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MEASURING SYSTEMS

PHYSICAL MECHANISMS OF FORMING A SYMMETRICAL GAS VELOCITY PROFILE IN PIPELINES BY FLOW STRAIGHTENERS AND FLOW CONDITIONERS AND THEIR CLASSIFICATION

Bilynskyi Y.
Doctor of Technical Sciences,
Professor, Department of General Physics
of Vinnytsia National Technical University,
Vinnytsia, Ukraine
Stetsenko A.
Candidate of Technical Sciences,
Doctoral researcher, Department of General Physics
Vinnytsia National Technical University,
Vinnytsia, Ukraine
Scientific direction: ultrasonic natural gas flowmeters
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Abstract

The physical mechanisms responsible for forming a symmetrical gas velocity profile in pipelines are examined, and a coordinated classification of flow straighteners and flow conditioners is proposed. Constructive, functional, and regulatory approaches are compared. The analysis distinguishes directional suppression of transverse flow, resistive redistribution of axial momentum, flow redirection, and dissipation. It is shown that identical design categories do not necessarily produce identical hydrodynamic or metrological effects. Structural classes and classes based on the dominant action mechanism are treated as separate classification dimensions, while metrological outcomes are considered non-exclusive assessment characteristics. The role of ultrasonic acoustic-path geometry in relating velocity-field changes to flowmeter measurement error is highlighted. Quantitative asymmetry and pressure-loss criteria are not repeated because they were addressed in the authors' separate CFD study. The proposed framework is theoretical and analytical and requires quantitative validation for particular designs.

Keywords: gas flow, ultrasonic flowmeter, flow straightener, flow conditioner, velocity-profile symmetry, swirl, classification.

1. Introduction

The accuracy of ultrasonic gas flow measurement depends on the spatial structure of the velocity field within the measuring section. Elbows, tees, valves, contractions, and other fittings cause axial-velocity asymmetry, swirl, and secondary flows. At constant volumetric flow rate, these disturbances can alter velocity projections onto the acoustic paths and bias the readings [1–4].

Flow straighteners and flow conditioners are used to reduce installation sensitivity. The former primarily suppress transverse motion and swirl, whereas the latter may additionally form the desired axial-velocity profile. Known designs affect the flow structure differently and generate different total-pressure losses [5–9].

The ISO 5167 standards specify particular designs and installation conditions for differential-pressure flow measurement, whereas ISO 17089-1 and AGA Report No. 9 include requirements for ultrasonic gas flowmeters [10–13]. Therefore, testing the combined "conditioner–flowmeter" system is not a new principle. What remains to be systematized is the relationship among structural class, dominant physical mechanism, velocity-field modification, and several simultaneous metrological outcomes.

The aim of this study is to substantiate the physical mechanisms of gas-flow symmetrization and, on that basis, harmonize the classification of straighteners and conditioners for selecting a device as part of an ultrasonic measurement system. The scientific and methodological contribution is a consistent linkage between two independent classification attributes and non-exclusive performance indicators, rather than the discovery of new laws of gas motion.

1.1. Existing classification and regulatory approaches: scope and limitations

Traditional distinctions among flow-conditioning devices are based primarily on design and purpose. ISO 5167-1 and ISO 5167-2 [10, 11] address straighteners and conditioners used to prepare flow for differential-pressure devices, including certain standardized configurations and installation conditions. However, requirements validated for orifice plates cannot automatically be transferred to ultrasonic flowmeters, which are sensitive to the distribution of velocity projections along acoustic paths.

ISO 17089-1 [12] specifies requirements for ultrasonic gas flowmeters, while AGA Report No. 9 [13] provides for testing the metering installation, including a conditioner, under specified disturbances. Thus, the system approach "meter–conditioner–pipeline" already exists and should not be claimed as novel. Nevertheless, qualification tests for a particular configuration and classification by physical mechanism address distinct questions: the former establish suitability of an installation, whereas the latter explain why and under what conditions individual designs may be effective.

Studies by Laws [5], Schlüter and Merzkirch [6], Xiong et al. [7], and Laws and Ouazzane [9, 15] investigate how configuration, installation location, channel length, and perforation geometry affect velocity-field recovery. They provide an important physical and experimental basis; however, descriptions of individual hydraulic mechanisms do not themselves constitute a unified classification connected to spatial averaging by ultrasonic meters.

