

# 3D-printed Acoustic Directional Couplers

Marcus MacDonell and Jonathan Scott

**Abstract**—Acoustic Directional Couplers permit separation of forward and reverse sound pressure waves. This separation opens the way to traceable precision acoustic reflection measurements. In order to span the audio frequency range, multiple couplers will be required, as each operates over a frequency range of slightly more than one octave. To reach 20kHz or above requires vary small, mechanically precise construction. We achieve this by 3D printing techniques. We manufactured two otherwise-identical couplers, one made with a powder-type 3D printer with photo-polymer support structure, the other made with an ABS-filament thermoplastic-type 3D printer. We compare the measured acoustic performance of these two couplers. The wavelength of sound at 20 kHz is comparable to that encountered at a microwave frequency of 18 GHz. We expect to be able to fabricate couplers that reach 55 kHz where the wavelength is 6 mm, corresponding to a frequency of 50 GHz in the electromagnetic spectrum.

**Index Terms**—Acoustical engineering, acoustic measurements, acoustic devices, directional couplers, waveguides

## I. INTRODUCTION

A Directional Coupler is a 4-port network in which portions of the forward and reverse traveling waves on a transmission line are separately coupled to two of the ports [1]. It is often assumed that a directional coupler is inherently an electromagnetic device, since the majority of commercial examples have either coaxial or electromagnetic waveguide ports. Nevertheless, acoustic directional couplers also exist. These are four port devices and behave much like a conventional directional coupler, except that the ports are acoustic waveguides that conduct pressure waves in a medium, typically air. A design for an acoustic directional coupler is described in [2]. For an acoustic coupler the required coupler material thickness is a non-negligible fraction of the wavelength and needs to be sufficiently stiff. Because of this a branch coupler is the most suitable design. A Branch coupler uses short sections of waveguide to couple the two mainlines. [2] Using a branch coupler also has an advantage, the thickness of the separating wall not only contributes to the isolation of the two mainlines but also improves the performance of the network. [2]

The Coupler can be used as a reflectometer to make extremely accurate measurements of a materials acoustic properties. These measurements can be used by the audio industry to better isolate recording studios, damp speaker cabinets, design concert halls and theaters. Vector correction techniques will allow a user to correct for all shortcomings of a coupler provided the directivity of the coupler is sufficient (usually better than 6–10 dB). [3]

The directionality of a coupler is thus the most important specification, and is the specification we are most concerned with for determining the performance of the acoustic directional coupler. The directionality or directivity is defined as

$10\log(P_c/P_d)$  where  $P_c$  is the power at the coupled port and  $P_d$  is the power at the decoupled port [1].

Recently a version of the Lagasse design has been used to fabricate an acoustic impedance meter [3]. The coupler used 60 mm-square waveguide and had a design frequency range of 1–2 kHz and a usable range of 800–2,200 Hz.<sup>1</sup> It was constructed by welding sheets and machined blocks of acrylic material. In [3] it was shown that vector correction allowed precise measurements of acoustic S-parameters. In order to create a measurement system that spans the audio range from 20–20,000 Hz a set of some 10 different-sized couplers would be required. Some applications would benefit from an instrument that reached or exceeded 50 kHz.

We created a SolidWorks model of the Lagasse coupler design. Once established, this design can be scaled, as dimensions scale inversely with operating frequency. We built two versions, 3D-printed on different printers. The first was a MakerBot Replicator 2X that employs an ABS filament material. It claims a layer resolution of 200 microns [0.0078 inches], and an X-Y resolution of 11 microns. The second was an Objet30 Pro powder-type 3D printer with photo-polymer support. This machine claims a layer thickness of 28 microns and a resolution of 100 microns [0.0039 inches].

We wish to determine if there is a minimum 3D printer resolution to maintain directionality or if the resolution has a considerable effect on directionality for the chosen operational frequency.

There is very little literature concerning the use, design and application of acoustic directional couplers. The original paper by Lagasse, [2], seems to have been largely ignored. In [3] the authors describe a number of systems in the literature that discriminate travelling waves, but all others use alternatives apart from directional couplers. The literature surrounding the use of electromagnetic couplers is very rich, in contrast. [1], [4]

## II. SOLIDWORKS MODEL AND CONSTRUCTION

The acoustic directional coupler model was designed to operate in a frequency range an order of magnitude higher than that of the hand-built coupler from [3]. The designed frequency range therefore is 10–20 kHz.

Figure 1 shows a block diagram of the coupler in use. A loudspeaker followed by a small pad introduces signal into port one. A matched load absorbs energy on port two. Ports 3 and 4 also have matching loads but each also has a microphone to sample the signal going into the side load.

