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OPERATIONAL FREQUENCIES OF MEASUREMENT SYSTEM COMPONENTS AS KEY DETERMINANTS OF APPLICATION POTENTIAL

This paper presents an investigation of an integrated measurement system combining sensors and data acquisition software, with a focus on how the operational frequencies of individual components determine overall system capabilities. The study explores the frequency-dependent application possibilities of such systems, demonstrating that their performance is not solely defined by hardware specifications but also by dynamic interactions between system elements. The analysis shows that these capabilities can extend beyond routine measurement tasks, enabling more advanced monitoring, diagnostics, and experimental applications. In addition, the potential integration of emerging artificial intelligence techniques is discussed as a means to further enhance system functionality, optimize signal processing, and expand the range of practical applications. Experimental validation and case studies illustrate how operational frequency characteristics influence measurement accuracy, responsiveness, and system adaptability. The results provide insights for the design and deployment of flexible, high-performance measurement systems in research and industrial environments, highlighting opportunities for AI-assisted enhancement of both system capabilities and application scope.
Keywords: Flow measurement, pressure sensor, AI, pressure fluctuations, flow oscillations.

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ОПЕРАЦІЙНІ ЧАСТОТИ КОМПОНЕНТІВ ВИМІРЮВАЛЬНОЇ СИСТЕМИ ЯК КЛЮЧОВІ ДЕТЕРМІНАНТИ ЇЇ ПРИКЛАДНОГО ПОТЕНЦІАЛУ

У статті наведено результати дослідження інтегрованої вимірювальної системи, що поєднує сенсорні елементи, канали збору та оброблення даних, а також програмні засоби аналізу, з акцентом на визначальній ролі робочих частот її компонентів у формуванні загальних функціональних можливостей. Показано, що частотні характеристики датчиків, аналого-цифрових перетворювачів і програмних алгоритмів оброблення сигналів визначають не лише діапазон коректного вимірювання, а й здатність системи реєструвати швидкоплинні процеси, пульсації та несталості у потокових середовищах. Обґрунтовано, що узгодження смуг пропускання окремих елементів і частоти дискретизації є критичним чинником забезпечення метрологічної достовірності та динамічної точності.
Проведений аналіз засвідчив, що завдяки оптимізації частотних параметрів інтегрована система може ефективно використовуватися не лише для стандартного вимірювання витрати й тиску, а й для задач розширеного моніторингу, діагностики технічного стану обладнання, дослідження турбулентних режимів і експериментального моделювання нестаціонарних процесів. Розглянуто вплив частотних обмежень на часову роздільну здатність, швидкодію, рівень шумів і адаптивність системи до змінних умов експлуатації. Наведено результати експериментальної верифікації та приклади застосування, які демонструють залежність точності вимірювання та чутливості до пульсацій від узгодженості частотних параметрів.
Окрему увагу приділено можливостям інтеграції методів штучного інтелекту для інтелектуального фільтрування сигналів, автоматичної ідентифікації режимів потоку, прогнозування аномалій і оптимізації параметрів вимірювання в реальному часі. Показано, що поєднання частотної оптимізації апаратної частини з алгоритмами машинного навчання дозволяє суттєво розширити прикладний потенціал системи, підвищити її гнучкість і забезпечити адаптивну обробку даних. Отримані результати можуть бути використані при проєктуванні високопродуктивних вимірювальних комплексів для наукових досліджень і промислових процесів, де важливою є реєстрація швидкозмінних параметрів середовища.
Ключові слова: вимірювання витрати, датчик тиску, штучний інтелект, пульсації тиску, коливання потоку.

INTRODUCTION

Advanced measurement systems are a key enabler of experimental research under increasingly demanding regulatory and performance constraints in the automotive and off-road sectors. In particular, the ability to resolve unsteady and transient phenomena depends strongly on the dynamic characteristics of sensors and data acquisition systems. The operational frequency ranges of individual measurement components define the overall system capability and therefore determine the range of feasible applications.

Modern experimental investigations increasingly involve complex, oscillatory flow and pressure phenomena whose accurate characterisation requires well-matched sensor bandwidths, sampling rates, and signal-processing

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strategies. Conventional measurement approaches are often limited by insufficient frequency response or by a lack of system-level consideration of dynamic interactions between individual components. As a result, experimental campaigns may become time-consuming, costly, and restricted to a narrow range of operating conditions.

