

Sensitivity Analysis of the GIF² Hydraulic Impulse System to Parameter Variations: Allowable Limits, Compensation Mechanisms, and Cyclic Stability Assessment

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Abstract.

This article presents a sensitivity analysis of the GIF² hydraulic impulse system to deviations of key parameters: closing angles of valves V2, V4, V7, water hammer pressure, rarefaction phase depth, and water level in the RTM tank. Allowable variation limits within which the system remains operational are determined. Compensation mechanisms are described: disc stops, accumulator-stabiliser, spring pressure damper, and W-shaped hydraulic seal. It is shown that even under simultaneous deviations of several parameters within the allowable limits, the system remains stable. The results are based on numerical modelling (method of characteristics) and data from previous works [1–3].

Keywords: hydraulic impulse system, GIF², stability, sensitivity, allowable deviations, valves, rarefaction phase, hydraulic accumulator, compensation mechanisms.

1. Introduction.

The GIF² (Gravity Impulse Flow Former) hydraulic impulse system is designed to convert a low-head gravitational flow (0.9 m) into a quasi-continuous high-velocity water jet by means of controlled water hammer [1]. In the nominal mode, the system exhibits stable cyclic operation with a frequency of 2.39 Hz, a water hammer pressure of 120.5 atm, and a flow velocity of 13.42 m/s before the impact. However, in real operating conditions, deviations of individual parameters may occur due to wear of mechanical parts, manufacturing inaccuracies, changes in hydraulic characteristics, or external factors (e.g., water level fluctuations in the tank).

The aim of this work is to quantitatively assess the allowable limits of variation of the key parameters of the GIF² system, as well as to analyse the built-in compensation mechanisms that ensure stable cyclic operation under deviations. The results will make it possible to determine the stability margins of the system and to create a basis for diagnostics and predictive maintenance.

2. Nominal parameters of the GIF² system.

Table 1 lists the main parameters of the GIF² system in the nominal mode, which are used as the baseline for the sensitivity analysis. The data sources are previous works [1–3] and the energy balance tables.

Table 1. Nominal parameters of the GIF² system:

Parameter	Symbol	Value	Source
Gravitational head	h	0.9 m	[1]
Flow velocity before water hammer (nominal)	v_nom	13.42 m/s	[1], Table 1
Water hammer pressure (V4)	P_hammer	120.5 atm	[1], Table 1

Parameter	Symbol	Value	Source
Pressure after stabiliser (at nozzle)	P_stab	78.48 atm	[1], sec. 2.6
Rarefaction phase (gauge pressure)	P_vac	-0.8 atm	[1], sec. 2.8
Pressure in pipeline 1 after damping	P_A1	1.887 atm	[1], Table A.5.1
Closing angle of valve V2	θ_{V2}	52°	[2], Table 16
Closing angle of valve V4	θ_{V4}	37°	[2], Table 16
Closing angle of valve V7	θ_{V7}	52°	[2], Table 16
Closing time of V2 (nominal)	t_cl_V2	0.765 ms	[2], calculation
Closing time of V4 (nominal)	t_cl_V4	1.34 ms	[2], calculation
Closing time of V7 (nominal)	t_cl_V7	2.42 ms	[2], calculation
Main module volume	V_main	141.3 L	[1]
Small module volume	V_small	0.26 L	[1]
Pulse frequency	f	2.39 Hz	[1], Table 1
Rarefaction recovery work	W_rec	38.5 kJ	[1], sec. 2.8

3. Sensitivity analysis of parameter deviations.

3.1. Mechanical deviations: valve closing angles

3.1.1. Valve V2 (flow interrupter, 52°).

The closing angle of V2 determines the flow capacity from reservoir R1 to working pipeline 3 and the closing time under the action of the shock wave front. The nominal closing time is 0.765 ms.