<sup>1</sup>It should be noted that while rectangular electromagnetic waveguides have a theoretical lower cutoff frequency, acoustic waveguides do not. For this reason an acoustic waveguide will theoretically work all the way from DC to the frequency at which multimoding is possible. In practice, the air-tightness will introduce a rolloff below some frequency. The upshot is that the operating bandwidth has the potential to be larger than 1 octave.

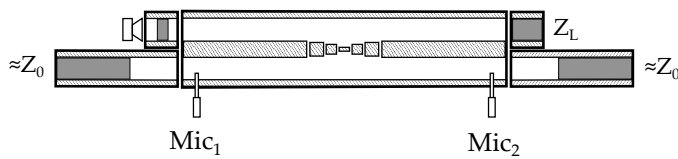


Fig. 1. “Block diagram of the acoustic hardware. Microphones sense the sound pressure level in the two side arms of the coupler. The source is a small loudspeaker mounted behind an attenuating pad constructed of the same foam rubber used to make the loads” [3].

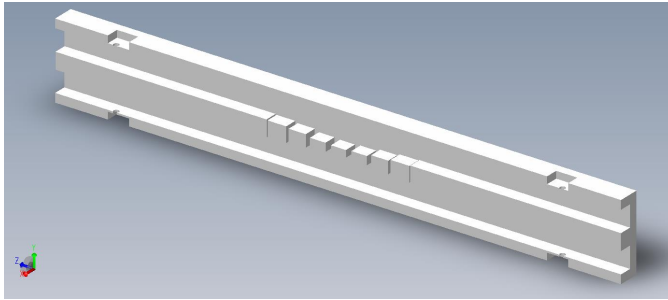


Fig. 2. SolidWorks model for the acoustic directional coupler.

In the SolidWorks model there are side-ports for the placement of MEMS (Micro-Electro-Mechanical Systems) microphones. The cross section view in Figure 2 also allows us to see the internal geometry which is responsible for the directionality of the coupler. The Block diagram shows loudspeaker and load placement.

The ABS filament type MakeBot created a Coupler with a noticeable grain from its crosshatched layering process. More importantly it also had collapsed portions in the waveguide. The collapsed portions left the surface finish damaged and the collapsed plastic had to be cleared before experiments could be started. The Coupler is also slightly warped from the cooling of the layers of plastic which affects its overall dimensional accuracy. These defects can be seen in Figures 3, 4 and 5.

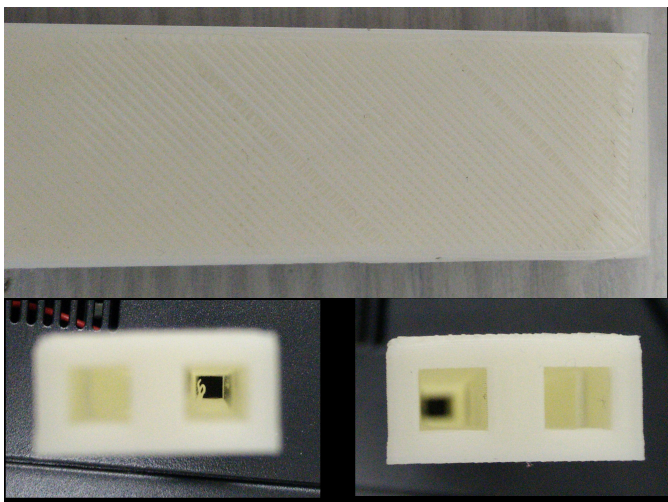


Fig. 3. MakeBot coupler surface finish (Top) and collapsed plastic (Bottom Left).

The Objet30 is printed with a support structure. The wanted structure and removable support layers are printed alternately



Fig. 4. Another MakeBot coupler, cross section: Cut with a band saw, poor surface finish can be seen on the roof of the coupler (upper half in the photo).



Fig. 5. MakeBot coupler cross section: At this angle inaccuracy in the internal geometry can be seen, the most extreme left and right wave guide portions are deformed and almost touching at points. The separation should be 0.276 mm or 276 microns.

layer by layer. The support structure makes a significant difference to the finish of the coupler as well as its dimensional accuracy. The support structure is removed with a dilute sodium hydroxide solution.

