ABSTRAK

PERANCANGAN PERANGKAT THREE DIMENSIONAL ULTRASONIK ANEMOMETER UNTUK MENDUKUNG PENGUKURAN FLUKS KARBON

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Pengukuran fluks karbon dengan metode eddy covariance (EC) menuntut data kecepatan angin tiga sumbu (u–v–w) berfrekuensi tinggi, berlatensi rendah, dan minim distorsi agar kovarians antara komponen vertikal angin dan konsentrasi gas terekam akurat. Rancangan anemometer 3D sebelumnya berbasis *airspeed sensor* (diferensial tekanan/termal) menunjukkan keterbatasan penting: respons frekuensi yang sempit dan *phase lag* pada turbulensi cepat; *cross-axis coupling* dan bias orientasi; sensitivitas tinggi terhadap suhu/kelembapan yang menuntut *re-zeroing* serta kalibrasi berulang; serta geometri *probe* yang menimbulkan *blockage* di volume ukur. Keterbatasan ini menurunkan fidelitas u–v–w dan meningkatkan ketidakpastian fluks. Untuk itu, kami mengembangkan anemometer 3D ultrasonik berbiaya terjangkau yang bebas inersia mekanik, mengukur *time-of-flight* pada lintasan ortogonal secara langsung, dan mempertahankan respons frekuensi tinggi, sebagai alternatif praktis dibanding unit komersial berharga mahal. Prototipe memanfaatkan enam set transduser ultrasonik yang membentuk tiga *baseline*, unit pemrosesan tertanam berbasis *singleboard computer*, serta protokol akuisisi dan telemetri terintegrasi untuk analisis fluks secara *real time*. Pengujian dilakukan di laboratorium dan uji lapangan terbatas: penalaan elektronik dan kalibrasi *time-of-flight*, uji respons terhadap aliran buatan (hingga ~6 m/s), serta pembandingan dengan *handheld anemometer*. Simulasi dinamika fluida komputasional (CFD) memandu desain *housing* untuk meminimalkan turbulensi parasitik, *recirculation*, dan gaya hambat di sekitar volume ukur. Hasil menunjukkan prototipe beroperasi stabil, peka arah dan kecepatan, serta mampu mengukur hingga 6 m/s. *Noise floor* pada kondisi tanpa angin sekitar ~1 m/s, sedangkan deviasi terhadap referensi *handheld* ±1 m/s pada rentang uji, memadai untuk tahap *proof-of-concept*. CFD mengonfirmasi berkurangnya *recirculation* dan meningkatnya keseragaman aliran pada jalur akustik. Ke depan, peningkatan resolusi waktu, kompensasi suhu/kelembapan per lintasan, serta kalibrasi multi-sumbu ditargetkan untuk menurunkan *noise floor* dan *phase error*, sehingga prototipe semakin layak untuk pengukuran fluks karbon berbasis EC.

Kata kunci: Angin, *Eddy covariance*, 3D anemometer ultrasonik, Fluks karbon.

ABSTRACT

DESIGN OF A THREE-DIMENSIONAL ULTRASONIC ANEMOMETER TO SUPPORT CARBON FLUX MEASUREMENT

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Accurate eddy-covariance (EC) flux estimation requires three-axis wind velocity (u, v, w) at high sampling rates, low latency, and minimal distortion so covariance with scalar concentrations is faithfully captured. Our previous 3D anemometer based on air-speed sensors (differential pressure/thermal) showed constrained frequency response and phase lag in high-frequency turbulence, cross-axis coupling, orientation bias, strong sensitivity to temperature and humidity requiring frequent re-zeroing and recalibration, and probe geometries that blocked flow. These limitations degrade u–v–w fidelity and inflate flux uncertainty. Ultrasonic 3D anemometry mitigates these issues, yet commercial units are costly. We therefore design a cost-effective ultrasonic 3D anemometer for carbon-flux applications. The prototype uses three orthogonal acoustic paths with transducers, an embedded singleboard computer for signal processing, and an integrated acquisition/telemetry protocol supporting real-time EC analysis. Laboratory and limited field tests covered time-of-flight tuning, response to forced flows up to ~6 m s^{-1}, and comparisons with a handheld anemometer. Computational fluid dynamics (CFD) informed a housing that minimizes turbulence around the sensing volume. Results show stable operation, directional sensitivity, and reliable measurement to 6 m s^{-1}. The still-air noise floor was ~1 m s^{-1}, and deviation relative to the handheld reference was ±1 m s^{-1}—performance suitable for a proof of concept. CFD confirmed reduced recirculation and improved flow uniformity. Findings demonstrate the feasibility of a low-cost ultrasonic 3D anemometer for EC-grade monitoring and the rationale for replacing air-speed-sensor designs. Future work will pursue finer timing resolution, path-specific temperature/humidity compensation, and calibration refinements to lower the noise floor and phase error.

Keywords: Wind, Eddy covariance, 3D ultrasonic anemometer, Carbon flux.