Acoustics • Shock • Vibration • Signal Processing **June 2003 Newsletter**

All Aboard!

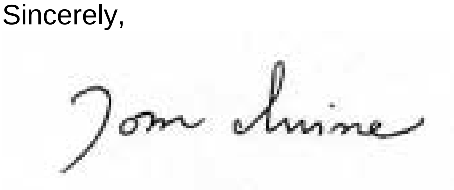
The Doppler shift of sound waves is a familiar topic in introductory physics courses, including homework and exam problems. A passing train sounding its horn is the classic Doppler shift example. Textbooks typically represent train horns as monotone sources, tuned to some arbitrary frequency, however.

Real-world train horn systems usually have three or five individual horns, called chimes. Each chime has a fundamental frequency as well as integer harmonics. Furthermore, each chime is tuned to a musical note, such as C# at 277 Hz.

This month's newsletter gives tables that show the tuning of train horn systems by model number. The tabular data is then used to clarify the spectral functions of recorded train horns. Furthermore, the Doppler shift is accounted for, given that each train is traveling at some velocity.

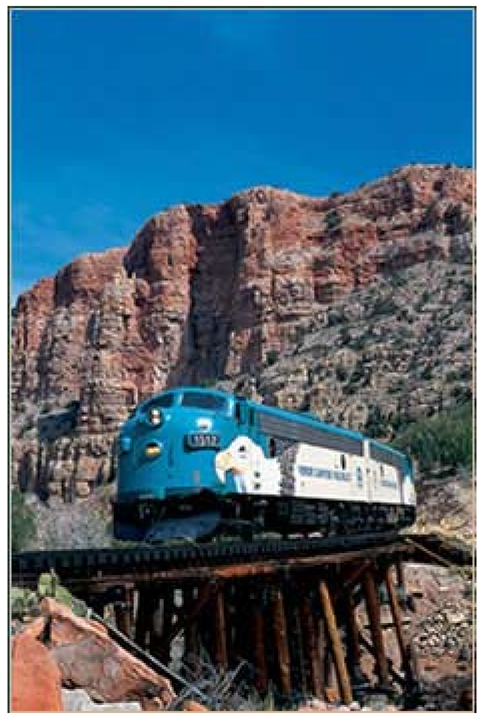
This data is then used to analyze the train horn sounding in Brian Wilson's *Caroline No*, which was the final song in the original release of the *Pet Sounds* album.

Sincerely,



Tom Irvine
Email: tomirvine@aol.com

Feature Articles



WELCOME TO VIBRATIONDATA

SHOCK & VIBRATION CD OFFER

The Vibrationdata CD contains over 150 tutorial papers, as well as NASA and military handbooks. Dozens of related software program are also included.

Topics include

- Acoustics
- Pyrotechnic Shock
- Shock Response Spectrum
- Random Vibration
- Signal Processing
- Dynamic Data Acquisition and Analysis
- Modal Testing
- Finite Element Methods
- Structural Dynamics
- Earthquake Engineering
- Arthur W. Leissa, NASA SP-160, Vibration of Plates

The price for the CD is $75.00 (US).

To order, please send a check or money order to:

Tom Irvine
Vibrationdata
2445 S. Catarina
Mesa, Arizona
USA 85202

Payment via PayPal is also accepted.