### III. MEASUREMENTS

We seek to measure the directionality of the coupler samples. Referring to figure 1, we hope that signal originating from the loudspeaker on port 1 will be mostly passed to port 2 (top right-hand port in the figure) and there absorbed by the load  $Z_L$ , if it is a good match to the characteristic impedance  $Z_0$ . A small proportion of the loudspeaker signal should be coupled to port 3 where it is sampled by Mic 2 and absorbed by the load in that arm of the coupler. If no signal is reflected from the load on port 2, no signal should be detected on the isolated port, port 4, sampled by Mic 1. The directionality of the coupler, in this case, will be the ratio of signals at Mic 1 to those at Mic 2. This directionality is ideally infinite. In practice we expect values in the range 10–40dB for realisable designs.

The measurement of directionality depends upon the quality of the loads used at ports 2–4. For example, if the load port, port 2, is terminated in a perfect reflection instead of a perfect

load, the directivity will disappear completely as the signals in the two microphones will ideally be the same. How then can we know that our measurement is reasonably reliable, that is that the measurement of directionality has not been compromised by non-ideality of the terminating loads? We gauge the quality of the terminating load by sliding it along the guide. This has the effect of changing the phase of any reflected component. As the phase changes, the magnitudes at the microphones are observed. If there is a significant component changing phase, there will be a significant change in measured signal amplitude. We observe very little. We believe that our terminations, visible in figure 6, reflect below -20dB of incident signal, and often -40dB.

In fact, we chose the material used as the loads by means of this sliding load method from [3]. It was found that generic yellow earplugs worked relatively well.

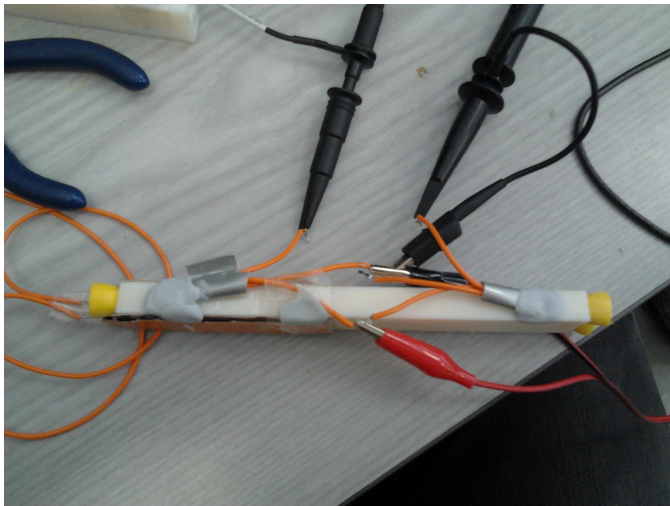


Fig. 6. Coupler experimental set up. Earplugs can be seen as the yellow foam inserted at the ends. Microphones are sealed into the top of the coupler with Bluetack™

For our experiments to measure directionality yellow earplugs were used as acoustic loads on three of the coupler's four ports. Measurements were made using an Agilent 33220A function generator into a Digitech stereo amplifier which powered a small diaphragm transducer on the input of the coupler. Two MEMS microphones attached to the coupler were used to detect the tone amplitude through a Tektronix TDS2014C oscilloscope. The MEMS microphones are powered at 3 V from a bench power supply. The experimental set up can be seen in Figure 6. All measurements were done by hand. It is hoped that there will be automated measurements shortly.

#### A. MakeBot Acoustic Coupler

In order to test the coupler we put a swept audio signal into port one with a matched load on port two. Ideally we would see a strong signal on the coupled port and a much smaller signal on the decoupled port. Figure 7 shows the result of the measurement. The amplitudes in the MakeBot acoustic coupler were measured as voltage signals from the microphones. We are most interested in the ratio of the coupled to decoupled port signals, the directivity of the coupler. Directivity is plotted

in figure 8. Directivity is expected to be better than 20dB from 10kHz to 20kHz, falling away around 7.5 kHz and 22.5kHz. Directivity is excellent from below 10kHz to at least 15kHz, but it appears as if the expected characteristic has been shifted towards lower frequencies. The MakeBot coupler demonstrated apparently excellent performance but not over the expected frequency range. The directionality was better than 15 dB from 6 kHz to 15 kHz, but disappeared completely at around 18 kHz. (The transducer prevented measurement at lower frequencies.) We attribute this unexpected performance to the mechanical imperfections of the printing process, and we believe the extended low-frequency performance is a coincidence upon which it will not be possible to rely.

