2.2 Experimental setup

Experiments were conducted in a cylindrical water tank 3 m in depth and 4 m in diameter, filled with freshwater. The suspension mechanism and experimental setup are shown in Fig. 2. TS data were collected with a transmitting and receiving system connected to a 50-kHz transducer mounted on the edge of the rotating arm and suspended at mid-water depth in the tank facing horizontally toward the fish (Fig. 2). Prior to the measurements, the echosounder system was calibrated using a tungsten carbide sphere of 38.1 mm diameter.

The fish used in the experiment was carefully suspended using a pair of nylon monofilament lines of 0.205 mm diameter and lowered to the center of the water tank at a depth of 190 cm, 160 cm away from the transducer (Fig. 2).

The procedure for measuring the TS was as follows. At first, keeping the fish at a 0° pitch angle, the transducer was slowly rotated in the horizontal plane around fish from 0° to 360°. The echo amplitude from the fish was measured at 1° intervals. Next, the pitch angle of the fish was increased to 10° and the transducer was rotated horizontally in the same way described above. This procedure was repeated at 10° pitch-angle intervals between 0° and 90° in the horizontal plane from 0° to 360°.

The orientation of the fish was kept stable. The pitch angle of the fish was determined by reading the inclination angle of the hanger that suspended the fish.

2.3 Acoustic data analysis

The target strength ($T_{\text{target}}$) was calculated according to the following equations:

$$T_{\text{target}} = 20 \log \left( \frac{V_{\text{target}}}{V_{\text{ref}}} \right) + T_{\text{ref}},$$  \hspace{1cm} (1)$$

where $V_{\text{target}}$ is the envelope voltage received from the target, $V_{\text{ref}}$ is the envelope voltage from a sphere at the same range, and $T_{\text{ref}}$ is the known TS of the sphere.

The maximum TS was defined as the peak value in the TS function against the horizontal incident angle of the fish. The average TS was determined by averaging the TS function with respect to the fish orientation.$^{15}$

The scatterer orientation can be described by the orientation angles ($\theta$, $\phi$), which specify the scatterer orientation observed from the transducer. In this case, the direction of the incident and the scattering wave (sound pulse) are the same direction in the coordinates. The direction of the incident sound is described by the unit $\hat{\theta}$. Thus, the orientation of the fish is defined by its yaw ($\alpha$), pitch ($\beta$), and roll ($\gamma$) angles. An interpretation of the scatterer orientation of a fish is illustrated in Fig. 3.

According to Tang et al.,$^{12}$ the average backscattering cross-section depends on the distribution of the fish orientation. Assuming that these distributions are independent of each other, then