Train Horn Acoustics by Tom Irvine

Doppler Shift

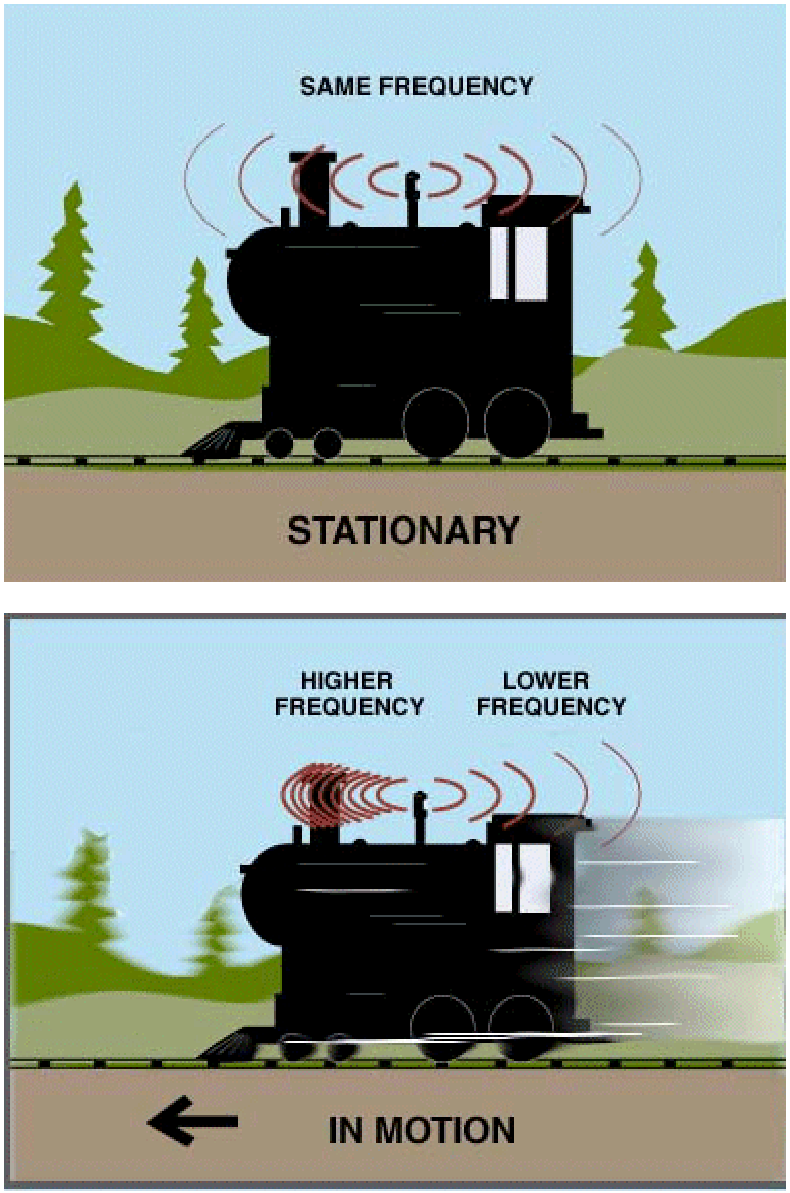


Figure 1. Doppler Effect

(Image courtesy of Reference 1)

The Doppler effect for a sound wave is illustrated in Figure 1, assuming a stationary receiver.

A sound wave undergoes a Doppler shift when either the transmission source or the receiver is moving. Austrian Scientist Christian Doppler (1803-1853) made this important discovery while experimenting with sound waves.

Doppler performed an experiment whereby a train pulled a freight car with trumpeters playing on top of it. Furthermore, he had the train do this repeatedly at different speeds.

He then had a musician capable of understanding the differences in tones listen as the train moved closer or further away. The results proved Doppler's theory.

Doppler later tried unsuccessfully to prove that his theory also applied to light. Eventually, the French physicist Louis Fizeau (1819-1896) proved this for light.

Consider a source and a receiver moving with respect to one another in a straight line. The Doppler shift equation for the apparent frequency $f_{apparent}$ of the resulting sound wave as heard by the receiver is

$$f_{apparent} = f_{source} \left(\frac{c - v}{c - u} \right) ,$$

for $u < c$ and $v < c$

(1)

where

f_{source}	is the frequency transmitted by the source
c	is the speed of sound in the medium
u	is the source’s velocity
v	is the receiver’s velocity

Notes:

1. Equation (1) is taken from Reference 2.
2. The equation is valid if either the receiver or the source is fixed, with zero velocity.
3. The velocity terms must have the correct sign.
4. Shock waves begin to form as the source’s velocity approaches the speed of sound, thus complicating the sound field.

Equation (1) may be restated as

$$f_{\text{apparent}} = f_{\text{source}} \left(\frac{1 - v/c}{1 - u/c} \right) \tag{2}$$

The source velocity can be expressed as

$$u = c\left[1 - \left(\frac{f_{\text{source}}}{f_{\text{apparent}}}\right)\right] + v\left(\frac{f_{\text{source}}}{f_{\text{apparent}}}\right) \tag{3}$$

The source's velocity u for the case of a stationary receiver is

$$u = c\left[1 - \left(\frac{f_{\text{source}}}{f_{\text{apparent}}}\right)\right] \quad , \quad \text{for } v = 0 \tag{4}$$

<u>Train Chimes</u>

Figure 2. K5LA Horn with Five Chimes (Photo courtesy of Brent Lee)

Steam locomotives had an audible whistle that served both as a warning device and as a signaling device. The whistle was produced by a column of steam resonating in a metal tube. Conventional horn systems are designed to somewhat mimic this sound. A typical horn is shown in Figure 2.

These horn systems consist of a group of individual horns called chimes that operate using compressed air to vibrate a metal diaphragm. The air pressure amplitude is typically about 100 psi.

Furthermore, some of the chimes may be mounted in reverse in bi-directional locomotives.