The proposed approach does not replace established structural classes. Instead, each device is assigned (1) a structural class, (2) a dominant hydrodynamic action mechanism, and (3) a vector of functional and metrological indicators. The first two attributes form the classification basis, while the third is a non-exclusive assessment. This distinction avoids assuming that the same hole pattern or construction name necessarily produces the same metrological result.

The working hypothesis is that the metrological suitability of a conditioner for a given acoustic-path geometry should be predicted not merely from its design name or the reduction in swirl, but from which components of the disturbed velocity field it suppresses and how the residual flow structure affects acoustic averaging. This proposition requires verification using numerical and experimental data but provides a consistent basis for developing selection criteria.

The objectives are to compare existing classification and regulatory approaches; identify the physical features of guiding, resistive, and combined mechanisms; explain the relationship between structural class and action mechanism; and establish the limits of translating hydrodynamic effectiveness into metrological benefit. Symmetrization indicators examined in the authors' separate CFD study [18] are used here only as context, not as new findings.

2. Physical model of velocity-field symmetrization

In a circular pipeline, the gas velocity field can be represented in cylindrical coordinates as the sum of axial, radial, and tangential components:

$$\vec{v} = v_z(r)\,\vec{e}_z + 0 \cdot \vec{e}_r + 0 \cdot \vec{e}_\theta, \quad (1)$$

Where: $v_z(r)r$ — the axial velocity depends on radial position;

$\vec{e}_z$ — is the unit vector along the pipe axis;

$\vec{e}_r, \vec{e}_\theta$ — are the transverse unit vectors, which have no mean contribution under the stated conditions.

For a time-averaged, axisymmetric, fully developed flow, axial velocity depends predominantly on the radius, and the mean transverse components approach zero:

$$v_z = v_z(r),\ \frac{\partial v_z}{\partial \theta} \to 0,\ v_r \to 0,\ v_\theta \to 0. \quad (2)$$

Therefore, symmetrization does not mean producing a uniform (flat) velocity profile. It means weakening azimuthal non-uniformity and transverse motion while permitting radial variation of axial velocity. After passing through fittings, the gas flow may lose axisymmetry:

$$\{v_z'(r,\theta),\ v_r\ v_\theta\} \quad (3)$$

$r\theta v_r, v_\theta$ — that is, axial velocity becomes dependent not only on radius but also on azimuthal angle, while the transverse components become nonzero. This corresponds to secondary flows, swirl, and profile asymmetry.

Without a conditioner, disturbances gradually decay through turbulent momentum transport and dissipation. However, the required straight-pipe length can sometimes reach tens of pipe diameters [5]. A flow-conditioning device aims to accelerate recovery to a state suitable for measurement, without necessarily reproducing a fully developed profile.

2.1. Distinguishing axisymmetry, swirl, and uniformity

Axisymmetry of the mean axial velocity means that, at a fixed radius, it does not vary with azimuthal position. This is not equivalent to the absence of swirl: $\boldsymbol{v_z = v_z(r)}$ can coexist with a nonzero tangential component $\boldsymbol{v_\theta(r)}$. Conversely, strong suppression of $\boldsymbol{v_\theta}$ does not necessarily remove a local shift of the maximum $\boldsymbol{v_z}$ toward the wall. Therefore, swirl reduction, axial-profile symmetrization, and the reproducibility of the velocity distribution should be assessed separately.

Here, symmetrization means bringing the time-averaged field closer to an axisymmetric state; instantaneous turbulent fluctuations do not disappear. For gas flow at moderate Mach numbers, the hydrodynamic estimates used here may be applied locally while accounting for density. A more complete model is needed for large pressure drops, significant compressibility, or nonuniform temperature fields.

The authors have already considered axial-profile asymmetry and pressure-loss assessment in a separate investigation of a DN 100 pipeline with a Zanker straightener [18]. That study used CFD velocity fields, integral asymmetry indicators, and relationships between residual non-uniformity and pressure loss. Their definitions and calculations are therefore not repeated here. Two questions should be distinguished: quantifying how much the profile has changed and explaining physically why a particular geometry caused that change. The present paper addresses the latter.

