ANALYSIS OF SUPPORTS OF THREE-LEGGED COMPLIANT SNAP-THROUGH STRUCTURE FOR APPLICATION IN AN EXCESS FLOW VALVE

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ABSTRACT

Installing excess flow valves in gas pipelines is an active protection to avoid accidents successfully. In case of damage or destruction of gas pipelines the gas flow is automatically shut off, when a predefined flow rate is reached. Current research work is focused on novel closing devices with a compliant three-legged snap-through structure instead of spring-loaded and guided closing disc. Contrary to the conventional valve design the new approach realizes a valve with a bistable switching behavior without any intermediate position, meaning that the valve is either completely open or completely closed. Additionally to the shape and the geometric parameters of the three-legged snap-through structure, the mounting of this structure in the valve housing also influences the switching behavior of the valve. In this contribution the influence of the kind of support to the force-displacement behavior especially the switching force of the excess flow valves using the finite element method (FEM) is analyzed.

Index Terms - compliant snap-through structure, gas excess flow valve, bistable switching behavior

1. INTRODUCTION

To avoid accidents, for instance due to gas explosions, and to improve the security of gas systems excess flow valves are installed in gas pipelines [1], [2]. Installation of such devices is recommended in main gas pipelines and in gas service lines [3]. If a damage or a destruction of gas pipelines, maybe by excavators or earthquakes or something else, occurs more gas, than the nominal flow rate can flow out due to the damage and the higher flow velocity. In such a case the current flow rate is higher than the critical predefined one and the excess flow valve will shut off the pipeline automatically in a very short time. Installing excess flow valves is obligatory required for new installation of gas systems and is an active protection for more security [3].
Commonly used excess flow valves, shown in Figure 1, consist of a spring-loaded pin with a closing disc, which is guided in the housing. The adjustable spring defines the critical flow rate of these conventional excess flow valves. Opened position of the valve in the case of a nominal gas flow rate is visualized in Figure 1 (a). When the critical flow rate is exceeded the gas flow pushes the closing disc against the spring in the valve seat and the gas flow is stopped. This closed position of the conventional valve due to a critical gas flow rate is illustrated in Figure 1 (b). But, there are disadvantage of all these spring-loaded devices. Because of the linear guide these excess flow valves are not resistant to dust and other depositions. In case of dusted or corroded guiding pin the motion to close the valve can stick and it will not be closed due to the critical flow rate. Furthermore, if the pressures on the front and back site of the disc are balanced due to the bypass, the valve opens uncontrolled.

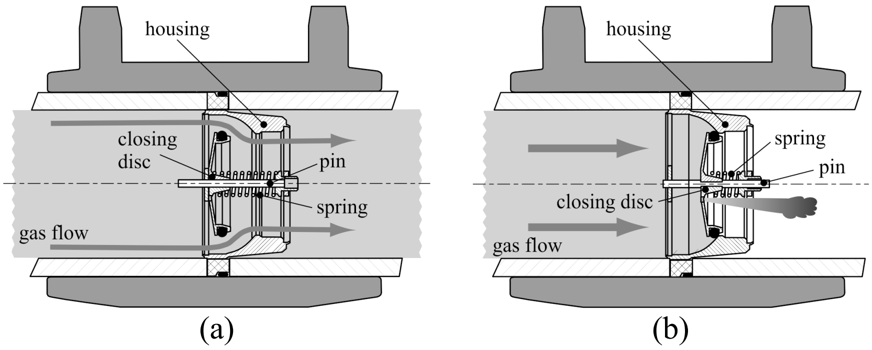


Figure 1: Commonly used spring-loaded excess flow valve [3]; (a) – opened position due to nominal gas flow rate; (b) – closed position due to critical gas flow rate

