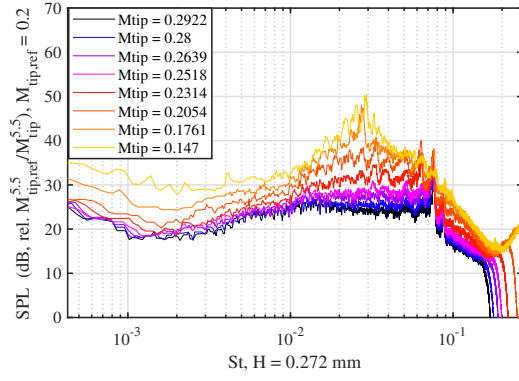
Figure D45. Scaling: Helmholtz,  $n = 3$ ,  $M_{\text{tip,ref}} = 0.2$ .



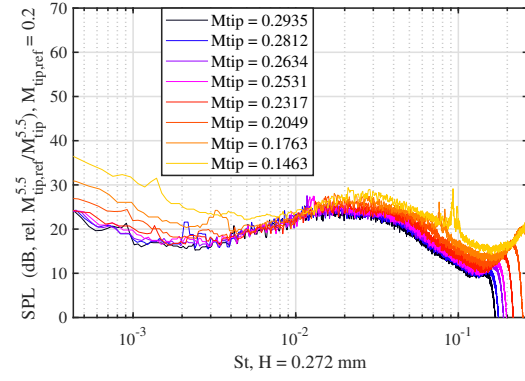
(a) SLA 3%



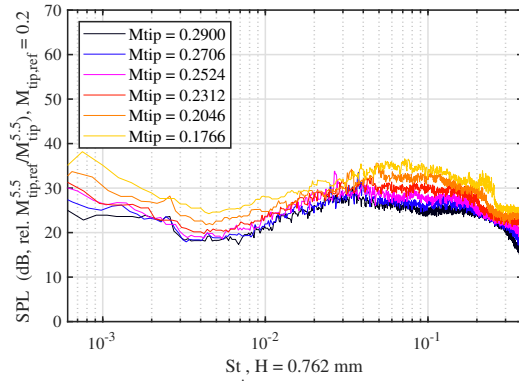
(b) SLS



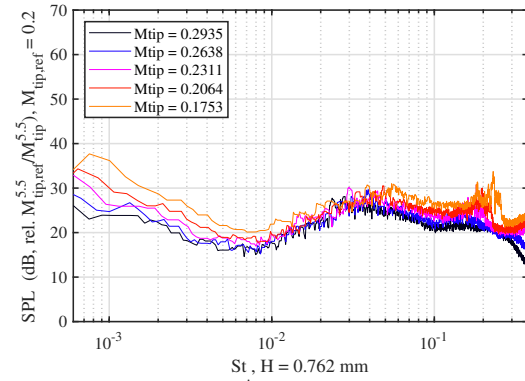
(c) FormLabs



(d) FormLabs-tripped

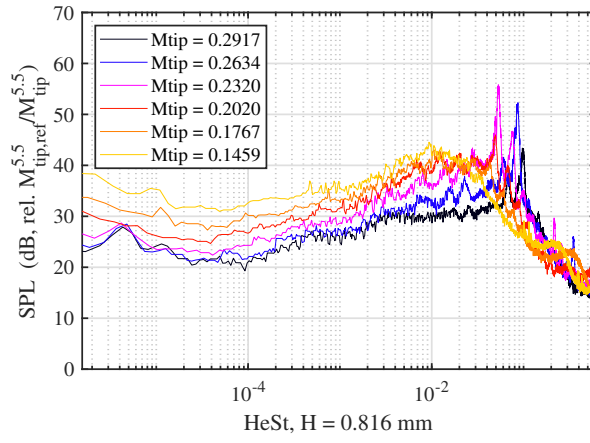


(e) COTS

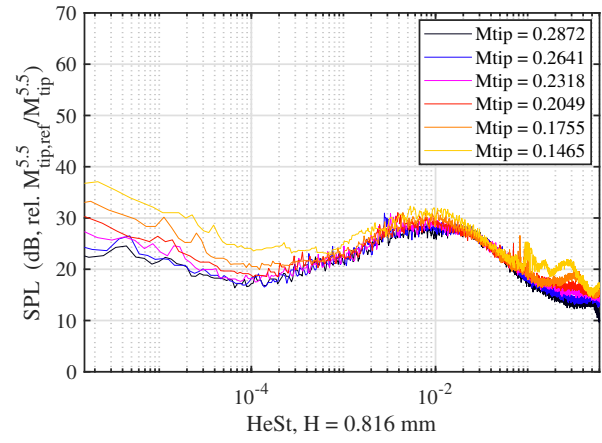


(f) COTS-tripped

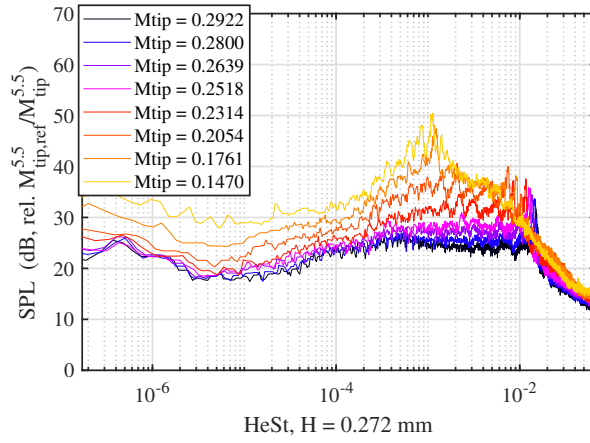
Figure D46. Scaling: Strouhal,  $n = 5.5$ ,  $M_{\text{tip,ref}} = 0.2$ .