The dominant mechanism should be identified from the nature of momentum transfer rather than the external appearance alone. When transverse motion is inhibited by interaction with elongated longitudinal surfaces, guiding action dominates. When the axial field is modified by nonuniform local losses through perforations, resistive redistribution dominates. Where both processes are comparable, the mechanism should be considered combined. This subdivision does not exclude dissipation, which accompanies every class and should not automatically form a separate mutually exclusive class.

3. Main physical mechanisms

Tube bundles and honeycomb structures divide the cross-section into parallel channels. Contact with the walls restricts radial and tangential motion and reduces swirl intensity, although the axial profile downstream may remain distorted. Important geometric parameters are length L, channel hydraulic diameter dh, and their ratio $\lambda = L/d_h$. This ratio does not determine performance by itself without considering open-area ratio, flow regime, and installation location [8, 14].

Perforated plates create distributed local hydraulic resistance. Where a local-loss model is applicable, it can be described as follows:

$$\Delta p_i = \xi_i \cdot \frac{\rho v_i^2}{2} \quad (4)$$

Where : ξ_i — is the dimensionless local resistance coefficient, depending on element geometry (contraction, expansion, elbow, grid, sensor assembly, etc.);

ρ — is the gas density;

v_i — is the characteristic local velocity in the cross-section associated with the element;

$\frac{\rho v_i^2}{2}$ — is the dynamic pressure, i.e., kinetic energy per unit volume.

Higher local velocities are associated, all else being equal, with greater pressure loss; varying the hole size and spatial density makes it possible to control the resistance distribution. However, the downstream velocity field also depends on three-dimensional pressure redistribution and jet interaction. Thus, the above equation is not a self-contained model of symmetrization [6, 7].

Vane-type or star-shaped guide elements exert forces that redirect the gas flow and reduce its tangential component. Their effectiveness depends on the structure and orientation of the incoming swirl. Suppressing swirl does not guarantee the elimination of axial-profile asymmetry.

A classical combined Zanker design consists of a perforated section with spatially varying permeability and a guiding structure. The former primarily reshapes the axial profile, while the latter reduces transverse motion. Certain perforated Zanker-plate variants should structurally be classified as perforated devices, even where deep holes also provide directional guidance [9, 15].

Dissipation of energy associated with disturbed motion is important for all mechanisms. The kinetic energy density of the transverse velocity components can be expressed as follows:

$$E = E_\perp + E_z, \text{ де } E_z = \frac{\rho}{2} v_z^2. \quad (5)$$

where$E_\perp$ — the quantity indicates the magnitude of deviations from purely axial motion.

$v_r \to 0 v_\theta \to 0 E_\perp \to 0$ — If both transverse components vanish, this quantity becomes zero, and the kinetic energy of the mean motion is entirely associated with the axial component.

A reduction in mean transverse velocities alone does not determine total pressure losses, which must be assessed separately, considering device resistance, turbulence, and flow regime [6–8].

The quadratic relation between local pressure loss and velocity qualitatively explains stronger resistance to faster jets but does not itself prove profile equalization for every geometry. In a real perforated plate, the holes are coupled through shared pressure fields, jets, separation zones, and turbulent mixing. Thus, the result depends not only on the local coefficient ξi but also on hole geometry, porosity, thickness, conditioner-to-meter distance, and inlet disturbances.

Likewise, a decrease in transverse kinetic energy should not always be attributed solely to local dissipation: energy may be redistributed among velocity components or transported downstream. Consequently, guiding action, axial-momentum redistribution, turbulent mixing, and irreversible hydraulic loss must be distinguished when describing the underlying mechanism.

The same structural class may involve different balances of physical processes. As the ratio of perforation length to diameter increases, a perforated element increasingly restricts transverse deflection within the holes in addition to creating local resistance. Conversely, a channel-type straightener, although structurally guiding, also produces friction and total-pressure losses and can modify the outlet radial profile. Structural class describes construction; mechanism class describes the physical action under specified operating conditions.

The Zanker family is a particularly illustrative example: a classical combination of perforated and guiding sections should not be conflated with a Zanker perforated plate. Elongated plate holes may generate both resistive and guiding effects. Thus, the mechanism is determined by channel configuration, length-to-diameter ratio, and flow regime rather than by a commercial or historical design name [9, 15].