2. EXCESS FLOW VALVE WITH SNAP-TROUGH STRUCTURE

As a result of recent research work [1], [4] a novel excess flow valve (Figure 2 (a)) is presented in this contribution. The mechanical system of linear guide, pin and closing disc is replaced by a special three-ledged compliant snap-through structure with closure body [1]. A thin sheet metal pattern with a circular inner part with a centrally arranged hole and three radial by an angle of 120° arranged legs is the functional part in the new excess flow valve. This planar sheet metal structure is geometrically determined by the sheet metal thickness, the width of the legs, the diameter of the inner ring and the outer diameter of the structure, which correlates with the length of the legs. Assembling this planar sheet metal structure and the valve housing with a supporting diameter, which is less than the outer diameter of the planar structure, the three-legged sheet metal structure bulges out and this gains the compliant snap-through structure as new functional element of the excess flow valve. The difference of the between the outer diameter and the supporting diameter fixes the geometrical preload as a displacement of each leg and finally the deflection of the inner ring as a result of the bulge. Figure 2 (b) illustrates this geometrical preload due to radial displacements and the mounting. This yields a bistable switching behavior of the valve, meaning that the valve is either completely open or closed without any intermediate positions. Moving the inner ring from one stable position into the other one is a snap-trough motion which requires a critical force.
The required critical force is determined by the geometry of the sheet metal structure, especially the shape and the dimensions of the legs, the Young's modulus of the material, the geometrical preload and the support of the legs in the housing.

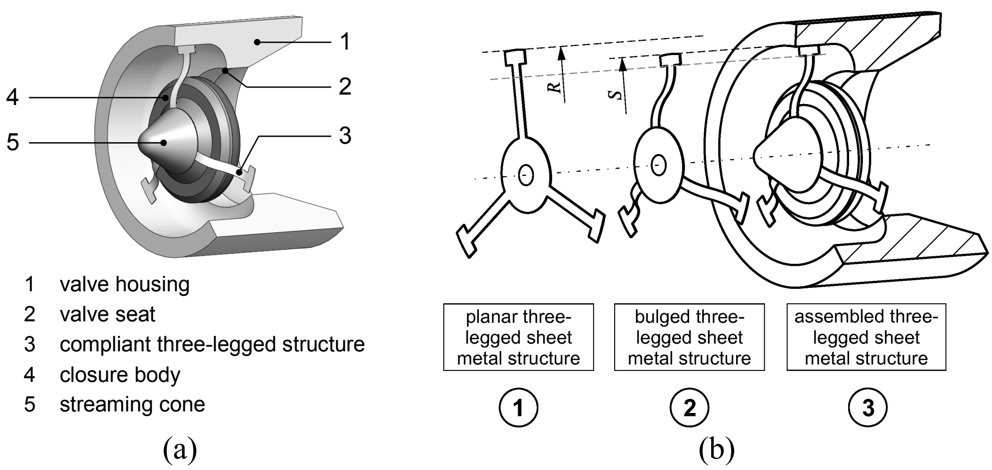


Figure 2: Excess flow valve with snap-through structure [1]; (a) – components of the valve; (b) – geometrical preload due to radial displacements and bulged structure

As in common excess flow valves the new valve with the three-legged snap-trough structure closes, if the flow rate exceeds a critical value. Therefore, the operating force, which is defined by the critical flow rate and the valve geometry according to equation (1) reaches a higher level than the required force determined by the structure. The closing behavior of the valve depends fundamentally on the design of the snap-trough structure (shape, dimension, material, support) because the operating force is fixed.

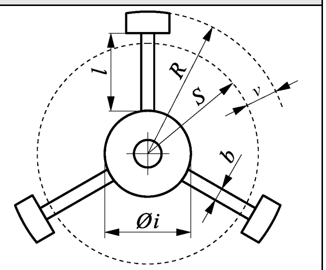
$$F_{op} = 8\, c_W\, \varrho\, A_S \left(\frac{V_S}{\pi\, d_R^2} \right)^2 \qquad (1)$$

F_{op} : operating force ϱ : density of gas V_S : critical gas flow rate
c_w : drag coefficient A_S : face to be streamed on d_R : pipe diameter

3. MOTIVATION AND AIM OF INVESTIGATION

As pointed out in section 2, different parameters define the required snap-through force of the presented device. One powerful feature to adjust the required snap-trough force to the operating force is the support of the three-legged compliant sheet metal structure. To analyze different supports for the three-legged compliant snap-through structure and not the structure itself, the shape of the sheet metal structure and the geometrical parameters are set to values summarized in Table 1. The deforming sheet metal structure is made of steel with a YOUNG's modulus of 200000 MPa and a POISSON's ratio of 0.3, assuming linear elastic deformation.