Five Chime Horn

Examples of five chime horn models are shown in Tables 1a and 1b. Each is an AirChime/Nathan model.

Table 1a.

Five Chime Horns, Notes and Corresponding Frequency (Hz)

K5LA	K5H	P5 (original tuning)	P5 (newer casting)	P5A
D# (311)	D# (311)	C# (277)	D (292)	C# (277)
F# (370)	F# (370)	E (330)	F (349)	E (330)
G# (415)	A# (470)	G (392)	G# (415)	G (392)
B (494)	C (523)	A (440)	A (440)	A# (470)
D# octave (622)	D# octave (622)	C# octave (554)	C (523)	C# octave (554)

Table 1b.

Five Chime Horns, Notes and Corresponding Frequency (Hz)

M5 (original tuning)	M5 (Alternate 1)	M5 (Alternate 2)	H5 (original tuning)
C# (277)	C# (277)	C# (277)	C# (277)
E (330)	E (330)	D# (311)	E (330)
G (392)	F# (370)	F# (370)	G (392)
A (440)	A (440)	A# (470)	A (440)
C# octave (554)	C# octave (554)	C# octave (554)	C# octave (554)

Many other variations were possible, though, even from the factory.

Note that H5, M5, and P5 horns each have the same chimes in their respective original configurations.

Three Chime Horns

Examples of three chime horns are given in Table 2. Each is an AirChime/Nathan model except for the RS-3L which is a Leslie.

Table 2.

Three Chime Horns, Notes and Corresponding Frequency (Hz)

K3LA	K3H	P3 (original)	P3 (newer castings)	RS-3L
D# (311)	D# (311)	C# (277)	D (294)	* (255)
F# (370)	F# (370)	E (330)	F (394)	D# (311)
B (494)	A# (466)	A (440)	A (440)	A (440)

* A frequency of 255 Hz does not correspond to a specific piano key. It is midway between a B and a C. A nominal C note is 261 Hz.

K5LA Example

K5LA horns are used on Amtrak, CSX, NS, and other railroads.

Figure 2 gives a spectral analysis of a K5LA on the Norfolk Southern, recorded in Three Bridges, NJ. The corresponding sound file is posted at

http://www.vibrationdata.com/K5LA.wav

The file is courtesy of the Moyer family.

The K5LA factory tuning is D#, F#, G#, B, D# octave, as shown in Table 1a. The respective frequencies of these notes can be compared with the spectral peaks in Figure 2 in order to determine the speed of the train, indirectly. The measured and nominal frequencies are shown in Table 3.