4. Classification of gas-flow conditioning devices

Two independent classification attributes are proposed: structural configuration and dominant physical mechanism. Functional and metrological effects form a separate assessment system because one device may influence several indicators simultaneously. The classification content of the original scheme is retained (Fig. 1).

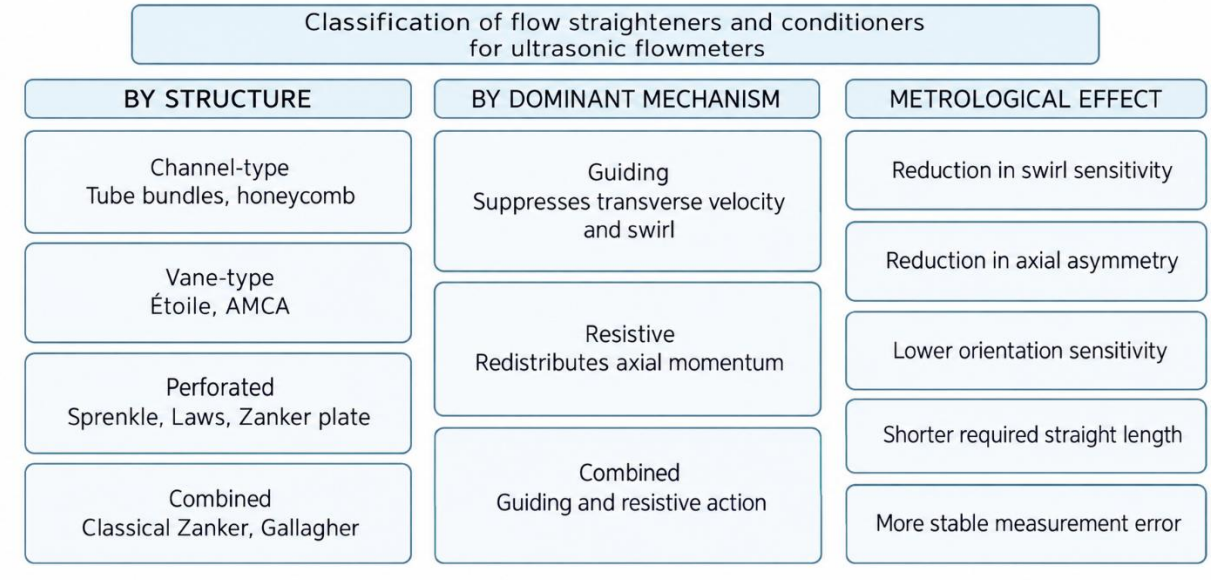


Fig. 1. Multilevel classification and assessment scheme for flow straighteners and conditioners used with ultrasonic flowmeters

Channel-type: tube bundles and honeycombs. Vane-type: including Étoile and AMCA. Perforated: Sprenkle, Laws, NEL/Spearman, and particular Zanker-plate variants. Combined: the classical Zanker, Gallagher, and other multistage devices. Boundaries between classes depend on the actual construction, not merely on commercial or historical names.

Guiding devices primarily constrain transverse motion or redirect the velocity vector. Resistive devices create local pressure drops and redistribute axial momentum. Combined devices incorporate both guiding and resistive mechanisms. Dissipation accompanies every class and therefore does not represent a separate mutually exclusive class.

One structural type can implement multiple mechanisms of different strengths. For instance, a thick perforated plate combines resistive action with guidance along its holes, while a short honeycomb suppresses some transverse motion but may leave axial-velocity asymmetry. A two-dimensional "structure + mechanism" matrix is therefore preferable to rigidly equating design names with physical effects.

The functional and metrological dimension is not a third mutually exclusive class: a device can simultaneously reduce swirl, axial asymmetry, installation sensitivity, and required straight-pipe length. (Table 1).

Table 1.