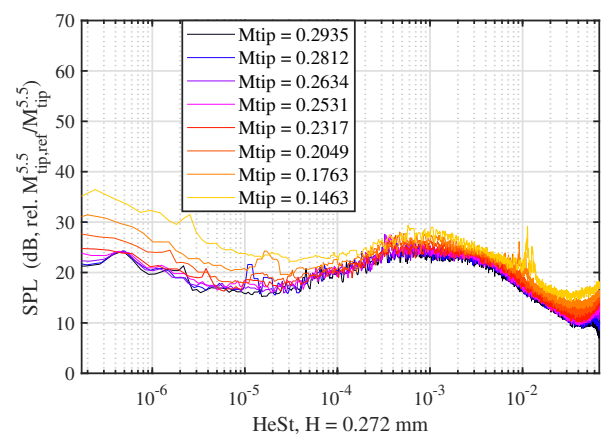
(a) SLA 3%



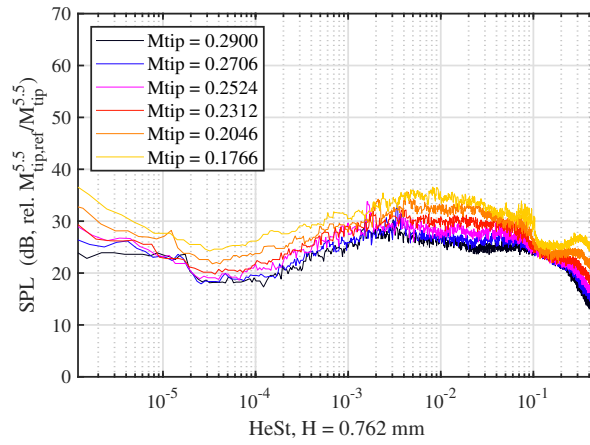
(b) SLS



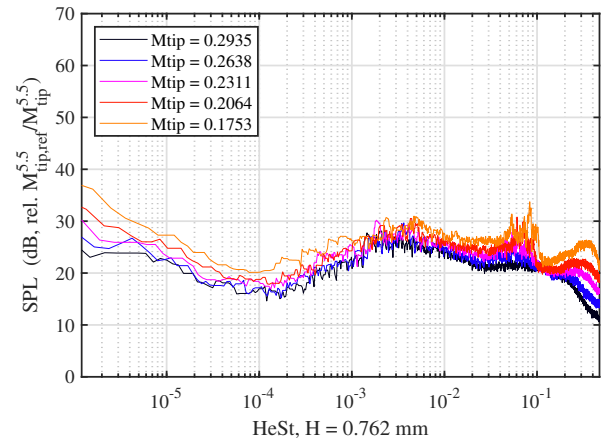
(c) FormLabs



(d) FormLabs-tripped



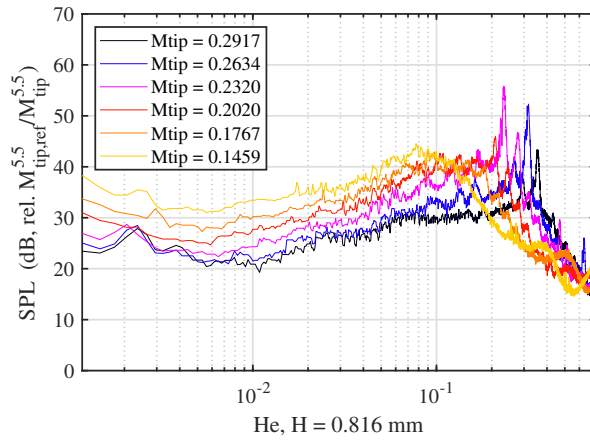
(e) COTS



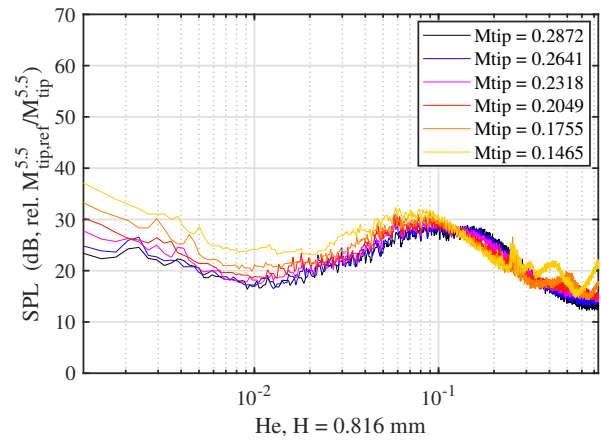
(f) COTS-tripped

Figure D47. Scaling: Helmholtz\*Strouhal,  $n = 5.5$ ,  $M_{tip,ref} = 0.2$ .