Table 1: Geometrical parameters of sheet metal structure and valve housing

parameter	symbol	value in mm	illustration
diameter of the inner ring	i	10	
length of legs	l	9	
width of legs	b	2	
sheet metal thickness	t	0,1	
sheet metal radius	R	16,5	
supporting radius	S	15	
geometrical preload	v	1,5	

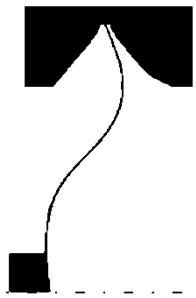
The design of the new excess flow valve is driven by fundamental requirements of the three-ledged compliant snap-through structure and especially of its support in the housing.

- In the German *DVGW VP 305-2* critical flow rate V_S is determined as 1.3 up to 1.8 times the nominal flow rate V_N [2].
- To minimize the pressure drop of the valve at nominal flow rate the lift of the closing disc has to be maximal.
- Due to a high functional reliability and easy manufacturing as well as assembling and low sensibility against dust the complexity of the support for the compliant three-legged structure is low as possible.

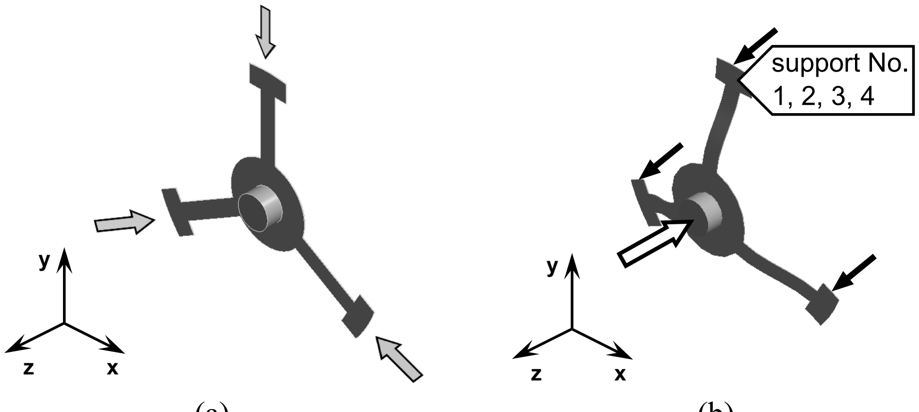
4. FEM-BASED ANALYSES OF DIFFERENT SUPPORTS

The support of the three-legged compliant snap-through structure in the housing influences the stiffness of the mechanical system and consequently the force required for the snap-through. Because of this, the force-displacement behavior, representing the stiffness, of four different supports listed and visualized in Table 2, is analyzed. To ascertain the force-displacement behavior ANSYS 14.5 Workbench is used for all FEM simulations. The geometry of planar three-legged sheet metal structure is imported from CAD in ANSYS. Essentially for all simulations is a high quality mesh of this structure to produce accurate results. For that, the thin sheet metal structure is meshed by solid-shell elements with an element size of 0.3 mm. Dependent on the type of the support, fixed support and rotational joint are modeled as boundary conditions included in ANSYS Workbench. Otherwise the contact-based supports with 60° or 80° V-shaped notch are modeled by additional bodies for each leg of the supports. These supports are reached by frictionless line contacts between the edge fillet front surface and the V-shaped notch for each leg.

