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A3 4 Testing the limits of strings

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Abstract

In this report, the theoretical upper limit on the distance over which a string and can phone can be used is calculated. Material properties of the nylon strings used are taken from Kodama et al. [1]. For a 200 Hz frequency signal falling from 70 dB to 20 dB in a silent environment, the maximum distance theoretically possible for the strings used is 852 m. This is an upper limit, as losses at the cans, air damping and any external string losses are neglected.

Introduction

A string and can phone consists of two cans joined by a taut string. Speech at one can makes the base of the can vibrate and thus causes the string to vibrate. The string then carries the vibration to the other can and the other can radiates it as sound. Despite its simplicity, it raises the question: how far can the signal travel along the string before it becomes inaudible?

The answer depends on how quickly the string dissipates vibrational energy and what counts as inaudible. The aim of this report is to calculate the theoretical upper limit, so certain assumptions will have to be made. We assume the frequency to be fixed at 200 Hz, which is within the range of typical female voices [2]. We also assume that the source has a level of 70 dB, which is at the higher end of typical speech [3], in order to increase the maximum distance. We assume that it is a silent environment on the receiver's side, and we take a minimum level of 20 dB as the detection limit because it is around the sound level of whispering [3]. The paper by Kodama et al. [1] uses guitar strings to determine the material values and so the material values are also assumed to apply to the string here. Two sets of nylon strings (NS110, Yamaha, and EJ32C, D'Addario) are used and are referred to as NY1 and NY2, respectively. Each set contains three strings with varying material values. Although cotton and flax are more commonly used materials, they can not be used as they are twisted from many fibres and do not fit the model of a cylinder. Typically cotton has a lower tensile strength than nylon and so would most likely result in a shorter distance reached [4].

Theory

The string is treated as a uniform viscoelastic cylinder with diameter d and mass per unit length σ. Its density is:

$$\rho = \sigma/(\pi d^2/4). \tag{1}$$

The stiffness of the material is described by the storage modulus E', and its internal energy loss by the loss modulus E''. Their ratio is the loss tangent:

$$\tan(\delta) = E''/E'. \tag{2}$$

This is the fraction of energy lost in each cycle. The values of d, σ, E', E'' and $\tan(\delta)$ come from

[1].

The signal is modelled as a longitudinal wave and its speed is given by:

$$V = \sqrt{E'/\rho}. \tag{3}$$

As the wave travels, internal damping causes the amplitude to fall exponentially with distance x:

$$a(x) = a_0 e^{-\alpha x}, \tag{4}$$

where α is the attenuation coefficient measured in nepers per metre. For a material with small losses ($\tan(\delta) \ll 1$) [5], the attenuation coefficient is:

$$\alpha = \pi f \tan(\delta)/V, \tag{5}$$

where f is the frequency of the wave.

Sound is measured in decibels, so converting from nepers to decibels gives:

$$L(x) = 20 \log_{10}(a_0 e^{-\alpha x}/a_f), \tag{6}$$

where a_f is the reference amplitude and $L(x)$ is the decibel level as a function of distance. Expanding Eq. (6) gives:

$$L(x) = 20 \log_{10}(a_0/a_f) - 20\alpha x \log_{10}(e), \tag{7}$$

and finally, simplifying Eq. (7) gives:

$$L(x) = L_i - 8.686\alpha x, \tag{8}$$

where L_i is the initial level of 70 dB and $L(x)$ is the level at the maximum distance, 20 dB.

Results

String	No.	Diameter d (10^{-3} m)	Line density σ (10^{-3} kgm^{-1})
NY1	1	0.718	0.438
	2	0.839	0.588
	3	1.038	0.915
NY2	1	0.725	0.440
	2	0.826	0.580
	3	1.036	0.900

Table 1: Diameter and line density [1]

String	No.	E' (GPa)	E" (GPa)	tan(δ)
NY1	1	3.74	0.09	0.02
	2	3.13	0.07	0.02
	3	2.86	0.08	0.03
NY2	1	2.93	0.06	0.02
	2	3.14	0.06	0.02
	3	2.80	0.07	0.03

Table 2: Material values [1]

String	No.	V (m s^{-1})	α ($10^{-3} Npm^{-1}$)	Distance (m)
NY1	1	1859	6.760	852
	2	1715	7.327	786
	3	1627	11.585	497
NY2	1	1658	7.579	760
	2	1704	7.375	781
	3	1619	11.643	494

Table 3: Calculated speeds, attenuation values and distances

Discussion and Conclusion

This report uses the data from Kodama et al. [1], to model a string and can phone to estimate the maximum theoretical distance over which communication can be achieved. In [1], Kodama et al. measured the string properties at 10 Hz, so a further assumption is that the string behaves similarly at 10 Hz and 200 Hz. There seems to be some correlation between the diameters and line densities of the nylon strings and the maximum distance reached. As the line density and diameter increase, there is a general decrease in the distance; however, this does not apply to NY2 string 2, as its maximum distance increases relative to string 1. This is because the storage modulus in Table 2 increases between string 1 and 2. The reason for this increase in storage modulus is unconfirmed, although Kodama et al. suggest manufacturing conditions as a possible cause [1]. In conclusion, the maximum theoretical distance achieved by the six nylon strings tested, for a 200 Hz signal falling from 70 dB to 20 dB, is 852 m. This is an upper limit, since losses at the cans, air damping and external string losses are neglected.

References

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