Investigating the Doppler effect with ultrasonic waves

Objects of the experiments

- Measuring the change of frequency perceived by an observer at rest as a function of the velocity v of the source of ultrasonic waves.
- Confirming the proportionality between the change of frequency Δf and the velocity v of the source of ultrasonic waves.
- Determining the velocity of sound c in air.

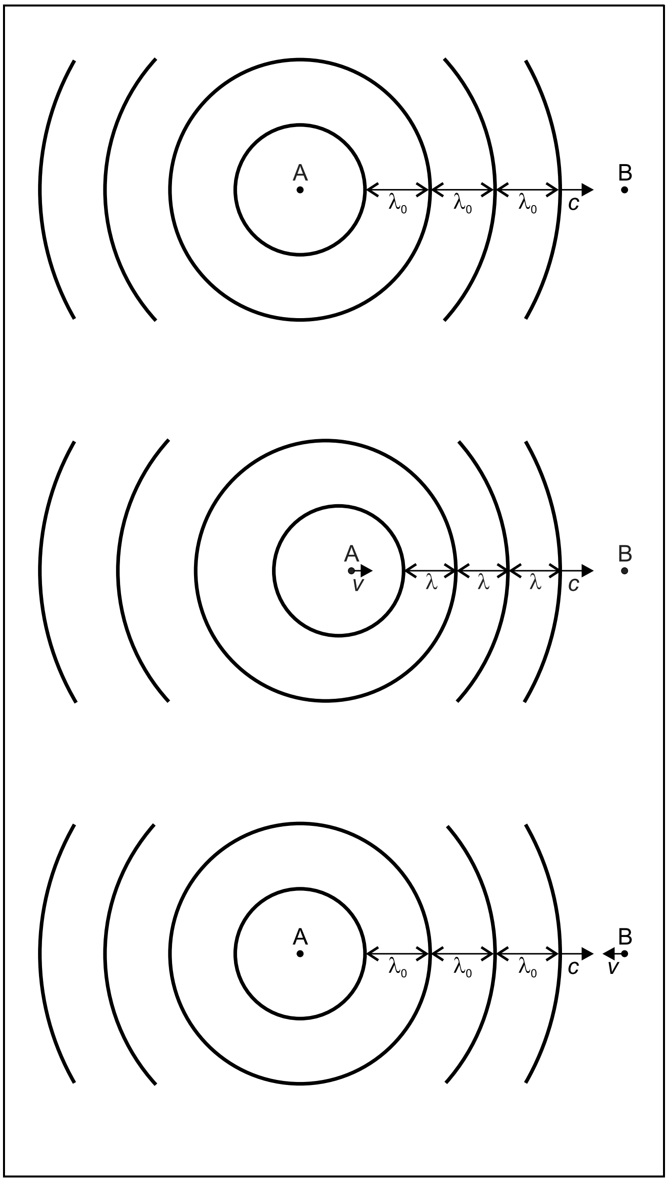

Fig. 1 The propagation of sound with the sound source and the observer at rest (above), with the sound source moving (middle), and with the observer moving (below)

Principles

The acoustic Doppler effect can often be observed in everyday life. For example, the pitch of an ambulance siren is higher while the vehicle is approaching the observer and lower while the vehicle is going away. The pitch changes abruptly at the moment when the vehicle passes the observer. Also an observer moving relatively to the sound source, which is at rest, hears a shifted frequency signal.

In order to understand this effect, consider first the case of a sound source A and an observer B both at rest with respect to the medium of propagation (see Fig. 1). The wave fronts starting from a sound source with a frequency f_0 have a distance λ_0 from each other. They approach the observer at the velocity of sound

$$c = f_0 \cdot \lambda_0 \qquad \text{(I)}$$

and reach him after the time

$$T_0 = \frac{1}{f_0} \qquad \text{(II).}$$

The situation changes when the sound source approaches the observer at the velocity v while the observer is at rest with respect to the medium of propagation. During one period of oscillation T_0, the sound source covers the distance

$$s = v \cdot T_0 \qquad \text{(III);}$$

the distance between the previous wave front and the one just generated is therefore

$$\lambda = \lambda_0 - v \cdot T_0 \qquad \text{(IV).}$$

The wave fronts propagate at the velocity c and reach the observer after the time

$$T = \frac{\lambda}{c} = T_0 \cdot \left(1 - \frac{v}{c}\right) \qquad \text{(V).}$$