- **Angle increase (>52°):** The maximum flow passage increases, but the closing time also increases (the disc travels a longer path). This may reduce the amplitude of the synchronising water hammer and disrupt synchronisation with valve V4. Allowable deviation – up to +2°.

- **Angle decrease (<52°):** The flow capacity decreases, which may lead to underfilling of the main module (141.3 L) and a reduction of the flow velocity before the impact. Allowable deviation – down to -2°.

- **Compensation:** A stop made of Stellite 6 fixes the limiting angle (52°), preventing over-opening. Automatic closing occurs under the action of the shock wave front generated after the water hammer at V4. Opening (return of the disc to the lying position) is provided by the disc's own weight and by the pressure difference during the rarefaction phase ($\Delta P \approx 0.887$ atm). No springs or external actuators are used. Manual adjustment is provided only for initial setting (shafts protruding to the outside), but during operation the system self-regulates dynamically. High wear resistance [2, Table 14].

3.1.2. Valve V4 (shock valve, 37°).

The closing angle of V4 determines the volume of the small module (0.26 L), the amplitude of the control water hammer, and the closing time (1.34 ms). The normal position is the disc tilted at 37° (open), facing the flow.

- **Angle increase (>37°):** The volume of the small module increases, leading to higher energy losses in the control branch (above 3.3 kJ). The water hammer amplitude may increase slightly, but remains within the margin of the accumulator (up to 150 atm). Allowable deviation – up to +1.5°.

- **Angle decrease (<37°):** The volume of the small module decreases, which may impair synchronisation (the small module may not generate a sufficient wave to open V7). The water hammer amplitude decreases, which may reduce the pressure at the inlet of the accumulator (item 10). Allowable deviation – down to -1.5°.

- **Compensation:** A stop fixes the limiting angle (37°). Closing occurs under the action of the hydrodynamic flow pressure (velocity 13.42 m/s). Opening is provided by the disc's own

weight after the pressure drop (rarefaction phase). If necessary, additional loading (e.g., a small counterweight) may be provided to ensure reliable return to the initial position. Automatic angle stabilisation is achieved by the balance of hydrodynamic forces and weight. High wear resistance [2, Table 14].

3.1.3. Valve V7 (delivery valve, 52°).

The closing angle of V7 determines the flow capacity for the exit of the main module (141.3 L) into the discharge pipeline 9. The closing time is 2.42 ms. The normal position is the disc vertical (closed).

- **Angle increase (>52°):** The closing time increases, which may prevent the disc from closing before the rarefaction phase, thereby breaking the hydraulic isolation of the module. Allowable deviation – up to +2°.
- **Angle decrease (<52°):** The flow passage decreases, creating additional hydraulic resistance and possibly hindering the full exit of the module. Allowable deviation – down to –2°.
- **Compensation:** A stop limits the maximum angle (52°). The disc opens under the action of the shock wave front from V4 (the disc “falls”). Closing occurs due to the disc’s own weight and the pressure difference between pipelines 3 and 9 when the rarefaction phase sets in. The flow dynamics ensure timely closure without additional springs. High wear resistance [2, Table 14].

Table 2. Allowable deviations of valve closing angles:

Valve	Nominal angle	Allowable deviation	Main risk	Compensation mechanism / automatic stabilisation
V2	52°	±2°	Change in closing time, synchronisation	Stop (limits the maximum angle); flow dynamics and shock wave front ensure closing; disc own weight promotes opening (disc lies down); rarefaction phase creates pressure difference for opening.
V4	37°	±1.5°	Small module volume, water hammer amplitude	Stop (limits the maximum angle); hydrodynamic flow pressure ensures closing; disc own weight returns it to the open position during rarefaction; additional loading (e.g., counterweight) may be provided if necessary.
V7	52°	±2°	Closing time, flow capacity	Stop (limits the maximum angle); shock wave front from V4 opens the disc; disc own weight (falling) ensures opening; pressure difference between pipelines 3 and 9 closes the disc during rarefaction.