Comparison of existing approaches and the proposed systematization

Approach	Main subject	What it provides	Limitations for this study
ISO 5167 [10, 11]	Differential-pressure metering installation	Standard designs, installation rules and suitability checks	Does not classify the acoustic sensitivity of ultrasonic meters
AGA 9 [13]	Ultrasonic flowmeter installation	Testing the particular combination of meter, conditioner, and pipeline	Does not define independent physical and structural device classes
Hydrodynamic studies [5–9, 15]	Individual designs and velocity fields	Experimental relations and physics of disturbance and recovery	Do not provide a unified multilevel assessment
Proposed framework	Device and its effects on velocity fields and acoustic paths	Links device class, mechanism, and verifiable criteria	Methodological at present; needs quantitative validation

Unlike ISO 5167, the proposed classification does not introduce new installation requirements or replace established designs. Its purpose is to compare devices of different structural origins using common physical principles. Unlike ISO 17089-1 and AGA Report No. 9, it does not replace metering-system qualification tests but explains which mechanisms may cause different meters to respond differently to the same disturbance. Compared with studies of individual conditioners, it provides a generalized framework separating dominant physical effects from particular constructions.

The contribution is not the discovery of new hydrodynamic laws or a previously unknown straightener, but a methodological combination of two classification dimensions and separate non-exclusive metrological outcomes. This approach highlights cases where structurally different devices perform similarly and visually similar devices operate through different dominant mechanisms.

5. Comparative analysis and metrological effects

For an ultrasonic flowmeter, the important question is not only how much a conditioner reduces swirl, but also how the downstream velocity field interacts with the particular acoustic-path arrangement. Even moderate swirl may be accompanied by residual azimuthal non-uniformity affecting estimated mean velocity where the paths do not represent the cross-section evenly [1–4, 16].

Functional and metrological assessment should consider swirl reduction, reduction of axial-profile asymmetry, dependence of error on disturbance orientation, error change relative to the reference installation, required straight length, stability of meter response, and pressure loss. These are parallel assessment criteria, not mutually exclusive device classes (Table 2).

Table 2.

Qualitative comparison of structural classes, mechanisms, and typical limitations

Class	Mechanism	Effect on flow	Limitation
Channel-type	Guiding	Attenuates swirl and transverse velocity	Axial-profile asymmetry may remain
Vane-type	Flow redirection	Suppresses swirl	Depends on inlet-disturbance orientation
Perforated	Predominantly resistive	Redistributes axial momentum	Additional pressure losses; potential jet effects
Combined	Guiding + resistive	Integrated reshaping of velocity field	Complexity, size, and pressure losses

These characteristics are qualitative generalizations: neither swirl suppression nor error reduction can be quantified solely from the class name. Quantitative conclusions require information on geometry, Reynolds number, inlet disturbance structure, and conditioner position relative to the flowmeter.

In a transit-time ultrasonic flowmeter, each acoustic path characterizes an integrated velocity projection onto the direction of sound propagation. To first order, at low Mach numbers and with an unchanged acoustic-ray path, the measured quantity for the i-th path is proportional to a linear functional of the velocity field:

$$u_i \approx \frac{1}{L_i}\int_{\Gamma_i} v(x)\cdot e_i\, ds\,, \qquad (6)$$

whereΓ_i — is the ultrasonic propagation path (acoustic ray);

L_i — is the length of that path;

e_i — is the unit vector along the acoustic ray;

$v(x)x$ — is the local velocity field at points along the ray;

u_i — is the mean projected velocity along the ray.

Normalization and calibration transformations may differ between meter configurations; the expression is used here to explain the physical basis of measurement sensitivity.

If flow rate is estimated using a weighted sum of the velocities measured along the acoustic paths, then:

$$\hat{Q} = A\,\frac{\sum_i w_i u_i}{k_i} \qquad (7)$$

where: A — is the pipe cross-sectional area;

$u_i i$ — is the mean projected velocity along the i-th acoustic path, as defined above;

w_i — are the weights accounting for ray geometry and sensitivity;

k_i — are calibration and normalization coefficients for the particular meter configuration;

$\hat{Q}$ — is the estimated volumetric flow rate.

The true volumetric flow rate is determined by integrating the axial-velocity component over the pipe cross-section:

$$Q = \int_A v_z\, dA, \qquad (8)$$

where: v_z — is the local axial velocity at a point in the cross-section;

A — is the pipe cross-sectional area;

dA — is an infinitesimal area element.