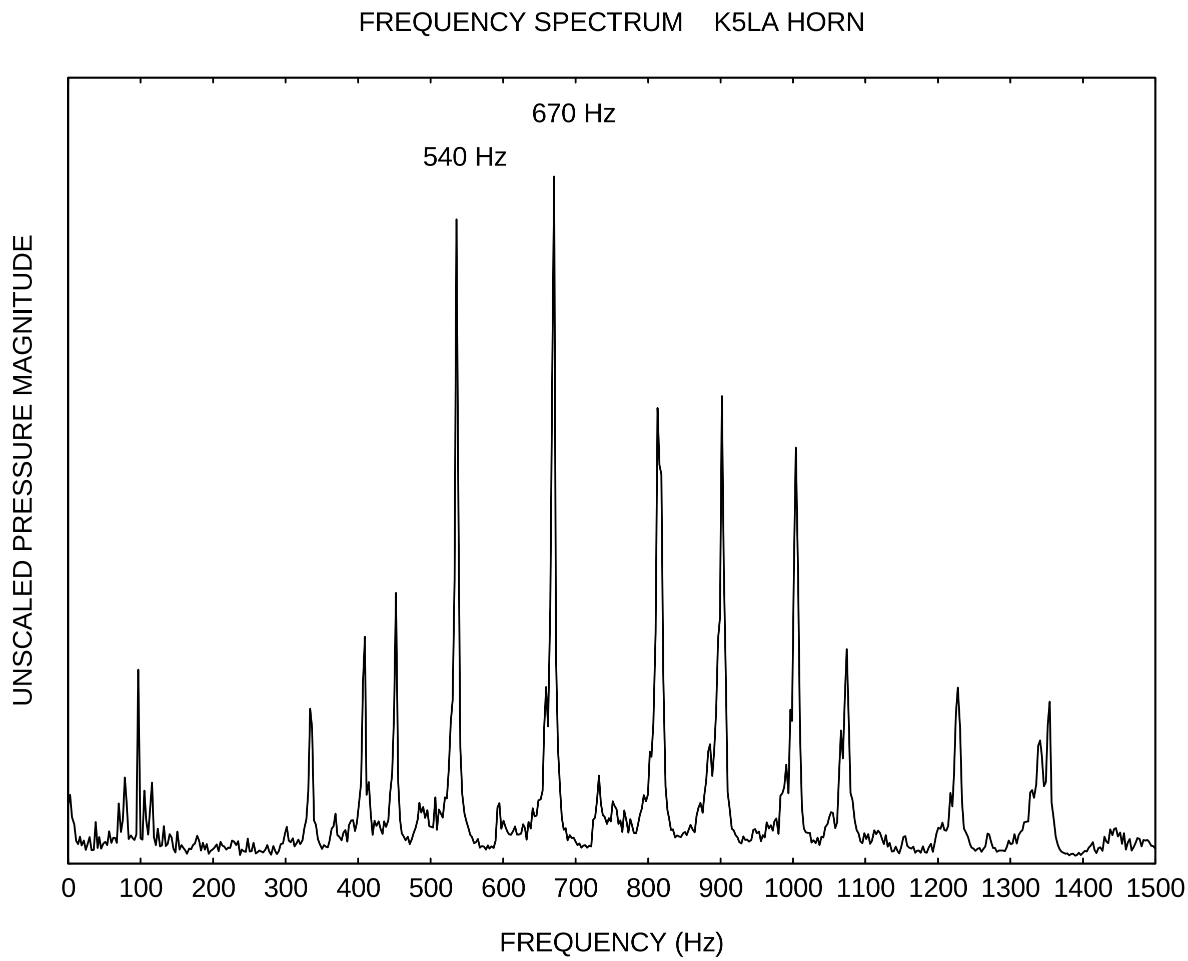


Figure 2.

Table 3. K5LA Horn Frequencies, Factory Tuning and Measured			
Note	Note Frequency (Hz)	Measured Frequency (Hz)	Frequency Ratio (note / measured)
D#	311	333	0.934
F#	370	410	0.902
G#	415	453	0.916
B	494	534	0.925
D# octave	622	670	0.928

The average frequency ratio = 0.921.

Assume

1. Each chime was perfectly tuned such that its frequency ratio was 0.921.
2. The receiver was stationary.
3. The speed of sound is 767 mph.

The speed of the train u is

$$u = c\left[1 - \left(\frac{f_{source}}{f_{apparent}}\right)\right] \quad , \qquad \text{for } v = 0 \tag{5}$$

$$u = (767 \text{ mph})\left[1 - 0.921\right] \tag{6}$$

The train was thus traveling toward the receiver at

$$u = 60 \text{ mph} \tag{7}$$

<u>Train Horn Sounding in Pet Sounds</u>

Figure 3. Pet Sounds Album Cover

The Beach Boys' *Pet Sounds* album originally was released on May 16, 1966. The album was Brian Wilson's masterpiece.

Michael Goldberg described the album as follows:

> *Pet Sounds* is the story of a young man coming of age, falling in love, shedding his innocence and romanticism — even as he tries to hang onto them. It culminates in "Caroline, No," Brian Wilson singing, "Where did your long hair go/ Where is the girl I used to know/ How could you lose that happy glow..."

The song *Caroline No* ended with the sound of passing train, with its horn blaring. This was apparently taken from a sound library, although Brian superimposed the barking of his pet dogs as an added effect.

The album notes do not mention the type of locomotive, its horn configuration, speed or other details. The task is thus to determine the horn configuration and the speed.

The train sound file is posted at

http://www.vibrationdata.com/cno_train.wav

A spectral analysis of a 1.5 second segment from this data is shown in Figure 4. The segment was taken as the train was approaching the receiver. Five fundamental frequencies are apparent, along with harmonics.

The horn will be hypothesized as a P5 model with original tuning. The P5 was a very common horn that was first produced in the early 1950's. The P5 had a chime sequence of C#, E, G, A, C# octave. This is an A major dominant 7th chord. The M5 and H5, both with original tuning, shared this chord. The M5 and H5 models were somewhat less common, however.

The results in Table 4 reasonably confirm the hypothesis, at least in terms of the chord.

The error of an individual chime could be attributed to one of the following sources:

1. Slight mistuning at the factory.
2. Mistuning through use and exposure to vibration, thermal cycling, etc.

Note that chimes require periodic service to maintain their tuning.