This work investigates an integrated measurement system composed of pressure sensors and data acquisition software, with a specific focus on its frequency-dependent performance and application potential. The study analyses how the operational frequency limits of individual components influence measurement accuracy, responsiveness, and adaptability. An experimental methodology based on standardised flow-measurement techniques according to ISO 5167-1 [7, 8] is employed to evaluate unsteady flow behaviour under realistic operating conditions.

The results demonstrate that the frequency characteristics of the measurement system are a decisive factor in capturing transient phenomena and extracting meaningful performance indicators. Furthermore, the study shows that such systems can support applications beyond routine measurement tasks. The integration of advanced data analysis methods and emerging artificial intelligence (AI) techniques is identified as a promising pathway to further extend the functional range and applicability of integrated measurement systems.

THEORETICAL BACKGROUND

A standard orifice-based air-flow measurement system, implemented in the portable multi-gas flowmeter GFT-50-25 [3] is based on differential pressure measurement and is used to determine air mass flow. Pressure fluctuations are measured using pressure probes, while gas temperature is monitored using a Type-K thermocouple. During data acquisition, the GFT-50-25 is employed for a preliminary estimation of the intake gas flow.

Applications of similar orifice-based air-flow measurement systems have been reported in several previous studies [1]. For clarity, this section provides a brief overview of the system model, adapted from [1] and illustrated in Fig. 1.
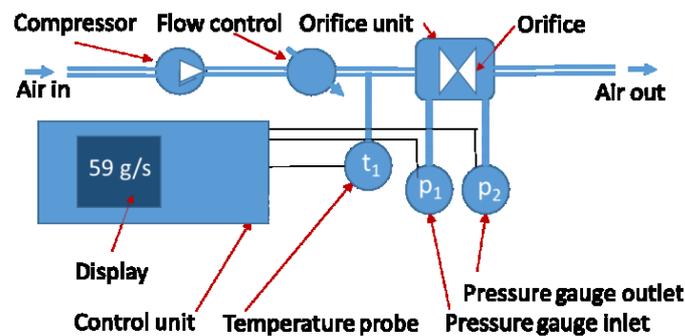

Fig. 1. Principal scheme of airflow measurement using an orifice [1]

The pressure sensors measure the pressure drop across the pre-installed orifice. As it was mentioned in [1], the air mass flow is determined indirectly via pressure and temperature at a measuring orifice. The mass flow is calculated according to the algorithm standardized in DIN EN ISO 5167 [7, 8], which was implemented in software 'Flowcounter' of the GFT. The absolute pressure in front of the orifice plate p_1, the pressure drop across the orifice plate Δp and the temperature T are required as incoming measured values. The calculated outputs are the mass flow m_a in in kg/s. The geometry values of the orifice plate (D, β) and the material parameters of the air (R, κ) are declared as constants in the code and therefore have to be changed accordingly when used with other orifices or fluids.

The method is essentially based on the iterative calculation of the flow coefficient C or the Reynolds number Re. The algorithm was implemented using equations as follows in a clear while loop and realized in the software 'Flowcounter' after several adjustments of sensors application.

The Reynolds number in front of the orifice plate is calculated using equation (1):

$$\mathrm{Re}_D = \frac{u_1 D}{v_1} \cdot \frac{\dfrac{4\dot{m}_a}{\pi D^2 \rho_1} D}{v_1} = \frac{4\dot{m}_a}{\pi \eta_1 D} \tag{1}$$

by rearranging (1) the mass flow can be defined (2):

$$\dot{m}_a \quad Re_{D \cdot} \eta_1 \frac{\pi D}{v 4} \tag{2}$$

where

$$\eta_1 = \frac{1.71 \cdot 395}{T + 122}\left(\frac{T}{273}\right)^{1.5} 0.00001 \tag{3}$$

According to the standard [7], the empirical equation for determination of the expansion number ε_1 for orifice plates can be estimated

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$$\varepsilon_1 = 1 - (0.41 + 0.35\beta^4)\left(\frac{\Delta p}{\kappa p_1}\right) \tag{4}$$

From these determined values, the invariant A_1 can now be calculated according to equation (5)

$$A_1 = \frac{\varepsilon_1(\beta D)^2 \sqrt{2\Delta p \rho_1}}{\eta D \sqrt{1 - \beta^4}} \tag{5}$$

The Reynolds number and flow coefficient are now determined by iteration {(4) and (5)}.

$$\text{Re}_D = A_1 C \tag{6}$$

The starting value is $C = C_\infty = 0.6276$. The termination condition for this iteration is the fulfillment of the accuracy criterion $Y < 0,0001\%$.