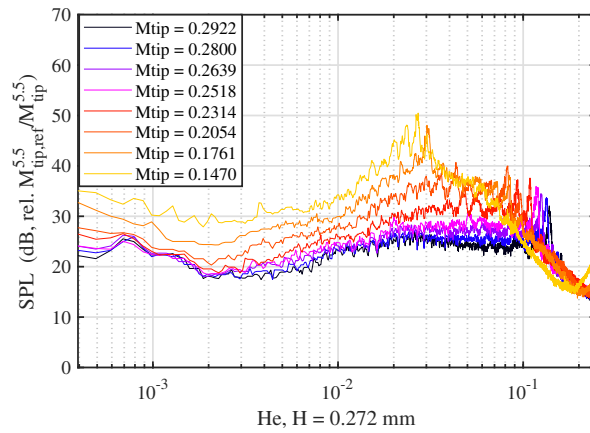




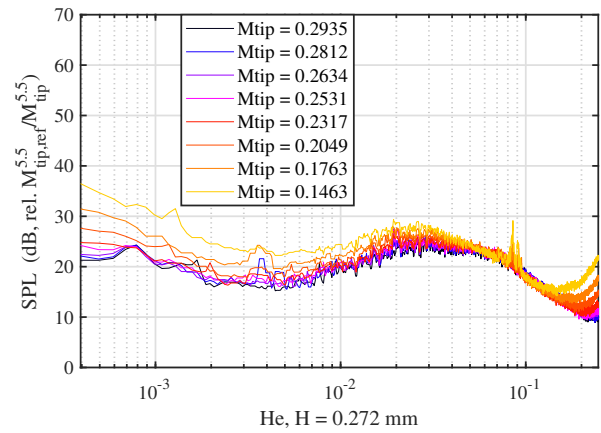
(a) SLA 3%



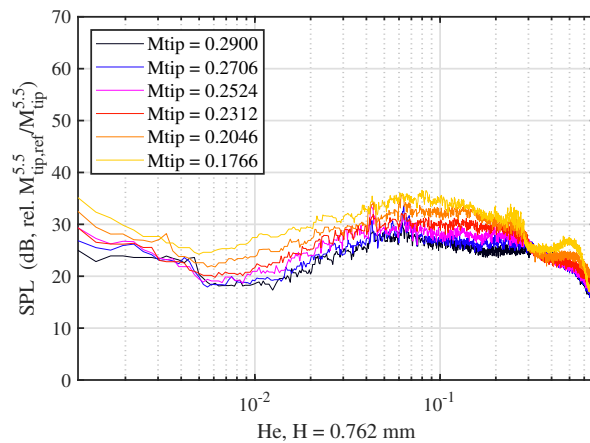
(b) SLS



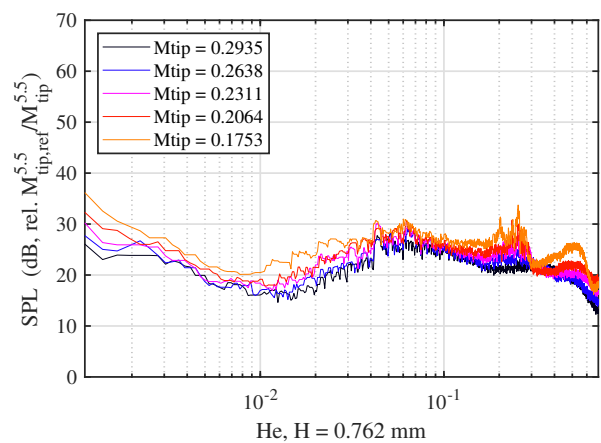
(c) FormLabs



(d) FormLabs-tripped



(e) COTS



(f) COTS-tripped

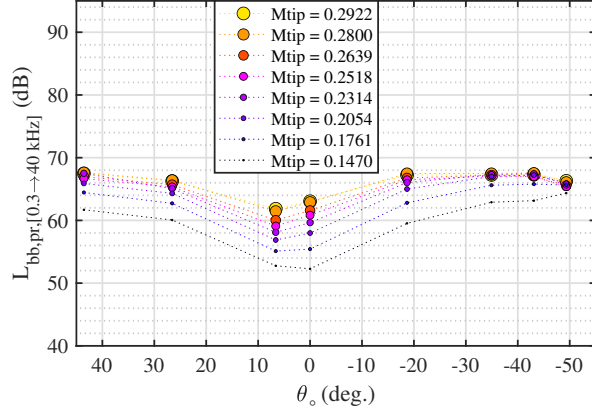
Figure D48. Scaling: Helmholtz,  $n = 5.5$ ,  $M_{\text{tip,ref}} = 0.2$ .

## Appendix E

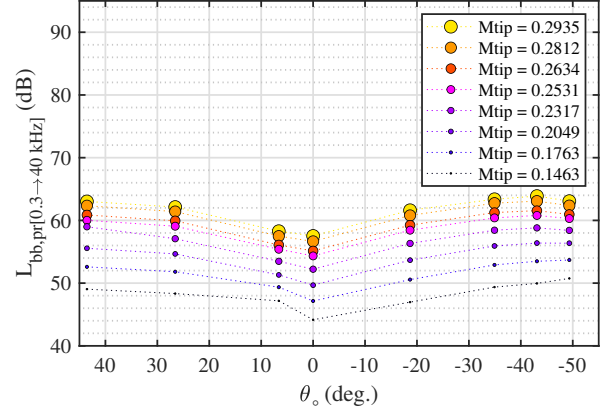
### Amplitude Scaling OASPL

This appendix illustrates amplitude scaling applied to directivity curves, as described in Section 6.