3.2. Deviation of water hammer pressure.

The nominal water hammer pressure at valve V4 is 120.5 atm (at a flow velocity of 13.42 m/s). After passing through the accumulator-stabiliser (item 10), the pressure is reduced to 78.48 atm at the nozzle inlet.

- **Pressure increase (up to 150 atm):** Possible due to an increase in flow velocity or a change in wave speed. The accumulator-stabiliser (item 10) is designed for an inlet pressure of up to 150 atm (body safety factor $n=4.9$). It ensures stabilisation of the outlet pressure at 78.48 atm even when the inlet pressure is exceeded. Allowable deviation – up to +25% (150 atm).

- **Pressure decrease (down to 100 atm):** Possible due to a decrease in flow velocity. The accumulator still stabilises the outlet pressure, but its value will be proportionally lower (for example, at 100 atm inlet, the outlet pressure will be ≈ 65 atm). This will reduce the jet power, but the system will not stop. Allowable deviation – down to -20% (≈ 96 atm).
- **Compensation:** The accumulator-stabiliser (item 10) with a membrane (reinforced PTFE) and a gas chamber (pre-charged to 83 atm) provides pulsation smoothing and maximum pressure limitation. The additional margin allows operation under deviations without loss of operability.

Table 3. Allowable deviations of water hammer pressure.

Parameter	Nominal value	Allowable deviation	Operability limit	Compensation
Water hammer pressure	120.5 atm	-20% / $+25\%$	96 – 150 atm	Accumulator 10

3.3. Rarefaction phase and flow recovery.

After the main module is ejected through valve V7, a rarefaction phase occurs in pipeline 3 with a gauge pressure of -0.8 atm (0.2 atm absolute) [1, sec. 2.8]. This rarefaction performs two functions:

1. It creates a pressure difference $\Delta P = P_{A1} - P_{vac} = 1.887 - (-0.8) = 2.687$ atm, which opens valve V2.
2. It provides recovery work $W_{rec} = 38.5$ kJ, which contributes to the pre-acceleration of the flow.

Important clarification: The main restoration of the flow velocity to 13.42 m/s occurs not due to the rarefaction, but due to the spring damper (item 17). After the water hammer at V2, the shock wave front reaches damper 17, which stabilises the pressure in pipeline 1 at 1.887 atm. When valve V2 opens (under the action of the pressure difference), it is this pressure (1.887 atm) that provides the flow velocity of 13.42 m/s.

- **Decrease of rarefaction depth (e.g., to -0.5 atm):** The pressure difference for opening V2 decreases to $1.887 - 0.5 = 1.387$ atm, which is still sufficient to open the valve. Damper 17 continues to maintain the pressure at 1.887 atm, so the flow velocity after V2 opens remains nominal (13.42 m/s). Thus, the rarefaction phase has a significant margin [4].

- **Complete disappearance of rarefaction (0 atm gauge):** The pressure difference becomes 1.887 atm, which is still sufficient to open V2. The system can continue to operate, but the recovery work will decrease, which may affect long-term energy efficiency.

- **Allowable deviation:** The rarefaction may decrease to -0.5 atm (gauge) without loss of operability. The margin is 37.5%.

Table 4. Allowable deviations of the rarefaction phase.

Parameter	Nominal value	Allowable deviation	Lower limit	Compensation
Rarefaction (gauge pressure)	-0.8 atm	down to -0.5 atm	-0.5 atm	Damper 17 (stabilisation of pressure at 1.887 atm)

3.4. Air suction through the drain line.

The GIF² system has a drain line (pipeline 5) through which the small module (0.26 L) is discharged into the RTM tank. To prevent reverse air suction, a W-shaped hydraulic seal (HZ-6)

is used [3, sec. 2.5]. Its end is submerged in the water of the RTM tank to a depth of at least 150 mm.