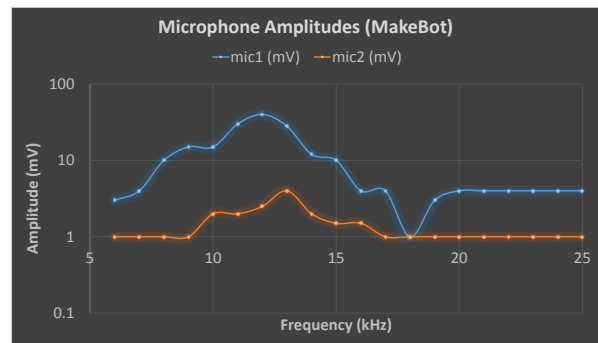


Fig. 7. The lower resolution print port amplitudes.

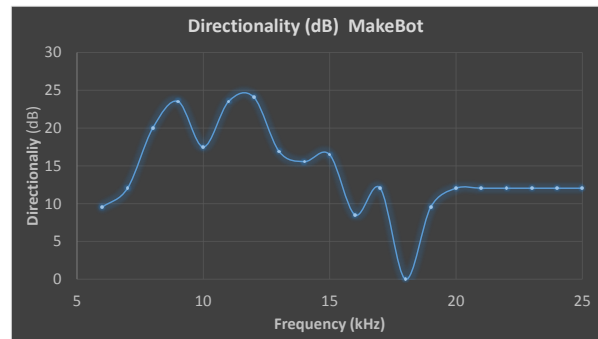


Fig. 8. The lower resolution print directionality.

#### B. Objet30 Acoustic Coupler

Using the same method the amplitudes on the coupled and decoupled ports of the Objet30 coupler were measured. Directivity is again expected to be better than 20dB from 10 to 20 kHz. Figures 9 shows the directionality for the Objet30 Coupler. The Directivity for the Objet30 coupler is excellent

and extends outside the designed range. The Directivity extends over a range of 7–22 kHz.

We believe the low frequency extension below 7 kHz is unreliable as the signal is heavily attenuated, approaching the noise floor. The Objet30 coupler behaves as expected and we attribute this to the increased resolution and accuracy of the printer due to its support structure stopping any collapsing during printing.

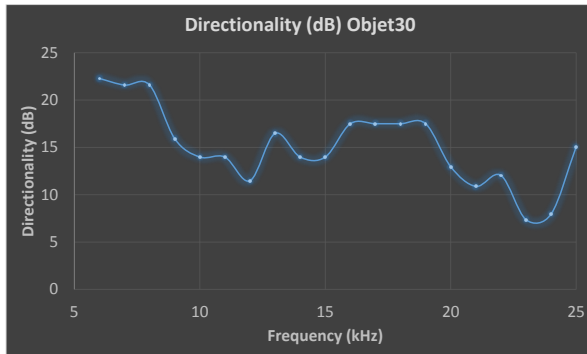


Fig. 9. Acoustic coupler directionality averages 15 dB over the expected usable frequency range.

#### IV. CONCLUSION

Directivity for both printed couplers was expected to be better than 20dB from 10 to 20 kHz, falling away around 7.5 kHz and 22.5 kHz. Both of the measured acoustic couplers displayed excellent directionality. However only the Objet30 version behaved as expected with a range of 7–22 kHz. The MakeBot coupler displayed its directivity over a lower frequency band, approximately 7–15 kHz.

The altered characteristics of the MakeBot coupler we believe can be attributed to the decreased resolution of the printer and the absence of a support structure. The internal geometry of the MakeBot coupler was inaccurate due to the lower resolution and absence of support structure. The absence of a support structure caused the walls of the coupler to collapse. These features and the damaged surface and excess plastic left in the waveguide of the coupler caused a change to its behavior.

The Objet30 coupler did not suffer any of these issues from its construction and we attribute its performance to its superior build quality.

#### REFERENCES

- [1] P.A Rizzi, "Directional Couplers" in *Microwave Engineering - Passive Circuits*. Englewood Cliffs NJ: Prentice-Hall Inc, 1988, 8, 3, pp 367 - 369.
- [2] Lagasse, P., "Realisation of an acoustical directional coupler", *Journal of sound and vibration*, 15(3), April 1971, pp367–372.
- [3] Scott, J. and K. E. Pennington, "Acoustic Vector-Corrected Impedance Meter", *IEEE Transactions on Instrumentation and Measurement*, 2014. DOI: 10.1109/TIM.2014.2327474

- [4] Rytting, Doug, "ARFTG 50 year network analyzer history", IEEE MTT-S International Microwave Symposium Digest, 2008, pp11–18.
- [5] ISO 10534-1:1996, "Acoustics—determination of sound absorption coefficient and impedance in impedance tubes—Part 1: Method using standing wave ratio".
- [6] ASTM Standard C384, 2004, "Standard test method for impedance and absorption of acoustical materials by impedance tube method".