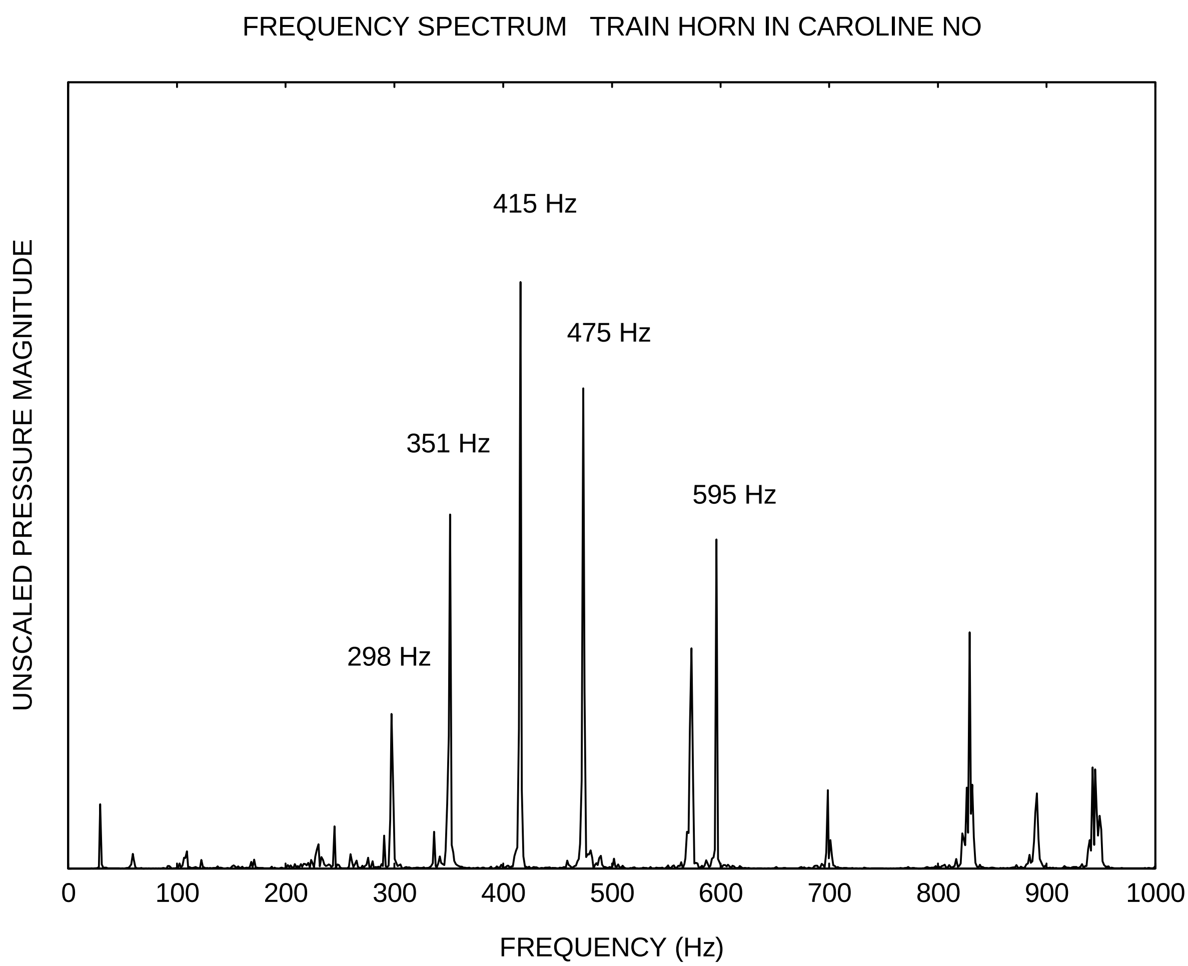


Figure 4.

Table 4. K5LA Horn Frequencies, Factory Tuning and Measured			
Note	Note Frequency (Hz)	Measured Frequency (Hz)	Frequency Ratio (note / measured)
C#	277	298	0.930
E	330	351	0.940
G	392	415	0.945
A	440	475	0.926
C# octave	554	595	0.931

The average frequency ratio is 0.934.

Assume

1. Each chime was perfectly tuned such that its frequency ratio was 0.934.
2. The receiver was stationary.
3. The speed of sound is 767 mph.

The speed of the train u is

$$u = c\left[1 - \left(\frac{f_{source}}{f_{apparent}}\right)\right] , \quad \text{for } v = 0 \tag{8}$$

$$u = (767 \text{ mph})[1 - 0.934] \tag{9}$$

The train was thus traveling toward the receiver at

$$u = 51 \text{ mph} \tag{10}$$

References

1. http://weathersavvy.com/Doppler3.html
2. W. Seto, Acoustics, Schaum's Outline Series in Engineering, McGraw-Hill, 1971. (see page 59).