HYDRAULIC QUARTER-WAVE STUB PULSATION SUPPRESSOR

Technical Specification: Transmission-Line-Derived Side-Branch Resonator Network for Gear Pump Ripple Attenuation

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Scope

This specification defines the geometry, material, installation, and acceptance requirements for a hydraulic side-branch stub network designed to attenuate periodic pressure ripple generated by a rotary gear pump. The specification is derived analytically from the transmission-line correspondence between hydraulic and electromagnetic distributed-parameter systems (KHEO mapping, M-series). No simulation software is required to generate, verify, or modify this specification. All parameters are closed-form expressions of system geometry and fluid properties. The specification is complete as written and is suitable for direct issue to a fabrication shop.

The design methodology transfers the RF quarter-wave stub technique — a standard impedance-matching tool in microwave and transmission-line engineering — to the hydraulic domain using the exact correspondence between hydraulic characteristic impedance and electromagnetic transmission-line impedance. The stub geometries, placement rules, and acceptance criteria all derive from this correspondence without approximation.

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1. Operating Principle

A gear pump with N lobes rotating at speed Ω (RPM) generates a pressure ripple at the fundamental gear-mesh frequency:

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f₀ = N × Ω / 60      [Hz]
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and harmonics at $k \times f_0$ for k = 2, 3, 4, ...

In the hydraulic domain, the pipe network is a distributed-parameter transmission line. The governing equations are the hydraulic telegrapher equations:

```
∂P/∂x = −(ρ/A) × ∂Q/∂t          [momentum]
∂Q/∂x = −(A/K_eff) × ∂P/∂t      [continuity]
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where P is acoustic pressure [Pa], Q is volume velocity [m³/s], ρ is fluid density [kg/m³], A is pipe cross-sectional area [m²], and K_eff is the effective bulk modulus [Pa] accounting for pipe wall compliance.

These equations are identical in form to the electromagnetic telegrapher equations:

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∂V/∂x = −L' × ∂I/∂t
∂I/∂x = −C' × ∂V/∂t
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with the correspondence:

Hydraulic variable	**EM variable**	**Correspondence**
Pressure P [Pa]	Voltage V [V]	Potential variable
Volume velocity Q [m³/s]	Current I [A]	Through-flow variable
Fluid inertia ρ/A [kg/m⁴]	Inductance per length L′ [H/m]	Stored kinetic energy
Pipe compliance A/K_eff [m³/Pa/m]	Capacitance per length C′ [F/m]	Stored potential energy
Hydraulic impedance Z_h = ρc_eff/A	Line impedance $Z_0 = \sqrt{(L'/C')}$	Wave impedance

The hydraulic characteristic impedance is:

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Z_h = ρ × c_eff / A      [Pa·s/m³]
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The effective wave speed including pipe wall compliance is the Joukowski speed:

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c_eff = √(K_fluid / ρ) / √(1 + (K_fluid/E_pipe) × (D/e))      [m/s]
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where D is the internal pipe diameter [m], e is the pipe wall thickness [m], and E_pipe is the pipe wall Young's modulus [Pa].

In EM transmission-line design, a quarter-wave shorted stub connected in shunt at a junction presents zero impedance (a short circuit) at its resonant frequency, diverting all energy at that frequency away from the downstream load. The hydraulic equivalent is a closed-end side branch of length L_stub = c_eff/($4f_0$): at resonance, the stub presents a pressure node at the main pipe junction, absorbing the pressure oscillation at f_0 into the stub resonance and blocking its downstream propagation.

The stub length rule is:

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L_stub = c_eff / (4 × f_target)     [m]
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This is the complete design equation. All other parameters in this specification are derived from it.

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2. Design Inputs

The following parameters must be provided by the system engineer before stub sizing is performed. Nominal values for the reference system used in the worked example (Section 4) are given.

Parameter	Symbol	Reference Value	Unit	Source
Pump lobe count	N	8	—	Pump datasheet
Pump rated speed	Ω	1450	RPM	Pump datasheet
Fluid density at operating temperature	ρ	998	kg/m³	Water at 20°C
Fluid bulk modulus	K_fluid	2.15×10^{9}	Pa	Water at 20°C
Fluid dynamic viscosity	μ	1.0×10^{-3}	Pa·s	Water at 20°C
Pipe internal diameter	D	52.5×10^{-3}	m	DN50 Sch.40 steel
Pipe wall thickness	e	3.91×10^{-3}	m	DN50 Sch.40 steel
Pipe Young's modulus	E_pipe	2.0×10^{11}	Pa	Carbon steel
Operating pressure	P_op	6.0×10^{5}	Pa	6 bar gauge

Minimum operating pressure	P_min	2.0×10^5	Pa	2 bar gauge
Number of harmonics to suppress	k_max	3	—	Specified

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3. Specification Tables

3.1 Derived System Parameters

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Fundamental ripple frequency:
    f₀ = N × Ω / 60 = 8 × 1450 / 60 = 193.3 Hz

Effective wave speed (Joukowski):
    c_eff = √(K_fluid/ρ) / √(1 + (K_fluid/E_pipe)(D/e))
          = 1466 / √(1 + (2.15×10⁹/2.0×10¹¹)(52.5/3.91))
          = 1466 / √(1 + 0.01075 × 13.43)
          = 1466 / √1.1444
          = 1466 / 1.0698
          = 1371 m/s

Pipe cross-sectional area:
    A = π(0.0525)² / 4 = 2.165 × 10⁻³ m²

Hydraulic characteristic impedance (main):
    Z_h = ρ × c_eff / A = 998 × 1371 / 2.165×10⁻³
        = 6.32 × 10⁸ Pa·s/m³

Acoustic wavelength at fundamental:
    λ₀ = c_eff / f₀ = 1371 / 193.3 = 7.09 m
```