- **Water level drop in the RTM tank:** If the water level falls below the pipe end, the hydraulic seal loses its properties, and air may be sucked into the system. This will disrupt the rarefaction phase and reduce recovery efficiency.

- **Compensation:** The RTM tank has a large volume (6 m³ for one module, scalable to 54 m³). The system operates in a closed loop, so water losses are minimal. An automatic air release valve (item 10) and level sensors (recommended) are provided. A short-term level drop to 100 mm (margin of 50 mm) is permissible without immediate loss of sealing.

- **Allowable deviation:** The water level may drop to 100 mm (from the nominal ≥ 150 mm) without impairing the operation of the hydraulic seal. If the level drops further, automatic refilling or an alarm is required.

Table 5. Allowable deviation of the water level in the RTM tank:

Parameter	Nominal value	Allowable deviation	Lower limit	Compensation
Pipe immersion depth	≥ 150 mm	down to 100 mm (short-term)	100 mm	Tank volume, level control, automatic air release valve

3.5. Influence of wave speed variation.

The wave speed $c=910$ m/s is a fundamental parameter that determines the water hammer amplitude ($\Delta P=\rho c \Delta v$), the wave propagation time, and the synchronisation of valve operation. Deviations of c may arise due to changes in gas content ($\beta \approx 0.007-0.01\%$), water temperature, pipe wall elasticity, or material degradation.

- Effect on water hammer pressure: A change in c directly proportionally affects the pressure amplitude. For example, an increase of c by 10% (to ≈ 1000 m/s) would raise the pressure to ≈ 132 atm, which is still within the margin of the accumulator (150 atm). A decrease of c by 10% (to ≈ 820 m/s) would lower the pressure to ≈ 108 atm, which is also acceptable (lower limit 96 atm). The allowable deviation of c is $\pm 10-12\%$.

- Effect on synchronisation: A change in c affects the arrival time of the shock wave front at valve V2 ($t=L3/c$). For a deviation of c by $\pm 10\%$, the time changes by $\approx \pm 0.33$ ms, which may affect synchronisation accuracy but does not critically disrupt it (the allowable range for the closing time of V2 is 0.765 ± 0.05 ms).

- **Compensation:** The accumulator-stabiliser (item 10) compensates for changes in pressure amplitude. The dynamic behaviour of the valves (closure under the action of the wave front) adapts to changes in wave speed without additional adjustments.

4. Summary table of allowable deviations and margins

Table 6. Summary of sensitivity analysis results:

Parameter	Nominal value	Allowable deviation	Operability limit	Compensation mechanism / automatic stabilisation	Source
V2 angle	52°	$\pm 2^\circ$ ($\approx \pm 3.8\%$)	50–54°	Stop; flow dynamics, shock wave front, disc own weight, rarefaction phase	[2]
V4 angle	37°	$\pm 1.5^\circ$ ($\approx \pm 4.1\%$)	35.5–38.5°	Stop; hydrodynamic flow pressure, disc own weight	[2]

Parameter	Nominal value	Allowable deviation	Operability limit	Compensation mechanism / automatic stabilisation	Source
				(additional loading possible if needed)	
V7 angle	52°	±2° (≈ ±3.8%)	50–54°	Stop; shock wave front, disc own weight, pressure difference (pipelines 3 and 9)	[2]
Water hammer pressure	120.5 atm	–20% / +25%	96–150 atm	Accumulator 10	[1], [2]
Wave speed (c)	910 m/s	±10–12%	≈800–1000 m/s	Accumulator 10; valve dynamics	[1], [4–6]
Rarefaction (gauge pressure)	–0.8 atm	down to –0.5 atm	≥ –0.5 atm	Damper 17 (pressure stabilisation at 1.887 atm)	[1], [2]
Pipe immersion depth (RTM tank)	≥150 mm	down to 100 mm	≥100 mm (short-term)	Tank volume, level control	[3]

5. Phase stability diagram of the GIF² system.

5.1. Definition of parameters and stability criterion.

To assess the stability of the cyclic operation of the GIF² system, dimensionless parameters of relative deviations are introduced:

$$\delta c = \frac{\Delta c}{c}, \quad \delta \theta = \frac{\Delta \theta_{V2}}{\theta_{V2}}, \quad (1)$$

where:

c - is the shock wave propagation speed (nominal 910 m/s);

θ_{V2} - is the closing angle of valve V2 (nominal 52°).