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Apparatus

2 ultrasonic transducers, 40 kHz	416 000
1 generator 40 kHz	416 012
1 AC-amplifier	416 010
1 trolley with electric drive	337 07
2 Mignon cells 1.5 V	200 66 264
2 precision metal rails, 1 m	460 81
1 rail connector	460 85
1 sets of pairs of feet	460 88
1 digital counter	575 48
1 two-channel oscilloscope 303	575 211
1 stopclock I, 30 s/15 min	313 07
2 saddle base	300 11
1 stand rod, 25 cm	30041
1 stand rod, 47 cm	300 42
1 Leybold multiclamp	301 01
1 clamp with ring	301 10
1 connection lead, 8 m, screened	501 031
1 set of two-way plug adapters, black	501 644
1 measuring cable BNC/4 mm	575 24

connection leads

For the observer, the frequency emitted by the sound source is thus

$$f = \frac{1}{T} = \frac{f_0}{1 - \frac{v}{c}} \quad \text{(VI).}$$

If, on the other hand, the observer approaches the sound source at a velocity v while the sound source is at rest, the distance between the wave fronts is λ_0. The wave fronts propagate in the medium at the velocity c, but they reach the observer with the time difference

$$T = \frac{\lambda_0}{c + v} = \frac{T_0}{1 + \frac{v}{c}} \quad \text{(VII).}$$

For the moving observer, therefore, the frequency of the sound source at rest is

$$f = \frac{1}{T} = f_0 \cdot \left(1 + \frac{v}{c}\right) \quad \text{(VIII).}$$

Eqs. (VI) and (VIII) give different frequencies for high velocities v. At low velocities, however, the difference is negligible. The frequency shift

$$\Delta f = f - f_0 = f_0 \cdot \frac{v}{c} \quad \text{(IX)}$$

is then proportional to the velocity v.

In the experiment, two equal transducers serve as transmitter (sound source) and receiver (observer) depending on their connection. One transducer is attached to a trolley with electric drive, the other is fixed to a stand rod. The frequency of the observed signal is measured with a high-resolution digital counter. In order to determine the velocity

$$v = \frac{\Delta s}{\Delta t} \quad \text{(X)}$$

of the moving transducer, the time Δt in which the trolley covers a given distance Δs is measured with a stopclock.

Setup

The experimental setup is illustrated in Figs. 2 and 3.

Basic setup:

– Connect the precision metal rails with the rail connector, and support them at both ends with the feet.
– Fix the ultrasonic transducer **(c)** with adhesive tape to the trolley with electric drive in longitudinal direction, and put the trolley onto the precision metal rail.
– Attach the clamp with ring **(d)** to the stand rod 47 cm.
– Connect the screened connection lead with the plug adapters to the pair of cables of the ultrasonic transducer, pass it through the ring **(d)**, and connect the free end to the output **(e)** of the generator 40 kHz.
– Fix the ultrasonic transducer **(f)** to the stand rod 25 cm with the Leybold multiclamp, connect it to the input **(g)** of the AC-amplifier, and align it so that both transducers are opposite each other at the same height.
– To avoid disturbing interferences with ultrasonic waves reflected at the metal rail, wrap both ultrasonic transducers with paper board or paper projecting 10 cm ahead.

Adjusting the resonance frequency:

– Set the generator 40 kHz to continuous operation and the AC-amplifier to “~”.
– Switch both devices on, and wait 15 minutes until the operation is stable.
– Feed the output signal of the AC-amplifier into the oscilloscope via the measuring cable BNC/4 mm (see Fig. 2).
– Observe the output signal with the oscilloscope and improve the alignment of the two ultrasonic transducers.
– Adjust the frequency at the generator 40 kHz so that the output signal has maximum amplitude (resonance frequency).
– At the maximum distance of the trolley set the amplitude of the output signal to about 0.7 V by adjusting the amplification of the AC-amplifier.

Measuring the frequency of the ultrasonic transducer:

– Switch on the digital counter, feed the output signal of the AC-amplifier via the measuring cable BNC/4 mm into input B (see Fig. 3), and press key B.
– Press the key Frequency, and choose the unit Hz.
– Set the input threshold at input B to 0.7 V with the rotary potentiometer **(h)** .