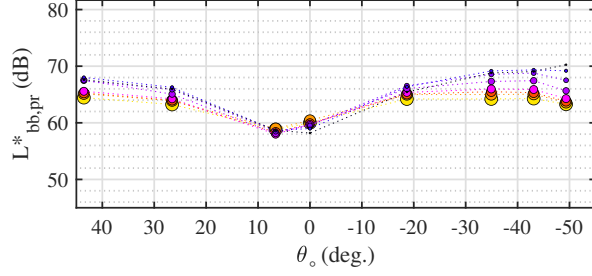




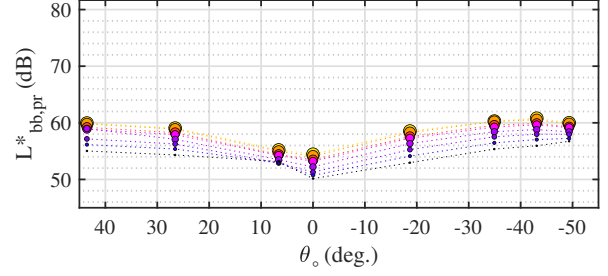
(a) FormLabs



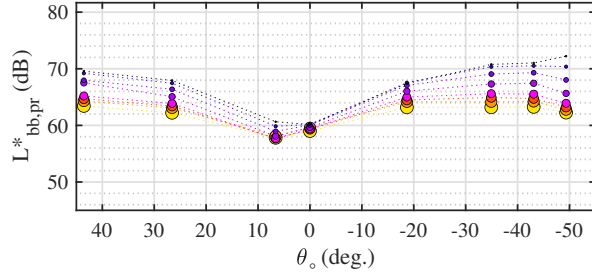
(b) FormLabs-tripped



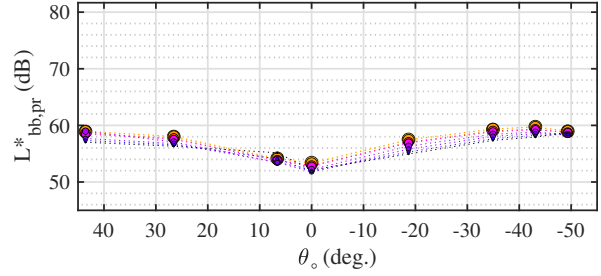
(c) FormLabs  $n = 3$



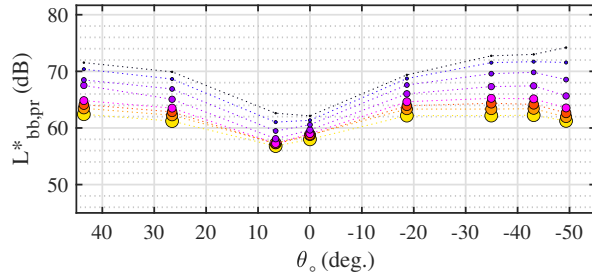
(d) FormLabs-tripped  $n = 3$



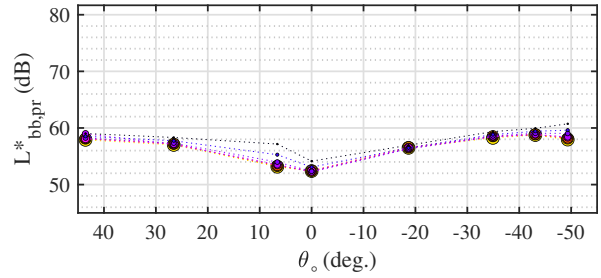
