ACOUSTIC MEASUREMENTS

USE OF TIME–FREQUENCY DISTRIBUTIONS TO ESTIMATE THE PARAMETERS OF MOTION OF A TONAL SIGNAL SOURCE

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Algorithms for obtaining estimates of the trajectory parameters of a moving signal source for the case of one receiver and two spatially separated receivers are considered. The optimization algorithm is based on the method of coordinate descent using a combination of the golden-section method and subsequent parabolic interpolation. For the interferometric scheme and moderate signal/noise ratios a distance estimation error of \( \pm (5-15\%) \), a traverse time error of \( \pm (1-2) \) sec and a velocity error of \( \pm (2-4\%) \) are attainable.

In a number of measurement experiments used in acoustics, optics, radiophysics, geophysics and hydrophysics, a characteristic and inherent property of the observed physical processes occurs, namely, they are unsteady [1-3]. Traditional methods of measuring the parameters of unsteady processes and wave fields, based on Fourier-analysis adaptation algorithms, in many cases do not possess the required frequency, spatial, and time resolution, due to the a priori disparity between the methods and means of measurement and possible classes of physical models of unsteady signals. Thus, in problems of Doppler ultrasonic tomography, acoustic calibration of a medium, and also inverse problems of radiation, the unsteadiness of the observed signals arises due to kinematic frequency–time distortions arising from mutual displacement (scanning) of the receiving–radiating devices. Inversion of the effects of scanning in signals observed at different points of space, and their subsequent spectral-correlation processing, enables a special type of spatial selectivity to be obtained, namely, trajectory selectivity, simultaneously with high frequency resolution, considerably less than the Doppler frequency shift [4].

Estimate of the Kinematic Parameters When Using a Single Receiver. If the spectrum of the source radiation contains a frequency-stable discrete component, then when the motion of this tonal-signal source is uniform and rectilinear with respect to a fixed receiver, the observed instantaneous Doppler frequency is described by the relation

\[
\nu(t) = \nu_0 \left(1 - \frac{\tau'(t)}{c}\right) = \nu_0 \left[1 + \frac{\nu^2 (t_0 - t)}{c^2 \sqrt{\nu^2 + \nu^2 (t - t_0)^2}}\right].
\]

where \(\nu_0\) is the radiated frequency, \(\tau'(t) = (1/c)\nu(t)\) is the rate of change of the transport delay, \(d\) is the minimum (traverse) distance, \(\nu\) is the linear velocity of motion of the source, \(t_0\) is the instant (time) of traverse and \(c\) is the velocity of propagation of the waves in the medium.

We will assume that the frequency of the radiation in the source has the form

\[
\nu'(t) = \nu_0 + \Delta \nu(t) = \nu_0 \left(1 + \delta(t)\right).
\]
Then, we mean by a stable discrete component the narrow-band signal (2) for which

$$\max_{t \in [t_0, t_0 + \Delta t]} |x(t)| \leq \frac{2\nu}{\varepsilon}.$$ 

where $T$ is the signal observation time at the receiver [where $T$ must be sufficiently long $T \geq (4-10)d/v$, in order to capture the "tails" of the trajectory (1)], and $\varepsilon$ is a relatively small quantity, for example, not greater than $10^{-1}$-10$^{-2}$.

Moreover, we will assume that the signal/noise ratio in a narrow band $df \geq (2.5-5)(v/c)f_0$, containing the chosen discrete component, at least in the neighborhood of the source traverse $t_0 \pm \Delta t$, $\Delta t \geq 2d/v$, is not worse than 3-6 dB.

Taking into account the fact that at low frequencies and low velocities of motion of the source the absolute value of the useful (informative) signal of the Doppler frequency shift is small (for example, for $f_0 = 30$ Hz and $v = 3$ m/sec, $\Delta f_0 = 0.12$ Hz) and the averaging time under the measurement conditions is limited, it is best for stable and detailed separation of the Doppler trajectories to choose the discrete component with a radiation frequency higher than 100-500 Hz.

The parametric model (1) gives the key to constructing algorithms for estimating the source parameters of motion.

The problem in solved in several basic stages [3, 4]:

1. In the neighborhood of the frequency $f_0$ a narrow-band signal $x(t)$ is separated in the band $\Delta f \geq (2.5-5)(v/c)f_0$ and a corresponding analytic signal $z(t) -$ a narrow-band complex envelope, is formed using a Hilbert transformation;