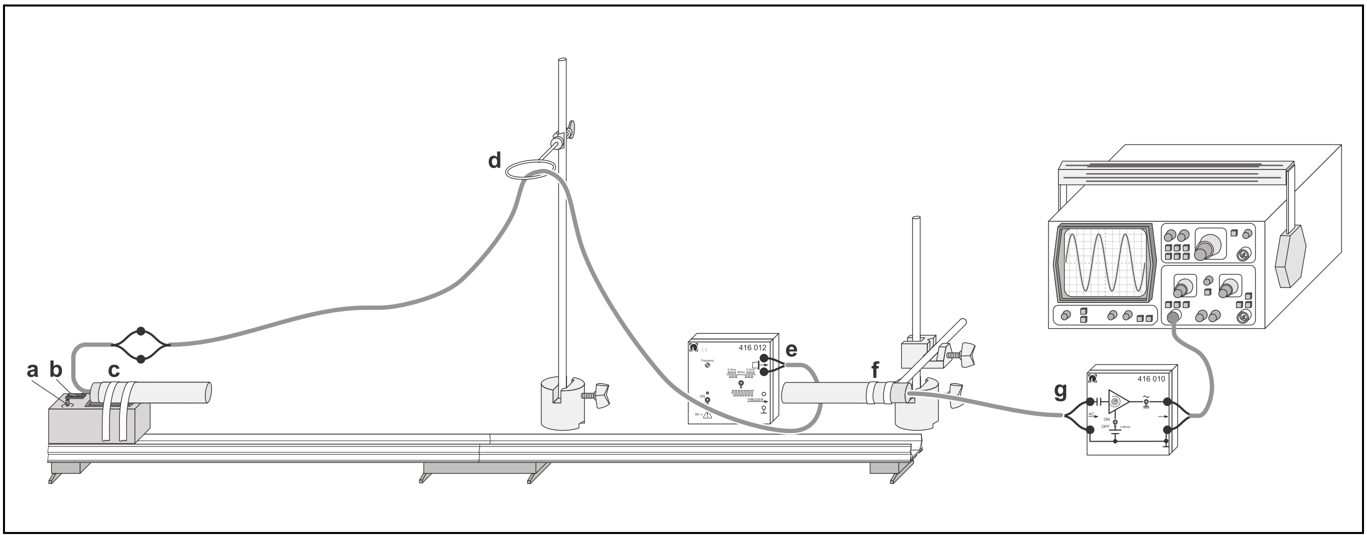


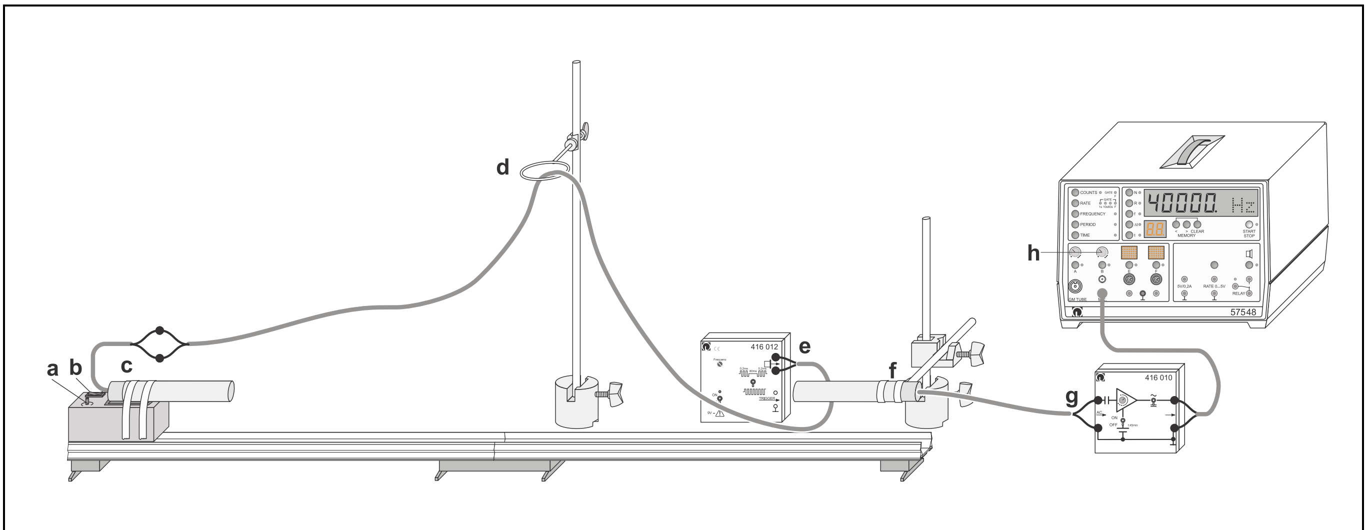
Fig. 2 Setup for adjusting the resonance frequency

Carrying out the experiment

Measuring the change of frequency with the source of ultrasonic waves moving.

- Set the velocity v of the trolley with the potentiometer **(a)**.
- Switch on the drive motor with the three-step switch **(b)**. To determine the velocity measure the time Δt in which the trolley passes a distance Δs of e.g. 1 m, and record it.
- Switch off the drive motor with the three-step switch, start the frequency measurement with the key Start Stop of the digital counter f_0, and stop it by pressing the key again.
- Press the three-step switch, measure the frequency f when the trolley moves “to the right” at a known velocity, and record the frequency.
- Switch the drive motor off with the three-step switch, and determine the rest frequency f_0 again.
- Press the three-step switch, measure the frequency f when the trolley moves with some velocity “to the left”, and record it.
- Repeat the frequency measurements with the trolley moving “to the right” and “to the left”.
- Set the velocity of the trolley to a smaller value. First measure the velocity v, then carry out the frequency measurements with the trolley moving “to the right” and “to the left”.
- Repeat the measurements for two other velocities v.