(e) FormLabs  $n = 4$



(f) FormLabs-tripped  $n = 4$

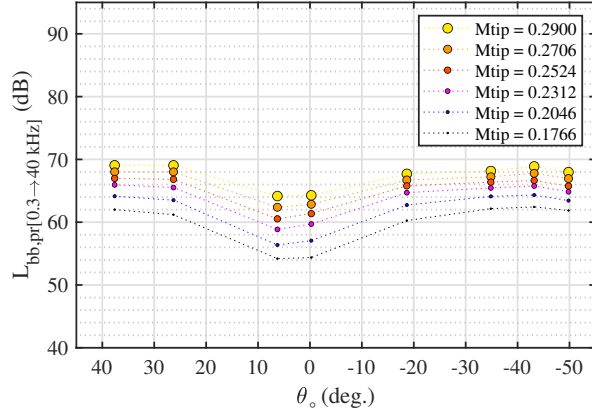


(g) FormLabs  $n = 5$

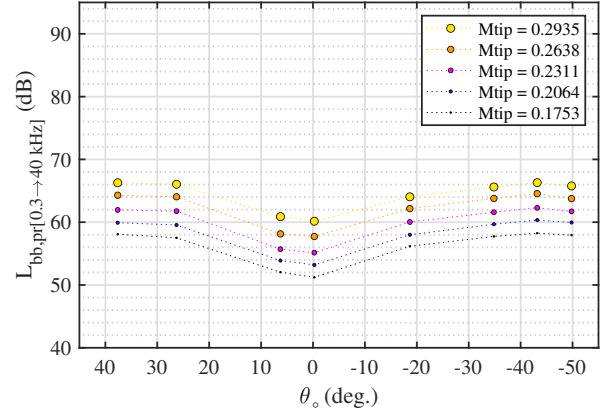


(h) FormLabs-tripped  $n = 5$

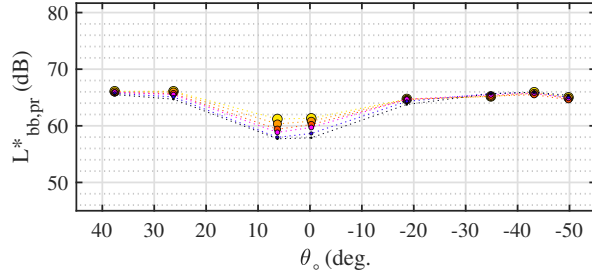
Figure E49. Amplitude scaling broadband noise for FormLabs and FormLabs-tripped rotors.