3.2 Stub Network — Dimensions and Materials

Each stub is a closed-end side branch of the specified length, constructed from the same pipe schedule as the main line. The closed end is a welded flat-plate cap. A Schrader valve port is incorporated at the closed end for resonant frequency verification by impulse test (Section 6.3).

Stub	**Target frequency**	**Stub length L_stub**	**Stub ID**	**Wall schedule**	**End cap**
S1 (fundamental)	193 Hz	1.774 m	52.5 mm	Sch.40 carbon steel	Welded flat cap
S2 (2nd			52.5	Sch.40	Welded

harmonic)	387 Hz	0.887 m	mm	carbon steel	flat cap
S3 (3rd harmonic)	580 Hz	0.591 m	52.5 mm	Sch.40 carbon steel	Welded flat cap

Stub lengths are measured from the centerline of the main pipe to the inside face of the end cap. Dimensional tolerance: ±5 mm on all stub lengths (corresponds to ±0.3% frequency error at the fundamental, within the acceptance band of Section 6.2).

3.3 Stub Junction Geometry

Each stub connects to the main pipe via a tee fitting. Requirements:

- Tee fitting type: full-bore (port area ≥ 98% of main pipe bore) to minimize insertion loss
- Branch angle: 90° perpendicular to main pipe axis
- Orientation: vertical (stub above or below main horizontal run) to prevent air trapping
- Weld quality: full penetration butt weld at stub-to-tee joint; no internal bead protrusion exceeding 1.5 mm
- Internal surface finish: no requirement beyond standard pipe mill finish (Ra ≤ 6.3 µm acceptable)

3.4 Stub Placement

Stubs must be located at positions of maximum pressure oscillation amplitude in the main pipe. For a pump discharging into a pipe with a downstream isolation valve or reflective termination, pressure antinodes occur at integer multiples of λ/2 from the termination and within λ/4 of the pump outlet.

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Maximum distance from pump outlet discharge flange to S1 centerline:
    x_max = λ₀/4 = 7.09/4 = 1.77 m

Recommended placement:
    x_S1 = 0.5 – 1.5 m from pump discharge flange
    x_S2 = x_S1 + 0.5 – 1.0 m (downstream)
    x_S3 = x_S2 + 0.3 – 0.6 m (downstream)
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Stubs should not be placed within 5 pipe diameters (5D = 0.26 m) of each other to avoid acoustic coupling between stub cavities. Stubs should not be placed within 10D of any elbow, valve, or reducer in the main line.

3.5 Adjustable-Length Option

If the pump speed is variable across a range of ±10% of rated speed, the stub closed end shall be replaced with a sliding piston end cap on a threaded rod, allowing length adjustment of ±10% of the nominal stub length. The piston shall be sealed with O-rings rated to 150% of maximum operating pressure. The adjustment rod shall be externally accessible without system depressurization.

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4. Worked Numerical Example

Performance estimate for S1 at the fundamental frequency (193 Hz).