Based on the sensitivity analysis results (Table 6), the following allowable limits are adopted:

$$|\delta c| \leq 0.12, \quad |\delta \theta| \leq 0.038.$$

The selected limit for the wave speed variation $|\delta c| \leq 0.12$ reflects the well-established sensitivity of wave propagation velocity to gas content, cavitation effects, and fluid–structure interaction. Classical studies of fluid transients indicate that even small amounts of entrained gas can significantly reduce the effective wave speed, typically on the order of 10–15% depending on system conditions [4,7]. Additional influences of two-phase effects and pipe–wall interaction are discussed in [4–6].

The allowable limit for the valve angle corresponds to a deviation of ±2° from the nominal value (52°), i.e. $|\delta \theta| \leq 0.038$, as obtained from the mechanical tolerance analysis (Table 2).

To account for the combined influence of parameters, a generalized stability criterion is introduced in the form of a quadratic expression:

$$F(\delta c, \delta \theta) = \left(\frac{\delta c}{0.12}\right)^2 + \left(\frac{\delta \theta}{0.038}\right)^2 + k \cdot \frac{\delta c \cdot \delta \theta}{0.12 \cdot 0.038} \quad (2)$$

The system is considered stable if: $F(\delta c, \delta \theta) \leq 1$,

where: k is a coefficient describing the mutual influence of parameters.

In the present study, the value $k=0.4$ was obtained from numerical simulations of the GIF² system using the method of characteristics (see [1]), by matching the temporal characteristics of valve operation and wave propagation.

The adopted quadratic form represents a phenomenological stability model that captures the coupled nature of wave dynamics and valve mechanics, consistent with the general interaction mechanisms discussed in [4–6].

5.2. Calculation of the stability region.

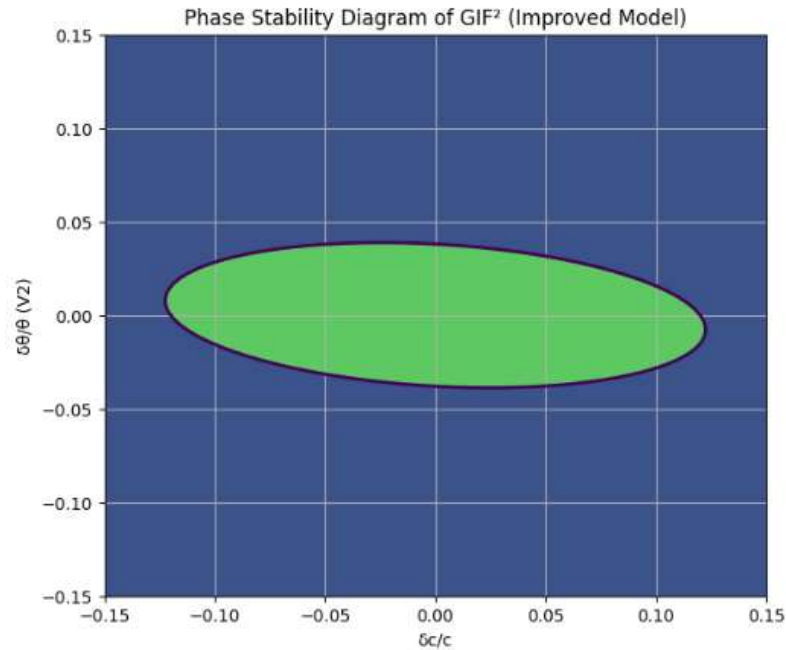
At the boundary of admissible deviations: $\delta c = \pm 0.12$, $\delta \theta = \pm 0.038$ the criterion yields: $F=1$ which defines the stability limit.