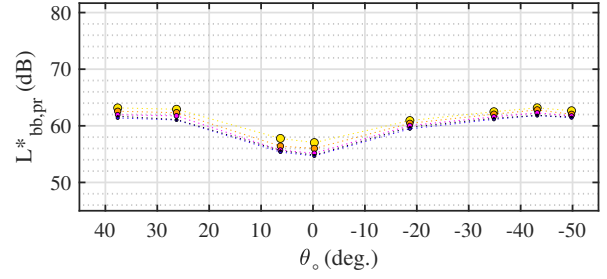
(a) COTS



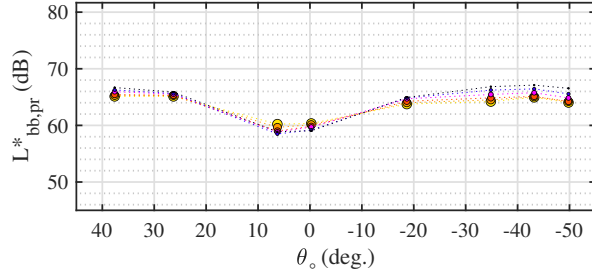
(b) COTS-tripped



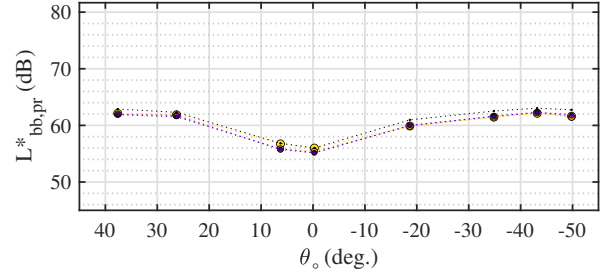
(c) COTS  $n = 3$



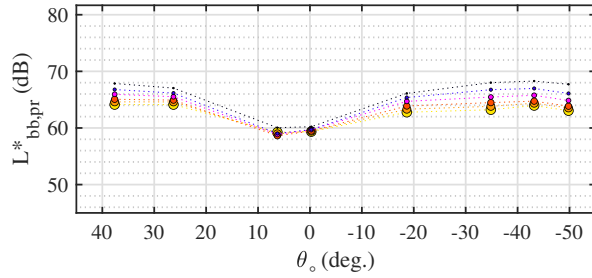
(d) COTS-tripped  $n = 3$



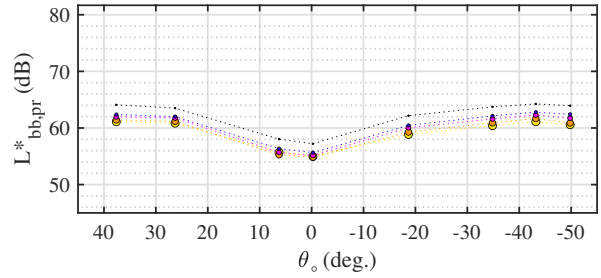
(e) COTS  $n = 4$



(f) COTS-tripped  $n = 4$



(g) COTS  $n = 5$



(h) COTS-tripped  $n = 5$

Figure E50. Amplitude scaling broadband noise for COTS and COTS-tripped rotors.



|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                             |                                               |                                             |                                                                      |                                                                                                                             |  |
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| <b>REPORT DOCUMENTATION PAGE</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                             |                                               |                                             |                                                                      | Form Approved<br>OMB No. 0704-0188                                                                                          |  |
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| <b>1. REPORT DATE (DD-MM-YYYY)</b><br>01-03-2026                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                             | <b>2. REPORT TYPE</b><br>Technical Memorandum |                                             | <b>3. DATES COVERED (From - To)</b>                                  |                                                                                                                             |  |
| <b>4. TITLE AND SUBTITLE</b><br>Aerodynamic Performance and Acoustic Impacts of Varying Tip Speeds and Tripping Conditions on Small Rotors in an Anechoic Hover Chamber                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                             |                                               |                                             | <b>5a. CONTRACT NUMBER</b>                                           |                                                                                                                             |  |
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| <b>6. AUTHOR(S)</b><br>Nicole A. Pettingill and Nikolas S. Zawodny                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                             |                                               |                                             | <b>5d. PROJECT NUMBER</b>                                            |                                                                                                                             |  |
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|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                             |                                               |                                             | <b>5f. WORK UNIT NUMBER</b>                                          |                                                                                                                             |  |