Formally, the systematic spatial-integration error may be expressed as:

$$\varepsilon_Q = \frac{\hat{Q}-Q}{Q}, \qquad (9)$$

цhere: $\hat{Q}$ — is the flow-rate estimate obtained from weighted acoustic-path measurements;

$Q = \int_A v_z\, dA$ — is the true volumetric flow rate;

ε_Q — is the relative integration error.

This is a model description of the dependence on the velocity field, not a universal algorithm for every ultrasonic flowmeter.

A reduction in swirl or asymmetry downstream of a conditioner does not uniquely determine ε_Q: the result depends on acoustic-path arrangement, inclination angles, weighting coefficients, and the velocity field. Consequently, the metrological benefit is not inherent in a design-class name; it arises from interaction between the hydrodynamic field and the specific measurement geometry.

6. Selection criteria for ultrasonic gas flowmeters

Device selection should follow the sequence “inlet disturbance → required physical mechanism → design → downstream velocity field → metrological result.” Where swirl is present with relatively little axial asymmetry, a guiding device may suffice. Where the axial profile is strongly distorted, resistive and combined solutions should be evaluated. These hypotheses must be verified for the specific metering installation.

Multicriteria selection should consider swirl suppression, axial-profile symmetrization, pressure loss, installation length, and error stability.

A promising approach is integrated CFD modeling of the chain “conditioner geometry → velocity field → acoustic paths → meter error,” followed by experimental validation. Another direction is integrating gas-flow conditioning elements into the meter body [17].

The proposed assessment procedure is to characterize the disturbance (asymmetric axial field, swirl, secondary flows, or combinations); select candidate geometries with suitable dominant mechanisms; calculate

Az and T⊥ at fixed control sections; determine Kp from total-pressure measurements; calculate acoustic-path signals and ε_Q for a known ray geometry; and repeat across Reynolds numbers, operating regimes, and disturbance orientations.

The classification hypothesis can be tested by comparing, under identical disturbances and operating conditions, how different structural classes alter axial and transverse velocity components, followed by assessment of the resulting metrological effect for a particular meter. Independent CFD calculations or experimental validation are required; the study does not claim a guaranteed reduction in measurement error for any class.

For reliable comparison, flow rate, gas properties, upstream fitting configuration, distances from the disturbance to the conditioner and meter, and measurement-body geometry must be fixed. Velocity fields may be obtained by validated numerical modeling or experimentally; error estimates must be verified against reference flow measurements.

This study provides a theoretical and analytical systematization. It contains no new series of CFD calculations or experiments and therefore establishes neither numerical device-performance thresholds nor universal coefficients nor proven superiority of a particular design. This limitation constrains the claims made and defines the next stage of research.

The physical analysis explains why suppression of transverse motion does not necessarily equalize the axial profile and why resistive symmetrization is associated with added pressure loss. However, the relations presented do not form a closed predictive model of measurement error. Such a model requires inlet and outlet velocity profiles, turbulence characteristics, hydraulic resistance coefficients, and acoustic-system parameters. Therefore, the proposed classification is a tool for comparison and informed selection, not experimental proof that any one class is superior.

Conclusions

Gas-flow symmetrization consists in bringing axial velocity closer to a function of radius and weakening transverse components, rather than producing a uniform velocity distribution across the section. Flow straighteners and conditioners operate through guiding suppression of transverse motion, resistive redistribution of axial momentum, or combinations thereof; dissipation accompanies each mechanism.

The structural classes (channel-type, vane-type, perforated, and combined) are aligned with classes based on the dominant mechanism (guiding, resistive, and combined). Metrological outcomes are properly treated as separate, non-exclusive indicators. Device selection should account for the compatibility between the mechanism and inlet disturbance, hydraulic losses, and interaction of the resulting field with acoustic-path geometry.

A quantitative relationship between the error of a particular ultrasonic meter, conditioner design, and spatial flow structure at specified pressure losses remains to be established. This requires CFD calculations and experimental validation.

The methodological contribution lies in separating structural and mechanism-based classifications from non-exclusive metrological effects.

The acoustic-integration model shows that velocity-profile changes must be considered together with acoustic-path geometry and weights. This provides a basis for evaluating the metrological compatibility of a conditioner and an ultrasonic meter. The conclusions have defined limits: the classification and indicators provide a theoretical and methodological basis, while quantitative performance, optimal geometries, and error reduction still require dedicated CFD and experimental verification.

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