For a representative case of simultaneous deviations: $\delta c=0.08$, $\delta \theta=0.02$, the value of the criterion is:

$$F = \left(\frac{0.08}{0.12}\right)^2 + \left(\frac{0.02}{0.038}\right)^2 + 0.4 \cdot \frac{0.08 \cdot 0.02}{0.12 \cdot 0.038} \approx 0.44 + 0.28 + 0.14 = 0.86 < 1. \quad (3)$$

Thus, the system remains within the stable operating region.

Fig. 1. Phase stability diagram of the GIF² system in the coordinates of relative deviations of wave speed (δc) and valve V2 closing angle ($\delta \theta$).



The green region corresponds to the stable operating mode ($F \leq 1$), while the boundary is defined by the quadratic stability criterion (Eq. 2), taking into account the coupled influence of parameters.

5.3. Interpretation of the phase diagram.

The resulting phase diagram (Fig. 1) has the form of a deformed elliptical region in the $(\delta c, \delta \theta)$ space.

The main observations are:

- Stability is governed by the combined deviation of parameters rather than their independent limits.

- An increase in the deviation of wave speed (δc) reduces the allowable deviation of the valve angle ($\delta\theta$), reflecting sensitivity of phase synchronization.
- The mixed term ($\delta c \cdot \delta\theta$) represents the coupled influence of hydrodynamic and mechanical processes, in line with interaction effects discussed in sensitivity and fluid–structure studies [5,6].
- The shape of the stability region indicates a distributed stability margin, which can be redistributed between parameters depending on operating conditions.

6. Conclusions.

1. Mechanical parameters (valve angles) allow deviations of $\pm 1.5\text{--}2^\circ$, significantly exceeding expected wear over long-term operation ($<0.01^\circ$). Mechanical stops and flow-driven self-regulation ensure stable operation without external control.
2. Water hammer pressure may vary within 96–150 atm without loss of operability. The accumulator-stabiliser compensates both increases and decreases, maintaining a stable outlet pressure (78.48 atm at nominal conditions).
3. The rarefaction phase has a substantial margin: even at reduced depth (-0.5 atm gauge), valve V2 opens due to pressure difference, while the nominal flow velocity (13.42 m/s) is restored by the spring damper maintaining 1.887 atm in pipeline 1.
4. Air ingress through the drain line is prevented by a hydraulic seal. Short-term reduction of water level to 100 mm does not compromise sealing; monitoring and refilling ensure reliability.
5. Wave speed is a critical parameter; however, deviations within $\pm 10\text{--}12\%$ ($\approx 800\text{--}1000$ m/s) do not lead to loss of operability due to compensating effects of the accumulator and valve dynamics. The phase stability diagram (Fig. 1) confirms that simultaneous deviations of wave speed and valve angle within allowable limits maintain stable operation according to the adopted criterion (Eq. 2).
6. All critical parameters are supported by built-in compensation mechanisms (mechanical stops, accumulator, damper, hydraulic seal). Even under simultaneous deviations within allowable ranges, the GIF² system maintains stable cyclic operation, as confirmed by numerical modelling (method of characteristics) and previous studies [1–3].
7. The results can be used for diagnostic and predictive maintenance systems, as well as for evaluating stability margins in the design of industrial HSPP implementations.

7. References.

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Conflict of Interest Statement

The patents for the GIF² system [1, 2] were filed by V. Orlov and licensed to FLOW JET ENERGY LTD, where the author holds the position of Managing Director. The author declares that the research was conducted with full scientific objectivity and transparency.

Data Availability Statement

The numerical data supporting the results of this study, as well as those of studies [1–3], are available from the corresponding author upon reasonable request.

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