Table 2: Supports of three-legged compliant snap-through structure in the housing

No.	(1)	(2)	(3)	(4)
Support	fixed support	revolute joint	V-shaped notch support (60°)	V-shaped notch support (80°)
Stiffness	high	low	medium	medium
FEM modeling	boundary cond.	boundary cond.	contact-based	contact-based
Illustration (side view)				

FEM simulation is done in two load steps where each one is divided in several sub steps. In a first load step all three legs of the planar sheet metal structure are pushed together in radial direction, presented in Figure 3 (a). In consequence of this the compliant three-legged structure bulges out and it is geometrically preloaded. The snap-through motion is simulated in a second load step. Modeling the type of support is either done as boundary condition (fixed support and revolute joint) or by additional bodies (contact-based supports with V-shaped notch). If the operating force (equation (1)) is applied to the closing body, this yields a force-controlled simulation with numerical instabilities. Instead of this a displacement-controlled simulation is implemented, meaning that a deflection in negative z-direction is applied to the closure body and the force reaction in z-direction is evaluated. To reach a converging simulation, the closing body is guided in z-direction. The material model is linear elastic and large deflection is activated in the analysis settings.



(a) (b)

Figure 3: FEM model with boundary conditions; (a) – first load step (geometrical preload due to radial displacement); (b) – second load step (displacement-controlled snap-through and force reaction)

5. RESULTS AND DISCUSSION

The force-displacement behavior for one shape of three-legged compliant snap-through structure but for four different types of supports is presented in Figure 4.

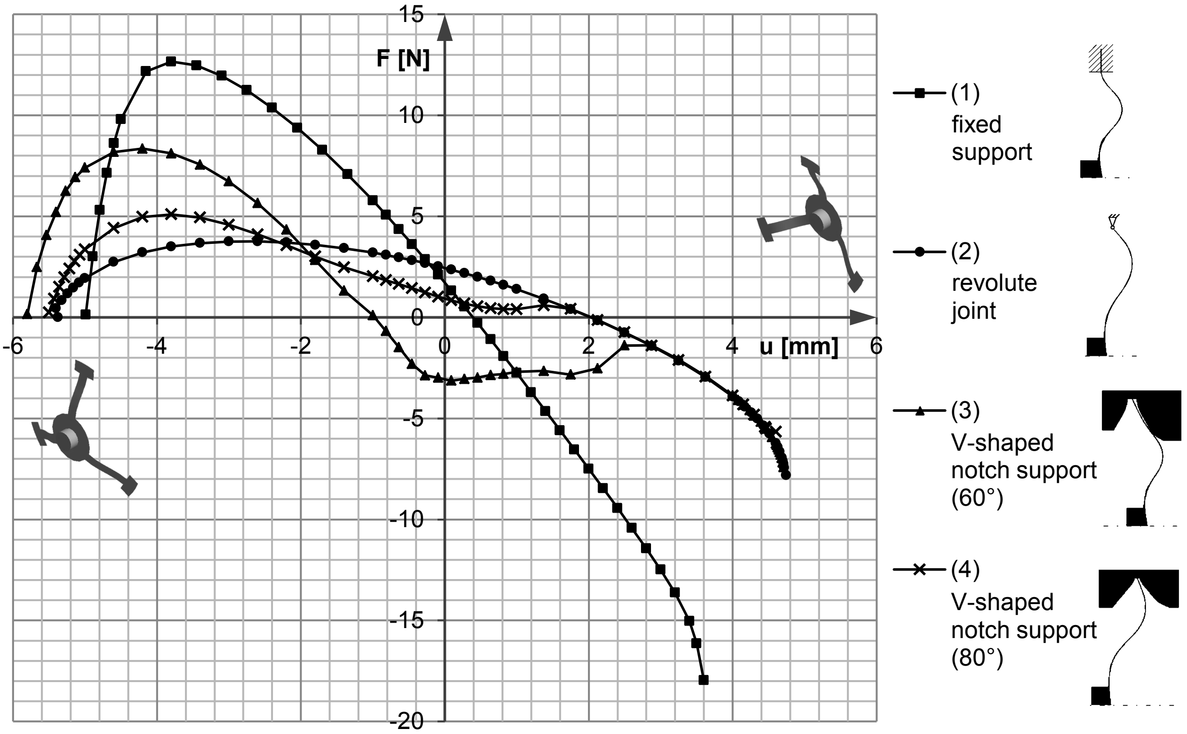


Figure 4: Force-displacement behavior of one three-legged compliant snap-through structure supported by four different types of supports in the housing