EXPERIMENTAL SETUP

The experimental procedures described in this paper are based on the use of conventional pressure probes and a dedicated high-frequency pressure transducer capable of resolving fast transient phenomena. These sensors formed part of a mass-flow measurement systems and a pressure investigation setups integrated into the fuel line and air intake of a hydrogen-powered Wankel [2, 3, 4, 5, 6, 9] engine. The engine served as a technology demonstrator during the airflow meter investigation described in detail in [3].

A Kistler 4818A2 pressure transducer, mounted flush at the trochoid [10] injection point and connected to a Kistler 5011 charge amplifier supplied by Delphin Technology, was used to record fuel-line pressure. The crankshaft position was measured using a digital shaft encoder from Susinet AG. The test rig was additionally equipped with standard engine instrumentation, including thermocouples for measuring oil, intake air, inlet manifold, and exhaust temperatures, as well as pressure gauges at relevant locations. Standard engine test-bed safety features, particularly those required for hydrogen operation, were also implemented. Data acquisition was carried out using in-house developed software.

Measured values were transmitted via an RS-232 interface for graphical display and recording. Air mass flow was measured using a Bosch hot-film anemometer. Exhaust gas probes were installed in the exhaust line close to the exhaust valve to measure engine-out emissions. The flow behaviour of hydrogen supplied by Linde was investigated using the engine test-rig systems. For fuel-flow measurement, a Bronkhorst F-1113AC flow meter was installed upstream of the injector. Fuel temperature was measured using a Type-K thermocouple.

The volumetric flow measurement method is based on the physical and aerodynamic processes occurring at the orifice as shown in Fig. 2. The control unit calculates the required flow variables by considering gas-phase aerodynamic effects and temperature dependency. This makes the system well suited for investigating transient flow behaviour in the engine intake duct. The unit allows the use of various pressure probes [1] to achieve the desired accuracy and measurement frequency of x Hz for air pressure and flow oscillations. The Kistler 4818A2 pressure transducer and the GFT were positioned upstream of the engine interfaces for hydrogen and air, respectively (see Fig. 2.)
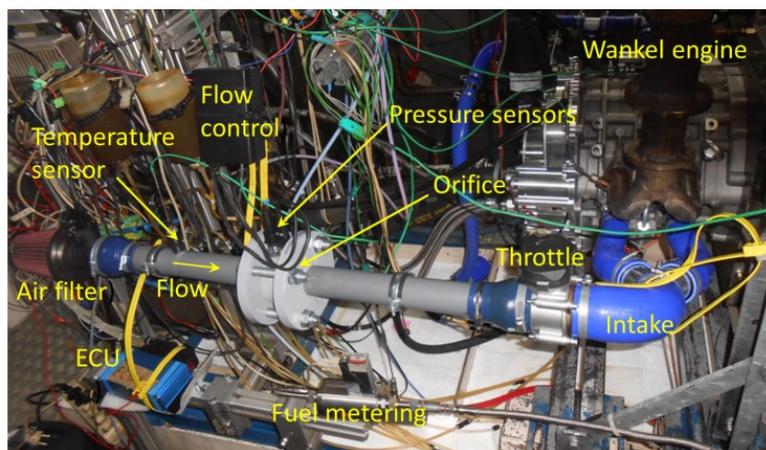

Fig. 2. GFT-50-25 gas flow meter installed at the Wankel engine KKM 502 H2 [3]

RESULTS AND DISCUSSION

Fuel-line pressure fluctuations are a key indicator of injector performance and its influence on engine output. In the absence of shock-tube experiments for hydrogen injectors, a comparative study was conducted using two fuel-pressure dampers (100 ml and 180 ml) installed upstream of the injector to evaluate their damping effect on pressure

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oscillations. Measurements were performed using a Kistler 4818A2 pressure transducer mounted flush at the trochoid injection point and connected to a Kistler 5011 charge amplifier via a Delphin Technology data acquisition system.