Fig. 3 Experimental setup for investigating the Doppler effect with ultrasonic waves with the sound source moving



Measuring example

Measuring distance: Δs = 1 m

Table 1: Compilation of the measuring values of the unshifted frequency f_0 and the shifted frequency f

$\frac{\Delta t}{s}$	direction	$\frac{f_0}{Hz}$	$\frac{f}{Hz}$
5.0	right	40144	40168
	left	40143	40121
	right	40142	40166
	left	40142	40117
6.0	right	40188	40207
	left	40186	40165
	right	40186	40204
	left	40185	40166
7.7	right	40193	40207
	left	40187	40171
	right	40185	40201
	left	40183	40167
10.0	right	40147	40157
	left	40147	40135
	right	40147	40157
	left	40146	40136

Evaluation and results

Determining the change of frequency:

Table 1 contains two pairs of measuring values f and f_0 associated with one velocity v or running time Δt of the trolley respectively (the sign taken into account). After the differences $\Delta f = f - f_0$ have been calculated, their mean values are determined. The result is summarized in Table 2. The velocities v calculated from the measuring distance Δs and the running time Δt are assigned to the corresponding frequency shifts.

Tab. 2: The change of frequency $\Delta f = f - f_0$ as a function of the velocity v of the trolley.

$\frac{v}{ms^{-1}}$	$\frac{\Delta f}{Hz}$
–0.2	–23.5
–0.17	–20
–0.13	–16
–0.1	–11
0.1	10
0.13	15
0.17	18.5
0.2	24

Confirming the proportionality between the change of frequency and the velocity:

Fig. 4 is a plot of the values of Table 2. Within the accuracy of measurement they lie on a straight line through the origin. Thus the change of frequency is proportional to the velocity of the sound source.

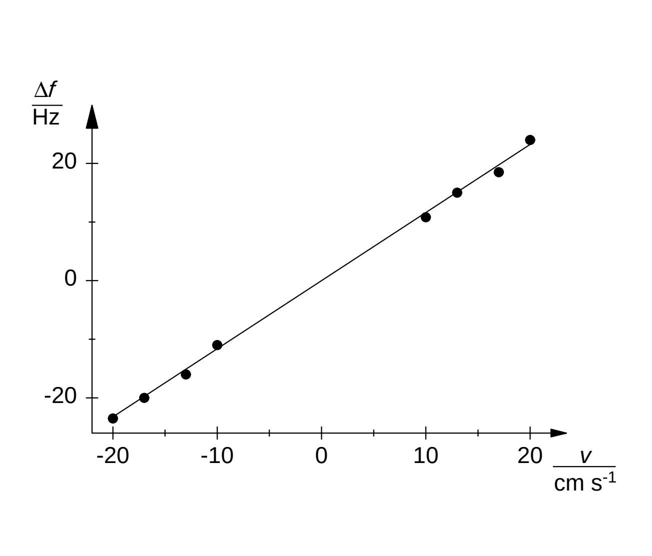


Fig. 4 The change of frequency $\Delta f = f - f_0$ as a function of the velocity v of the trolley.

Determining the velocity of sound in air:

The slope of the straight line drawn through the origin in Fig. 4 is

$$\frac{f_0}{c} = 1.162 \frac{\text{Hz}}{\text{cm s}^{-1}}$$

The mean value of the measured rest frequencies in Table 1 is f_0 = 40165 Hz. With these values the velocity of sound c in air is obtained:

$c = 346 \text{ m s}^{-1}$.

Value quoted in the literature:

$c(25\,°\text{C}) = 346.3 \text{ m s}^{-1}$.

Supplementary information

The experiment for investigating the Doppler effect can also be carried out with a moving observer. In order to do so, the ultrasonic transducer on the trolley has to be connected to the input of the AC-amplifier via the connection lead, and the fixed transducer has to be connected to the output of the generator 40 kHz.

Make certain that the ultrasonic transducers are carefully aligned with each other and that an appropriate amplification is chosen as the amplitude of the output signals must, in any case, exceed the input threshold of the digital counter.

LD DIDACTIC GmbH · Leyboldstrasse 1 · D-50354 Hürth · Phone (02233) 604-0 · Telefax (02233) 604-222 · E-mail: info@ld-didactic.de