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| <b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b><br>National Aeronautics and Space Administration<br>Washington, DC 20546-0001                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                             |                                               |                                             | <b>10. SPONSOR/MONITOR'S ACRONYM(S)</b><br>NASA                      |                                                                                                                             |  |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                             |                                               |                                             | <b>11. SPONSOR/MONITOR'S REPORT NUMBER(S)</b><br>NASA/TM-20250003316 |                                                                                                                             |  |
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| <b>13. SUPPLEMENTARY NOTES</b><br>An electronic version can be found at <a href="http://ntrs.nasa.gov">http://ntrs.nasa.gov</a> .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                             |                                               |                                             |                                                                      |                                                                                                                             |  |
| <b>14. ABSTRACT</b><br>Performance and acoustic measurements were taken in a hover chamber for various optimum hovering rotors (OPT2) and a commercial-off-the-shelf (COTS) rotor. A total of 10 rotors are included in this report, all of which have two blades and a tip radius of 0.1905 m (7.5 in.). For the OPT2, results for three additive manufacturing methods of fabrication are presented: stereolithography (SLA) using Accura Xtreme, SLA using FormLabs 10K resin, and selective laser sintering (SLS) using mineral-filled PA12 nylon material. All but one set of rotors were designed with a trailing edge bluntness that is 3% of the chord length, and one set was designed with a bluntness that is 1% of the chord length. Spanwise boundary layer trips were applied to the SLA, FormLabs and COTS rotors. Performance comparisons between untripped and tripped configurations demonstrate the impact of boundary layer state on rotor efficiency. Acoustic results, including periodic and broadband noise components, are presented. The effects of tripping these rotors near the leading edge are also presented. For some of the rotors, acoustic spectra of tip speed sweeps are presented to show how the frequency content changes with tip speed. Amplitude and frequency scaling methods are used to collapse broadband spectra at various tip speeds towards a unified curve. These findings contribute to the understanding of small rotor aeroacoustics and provide valuable datasets for computational model validation in urban air mobility applications. |                             |                                               |                                             |                                                                      |                                                                                                                             |  |
| <b>15. SUBJECT TERMS</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                             |                                               |                                             |                                                                      |                                                                                                                             |  |
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