Figure 3 shows examples of fuel measured mass-flow fluctuations at 3000 rpm / 16 Nm and 4000 rpm / 24 Nm under a fuel pressure of 10 bar without dampers. The left diagram corresponds to shorter injector opening times (narrow downward red peaks), while the right diagram shows longer opening times (wider downward red peaks).
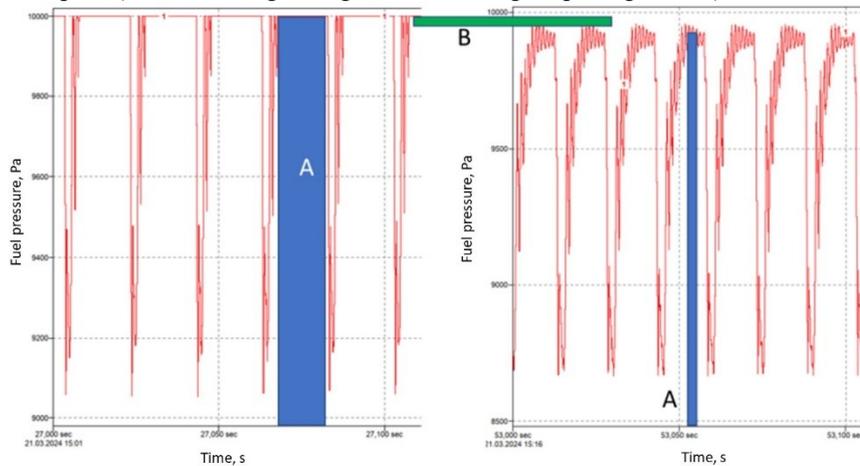

Fig. 3. Comparison of fuel mass flow fluctuations at 3000 rpm and 16 Nm (left) versus 4000 rpm 24 Nm at pinj = 10 bar [3]

The two blue rectangles marked "A" in Fig. 3 illustrate that a longer injector opening time results in a shorter duration of the constant-pressure plateau and a less steep pressure rise after valve closure. In the left diagram, the wider rectangle indicates the longer plateau associated with a shorter injector opening time. In contrast, the narrower rectangle in the right diagram highlights the reduced plateau duration caused by the longer injector opening time. The green rectangle "B" shows that a longer injector opening time at higher load (24 Nm) leads to a reduction in the maximum pressure upstream of the injector. This analysis, performed using a Kistler pressure sensor, confirms the feasibility of applying such sensors for the optimisation of intake fuel-flow oscillations.

Examples of air flow measurements in the engine air intake are shown in Fig. 4. The displayed curves were calculated based on the measured pressure values. Similar aerodynamic phenomena were introduced and discussed in detail in [12].
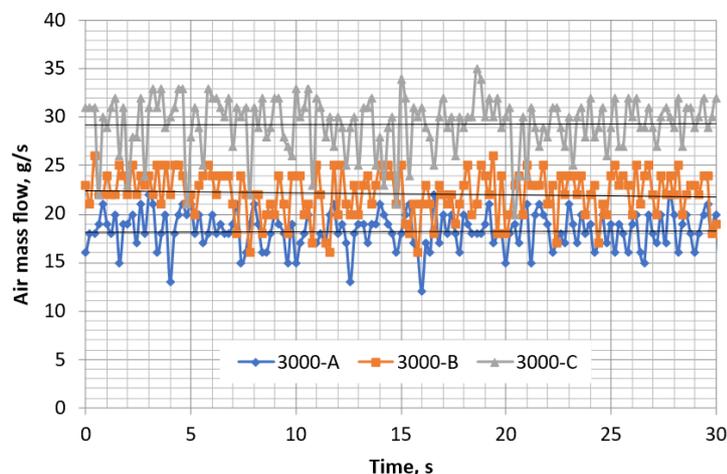

Fig. 4. Comparison of air mass-flow fluctuations at 3000 rpm for different engine loads [9]

An analysis of Fig. 4 shows no significant influence of engine load on the amplitude of air-flow fluctuations at 3000 rpm. The majority of air mass-flow values within the 6σ criterion fluctuate in the range of approximately 10–12 g/s across all investigated loads.

Based on results reported in the literature [3, 10, 11] and obtained in the present study, conclusions can be drawn regarding the range of potential applications for pressure-based measurements. Table 1 illustrates how the choice of pressure measurement system frequency critically influences suitability for different applications. Low-frequency measurements (up to 1 Hz) are well suited for static mass-flow evaluation but are limited for dynamic flows, intake air oscillations [12], engine diagnostics, and thermodynamic cycle studies. Mid-range frequencies (1–50 Hz) provide optimal resolution for dynamic mass flow and moderate capability for static flow and intake oscillations [12], but remain suboptimal for engine diagnostics and cycle research. Higher frequencies (0.5–1 kHz) are particularly

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effective in capturing transient phenomena, while very high frequencies (1–500 kHz) enable the resolution of fine-scale oscillatory dynamics and thermodynamic cycle processes, albeit with limited suitability for static flow measurements.