Attenuation at resonance:

The transmission loss of a side-branch resonator in a pipe is:

$$TL = 10 \log_{10} [1 + (Z\_h / 2 \cdot Z\_stub\_in)^2] \qquad [dB]$$

At the resonant frequency of a lossless closed-end stub, Z_stub_in → 0, giving TL → ∞. With viscothermal losses in the stub, the residual stub input impedance at resonance is approximately:

$$Z\_stub\_in|resonance \approx Z\_h\_stub \times \alpha\_stub \times L\_stub$$

where α_stub is the plane-wave attenuation coefficient [Np/m] due to viscous boundary layer losses:

$$\alpha\_stub = (1/D\_stub) \times \sqrt{(2\mu\omega/\rho)} \times (1 + (\gamma-1)/\sqrt{Pr}) \qquad [Np/m]$$

For water at 20°C, $\mu = 1.0\times10^{-3}$ Pa·s, $\gamma \approx 1.0$ (nearly incompressible at these frequencies), $Pr \approx 6.9$, $\omega = 2\pi\times193 = 1213$ rad/s, D_stub = 0.0525 m:

$$\sqrt{(2\mu\omega/\rho)} = \sqrt{(2 \times 1.0\times10^{-3} \times 1213 / 998)} = \sqrt{(2.43\times10^{-3})} = 0.0493\ m/s\hat{}(1/2) \cdot (Pa \cdot s/k$$

$$\alpha\_stub \approx (0.0493/0.0525) \times (1 + 0) \approx 0.94 \times 10^{-3}\ Np/m \approx 8.1\times10^{-3}\ dB/m$$

Stub Q factor at 193 Hz:

$$Q = \pi/(2 \times \alpha\_stub \times L\_stub) = \pi/(2 \times 0.94\times10^{-3} \times 1.774) \approx 940$$

At this Q, the residual input impedance is approximately $Z\_h\_stub/Q \approx 6.32\times10^8/940 \approx 6.7\times10^5$ Pa·s/m³.

Transmission loss estimate:

$$
\begin{aligned}
TL &\approx 10 \log_{10} [1 + (6.32\times10^{8} / (2 \times 6.7\times10^{5}))^{2}] \\
&= 10 \log_{10} [1 + (471)^{2}] \\
&= 10 \log_{10} [1 + 221{,}841] \\
&\approx 10 \times 5.35 \approx 53.5 \text{ dB}
\end{aligned}
$$

This is the lossless-stub analytical upper bound. In practice, fabrication tolerances, tee geometry, and coupling losses reduce measured attenuation; 20–30 dB is the conservative design target and minimum acceptance criterion. The analytical estimate provides headroom of > 20 dB against the acceptance floor.

Attenuation bandwidth:

$$
\begin{aligned}
&\text{Bandwidth } (-3 \text{ dB from peak attenuation}): \\
&\quad \Delta f = f_0/Q \approx 193/940 \approx 0.2 \text{ Hz}
\end{aligned}
$$

This bandwidth is narrower than the speed variation of a mains-frequency-driven pump. For a pump at 50 Hz mains supply ±1% (1449–1451 RPM), the ripple frequency variation is ±0.2 Hz — within the stub bandwidth. For a VFD-driven pump with wider speed range, the adjustable-length option (Section 3.5) is mandatory.

Mean-flow pressure drop:

The tee fitting and stub volume add a minor increase in local pipe volume. Estimated head loss through the tee junction (full-bore fitting, K = 0.3):

$$
\Delta P_{stub} = K \times (\rho/2) \times v_{mean}^{2}
$$

At mean flow velocity v_{mean} = 1.0 m/s in DN50 pipe:

$$
\Delta P_{stub} = 0.3 \times (998/2) \times 1.0^{2} = 150 \text{ Pa per tee fitting}
$$

Total for three stubs: 450 Pa ≈ 0.0045 bar — 0.075% of the 6 bar operating pressure. Well within the 0.5% specification limit.

Cavitation check in stub:

Minimum absolute pressure in stub at resonance must exceed the fluid vapor pressure P_{vapor} = 2337 Pa (water at 20°C). At P_{min} = 2 bar gauge + 1 bar atm = 3 bar absolute = 3×10^{5} Pa, and with maximum expected pressure oscillation amplitude in stub ≤ $P_{min}/2$ = 1.5×10^{5} Pa, the local minimum is ≥ 1.5×10^{5} Pa >> P_{vapor}. No cavitation risk at the specified operating pressure floor.

5. Installation Requirements

I1. Stub axes shall be oriented vertically or within 30° of vertical to prevent air accumulation in the stub cavity.

I2. The stub shall be filled with system fluid and fully bled of air before commissioning. A manual bleed valve or automatic air release valve shall be fitted at the stub closed end if the stub is below horizontal.

I3. The stub shall be hydrostatically tested at 1.5× maximum operating pressure before installation into the main line.

I4. Stubs shall be thermally insulated to the same standard as the main pipe to prevent differential thermal contraction errors in stub length.