Initial state in all cases is the bulged three-legged sheet metal structure due to a radial displacement of each leg. The points representing this stable state for all supports are located directly on the displacement-axis between -5 mm and -6 mm. This specific displacement is one half of the complete stroke of three-legged compliant snap-through structure. Noticing that there is no force reaction in z-direction, the points are relatively close together and consequently the stroke is minor dependent on the type of support. If the displacement, applied to the closure body, is increased, the force, which is the sum of the force reactions of each leg, also increases until a maximum. This maximum point is the snap-through point for the compliant three-legged structure. A small increase of force or displacement at this point accomplishes the snap-through, meaning that form this point the motion, which ends in second stable position, is uncontrollable. The maximum of the force and the corresponding displacement is influenced by the type of support. A fixed support generates a force maximum of approximately 12.5 N at -3.8 mm, which is much higher than the force maximum of the revolute joint support of approximately 4 N at -2.6 mm. The V-shaped notch support with 60° angle yields a force maximum of approximately 8.3 N at -4.2 mm and the 80° angle yields approximately 5 N at -3.8 mm. This reflects the stiffness behavior of the supports, which was mentioned in Table 2. For the fixed support and the V-shaped notch support with 80° angle the displacement at force maximum is nearly the same, it is about -3.8 mm. When the local maximum is passed the slope of all curves turns to negative values. At a certain displacement the curves cross the displacement-axis and the force changes from positive values to negative ones. As one can see in Figure 4 this specific displacement is heavily depending on the type of support. The zero-crossing point is usually at positive displacements, meaning that this point is behind the half of the stroke. For the fixed support this point is at 0.4 mm and for

revolute joint it is the same as for V-shaped notch support with 80° angle at 2 mm. But for V-shaped notch support with 80° angle the zero-crossing point is in front of the middle position (u = 0 mm) at -1 mm. In contrast to the force-displacement behavior of fixed support and revolute joint, there are additional local maximum points in the characteristic of the V-shaped notch supports. Hence, there are further disturbing snap-through points.
The curves, shown in Figure 4, are the basis to design an excess flow valve with a snap-through structure. An important factor for this is the force maximum. This force maximum is the critical force, which is required to accomplish a snap-through motion due to an operating force. In order to the requirements of the valve and remembering equation (1) the force maximum for the snap-through motion has to be adapted to the gas flow rate and the geometrical parameters of the valve. Adaption can be achieved by a change of shape and geometrical parameters of the sheet metal structure as well as the support of the structure in the valve housing. By changing the type of support of the three-legged compliant snap-through structure in the housing, the switching behavior of the valve can be influenced. A fixed support would require a higher critical gas flow rate than a revolute joint support under assumption of equal material and geometrical parameters.

6. SUMMARY AND OUTLOOK

This contribution deals with a new type of excess flow valve based on a snap-through motion. The effect of the type of support of the compliant three-legged snap-through structure on the switching behavior of the valve was investigated, using the finite element method. As a result of this investigation, it is possible to adapt the mechanical system to the requirements with a change of the support. In comparison to a fixed support a revolute joint support reduces the required force for a snap-through by a factor of three. But, the type of support has only a minor influence on the stroke of the snap-through. So, this is a very good reason to optimize the support, if a certain sheet metal structure due to a predefined stroke is necessary.
Further work is directed to the investigation of the shape and the geometrical parameters of the compliant three-legged snap-through structure and the housing. Subsequently, all results are used to develop a prototype on the basis of [2] for measuring and validation.

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