Table 1

Possible systems applications depending on pressure measurement sensors frequency

Application	Up to 1 Hz	1 – 50 Hz	0,5-1 kHz	1 kHz -500 kHz
Mass flow (static)	++	+	+	-
Mass flow (dynamic)	+	++	-	+
Intake air Oscillation	-	+	++	+
Engine diagnostic (AI)*	-	-	++	+
Thermodynamic cycle research	--	-	+	++

*proposed applicational direction for future use of pressure probes with following data aquisition supported by AI

Engine diagnostics relies on accurately capturing pressure fluctuations within the intake and combustion systems, which are critical indicators of engine performance, efficiency, and potential faults. Key measurable quantities include intake manifold pressure, cylinder pressure, and exhaust backpressure, each reflecting different aspects of engine operation. Low-frequency pressure variations (up to 1 Hz) are typically insufficient for detailed diagnostics, as they capture only quasi-static conditions such as mean manifold pressure. Mid-range frequencies (1–50 Hz) can provide information on slower dynamic phenomena, such as volumetric efficiency changes and transient load variations.

For advanced diagnostics, higher frequencies in the 0.5–1 kHz range are particularly valuable, as they capture rapid pressure oscillations associated with valve events, combustion irregularities, knock, and turbulence. Very high-frequency measurements (1–500 kHz) can resolve fine-scale oscillations, enabling the detection of fast combustion anomalies or injector events that are otherwise inaccessible with conventional sensors.

Recent advances in artificial intelligence (AI) have opened new avenues for engine diagnostics. By combining high-frequency pressure data with machine learning algorithms, it is possible to automatically identify patterns indicative of faults, wear, or inefficiencies. AI models can learn from large datasets of pressure signals to predict misfires, timing irregularities, or abnormal combustion events, offering real-time diagnostic capabilities that exceed traditional threshold-based methods.

In conclusion, effective AI-based engine diagnostics requires carefully selected pressure measurement bandwidths. Low-frequency measurements suffice for coarse performance monitoring, but dynamic and high-frequency pressure data are essential for detecting subtle anomalies and enabling predictive maintenance. By aligning sensor frequency characteristics with the temporal dynamics of the engine processes, AI-driven diagnostics can provide highly detailed, actionable insights into engine health and performance.

CONCLUSION

This study demonstrates that the applicability and effectiveness of pressure-based measurement systems are strongly governed by sensor bandwidth relative to the temporal characteristics of the investigated phenomena. By combining literature findings [10, 11] with experimental results, which were documented in [3], a comprehensive framework has been established linking pressure measurement frequency ranges to specific applications, including static and dynamic mass-flow evaluation, intake air oscillations, engine diagnostics, and thermodynamic cycle research.

The results confirm that low-frequency measurements are suitable for static flow evaluation, whereas dynamic and diagnostic applications require high- and very high-frequency pressure data. In particular, advanced engine diagnostics benefit from pressure measurements capable of resolving rapid transient events. When combined with AI-based data analysis, such measurements enable predictive, high-resolution insights into engine performance and health.

Based on these findings, the application of an orifice-based pressure measurement system directly at the test engine, alongside standard airflow measurement procedures, is recommended for investigating engine performance and combustion instabilities caused by intake air-flow fluctuations. The reported results are highly promising and form a solid basis for future work. Ongoing investigations focus on flowmeter performance at higher frequencies (approximately 40 Hz) and the development of new measurement algorithms supported by AI targeting high-frequency oscillations relevant to mixture formation. These results will be presented in a forthcoming publication.

Nomenclature

A	invariant
AI	artificial intelligence
BTDC	before top dead center, deg
B	orifice plate coefficient
C	flow coefficient
D	inner diameter of test tube, m

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D_o	outer diameter of test tube, m
d	hole diameter of perforated tape, m
e	thickness of tape, m
ε_1	expansion number
f	friction factor
GFT	gas flow tester
h	convective heat transfer coefficient, W/m^2-K
k	adiabatic exponent
L	length of test section, m
$\dot{m}$	mass flow rate, kg/s
ΔP	pressure drop, Pa
Pr	Prandtl number
Q	heat transfer rate, W
R	gas constant, J/mol K
Re	Reynolds number
RPM	Revolutions per Minute
SFC	Specific Fuel Consumption, g/kWh
T	temperature, K
TDC	top dead center
U	mean air velocity, m/s
ρ	fluid density, kg/m^3
v	kinematic viscosity, m^2/s
Y	accuracy criterion

Subscripts

1	inlet
a	air
f	fuel
inj	injection
o	outlet
w	wall

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