I5. Where the main pipe is subject to vibration isolation mounts, each stub shall be supported independently with a flexible hose section or bellows joint within 0.3 m of the main pipe tee, to prevent stub length change under pipe deflection.

I6. The Schrader valve port at the stub closed end shall remain accessible after installation for resonant frequency verification.

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6. Acceptance Criteria

6.1 Pressure ripple attenuation shall be measured with calibrated dynamic pressure transducers upstream and downstream of the stub network at rated pump speed. The measurement band shall be 10–2000 Hz. Acceptance: attenuation at each target frequency ≥ **20 dB** relative to the no-stub baseline.

6.2 Resonant frequency of each stub shall be within **±5%** of the target frequency. Measurement method: impulse test via the Schrader valve port with the stub isolated from main flow. Apply a short pressure impulse, record the decaying oscillation with a dynamic pressure transducer at the closed end, extract f_resonant from the FFT. Tolerance: f_0_measured within ±9.7 Hz of specified for S1, ±19 Hz for S2, ±29 Hz for S3.

6.3 Mean flow pressure drop across the stub network shall be measured at rated flow. Acceptance: total pressure drop across the three tee junctions < **0.5% of operating pressure** (< 30 mbar at 6 bar operating).

6.4 No cavitation shall be detectable by acoustic emission measurement on the stub body during operation at minimum operating pressure and rated speed. Acceptance: no broadband acoustic emission spike characteristic of cavitation collapse in the 10–100 kHz band.

6.5 Dimensional verification of stub lengths shall be performed before installation. Measure from main pipe centerline to inside face of end cap using a calibrated steel rule or laser distance tool. Acceptance: within ±5 mm of specification.

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7. Failure Mode Register

Failure Mode	Cause	Consequence	Detection	Repair
Stub length error	Fabrication tolerance, temperature change	Resonant frequency shifts off target; attenuation drops at f_0	Impulse test; residual ripple above 20 dB floor	Adjust piston end cap if adjustable; replace stub if fixed
Air entrainment in stub	Incomplete bleeding, dissolved gas release	Effective stub length changes; c_eff rises; resonant frequency increases	Impulse test shows f_resonant above specification	Bleed stub; install automatic air release at stub closed end
Tee fitting partial bore	Full-bore fitting not installed; reducer tee used	Insertion loss increases; attenuation reduced	Pressure drop exceeds 0.5% specification	Replace with full-bore tee
Cavitation in stub at low pressure	System pressure drops below stub oscillation amplitude	Broadband noise; stub erosion	Acoustic emission spike at stub body	Raise minimum system pressure; reduce stub inlet restriction
Stub-main pipe decoupling	Flexible joint introduces impedance break	Stub isolated from main; no attenuation	Ripple attenuation disappears; impulse test shows stub response unchanged with and without main flow	Remove or relocate flexible joint; keep stubs on rigid section of main

Pump speed change	VFD application without adjustable stubs	f_0 shifts outside stub bandwidth; residual ripple increases	Persistent ripple at downstream point	Install adjustable-length option; or add additional stubs at new target frequency
Harmonic aliasing	Pump generates non-integer sub-harmonics (cavitation in pump)	Ripple frequencies not covered by stub network	FFT shows energy at non-target frequencies	Address pump cavitation; redesign stub network for actual frequency set

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8. Cross-Domain Derivation Notes

All design equations in this specification are applications of the following exact correspondence from the KHEO transmission-line mapping (M1–M3):

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M1:  ΔP = ρc_eff Δu  ↔  ΔV = Z₀ ΔI              (EXACT: wave impedance relation)
M2:  τ = L/c_eff      ↔  τ = L√(L'C')             (EXACT: transit time)
M3:  Γ = (Z₂−Z₁)/(Z₂+Z₁)                          (EXACT: reflection coefficient,
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The RF engineering principle exploited is: a quarter-wave shorted stub in shunt across a transmission line presents zero input impedance at $f_0 = c/(4L\_stub)$, diverting all energy at that frequency into the stub and away from the downstream load. The hydraulic closed-end side branch is the direct implementation of the shorted stub: the closed end is the short circuit, the stub length sets the quarter-wave resonance, and the main pipe junction is the shunt connection point.

No hydraulic-specific empiricism is used in the stub length calculation. The design is fully traceable to RF stub-matching methodology via the exact variable correspondence.

Selected References

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Prepared by InTelluric. This specification is suitable for issue to a fabrication shop without modification. Field verification of stub resonant frequency by impulse test is required before acceptance. All calculations assume the fluid and geometry parameters given in Section 2; changes to pump speed, fluid type, or pipe schedule require recalculation of stub lengths.

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