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ARTICLE

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ANALYSIS OF THE POSSIBILITY OF AN INCORRECT SHIFT OF THE MECHANICAL INDEX OF A DIAPHRAGM GAS METER WORKING UNDER VIBRATION

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Abstract: The article discusses the operation of bellows gas meters, commonly used to measure household gas consumption. It was noted that their testing and certification scope covers laboratory conditions, including work in vibration-free conditions, while vibrations occur in actual situations. It should be noted that the presented analysis is part of analyzing illegal gas consumption – UAG (unaccounted for gas), which is the subject of scientific research both in Poland and globally. The Oil and Gas Institute itself states [1] that it has received approximately 1,400 expert opinions, in which the gas meter user indicated that the counter had been skipped, while laboratory tests of the gas meter did not confirm any irregularities. The author, therefore, addresses the topic by asking whether the design of bellows gas meters with a mechanical counter may contain a design defect that may cause the counter to skip and then "disappear". As part of the research, an analysis was made of whether vibrations had any impact on the operation of the gas meter, and after confirming the implications, the counter was dismantled, and an attempt was made to determine the causes of the impact of vibrations. Finally, it was indicated what values of forces and acceleration are sufficient to cause measurement errors, and it was recommended that the construction of the counter be modified to prevent this phenomenon from occurring. The conclusions show that if the gas meter is used outside the scope of its certification, the counter may jump. Still, this jump will not leave any mechanical traces, and the gas meter may ultimately function appropriately after the vibrations stop.

Keywords: diaphragm gas meter, mechanical index, incorrect shift of gas meter index, illegal gas consumption, gas theft, unaccounted-gas lost, expertise

1. Introduction

In the gas distribution system, both in Poland and worldwide, bellows gas meters with a mechanical counter are most commonly used, especially for individual customers. A few years ago, there were about 8 million such gas meters in Poland [2–7]. One of the important aspects of using gas meters are errors reported by their users ("meter jumps"), which, although theoretically possible, could not be demonstrated in previous research studies either under what conditions they occurred or confirmed that they occurred at all [1]. In particular, the 2022 publication indicates a very laborious analysis performed by the authors, who examined a number of gas meters simulating approx. 10 years of gas consumption and did not notice the possibility of a jump, even despite hitting the meter with a force of up to 0.62 N [1].

The PN-EN 1359:2017 [8] standard for gas meters indicates that they are adapted to work in situations where vibrations and shocks are of little significance. However, to the best of the author's knowledge, no work has been carried out to answer the question of what vibrations of little significance mean.

In practical situations, gas installation pipes run under streets, which are often corrugated or have gaps in the roadway, and each passage of a heavy vehicle can cause vibrations that will be transferred to the meter through the gas installation pipes. Moreover, it happens that earthworks are carried out near the gas meter, including work using vibrating road rollers. Such rollers generate vibrations with a frequency of up to 50 Hz (3,000 cycles per minute) with an excitation of 2 mm, which means a direct interaction with an acceleration exceeding 24 times the value of the acceleration of gravity (g).

$$a = -A\,\omega^2 \sin(\omega\, t) \tag{1}$$

Substituting the parameters of the vibrating roller:

$$\omega = 55\ \text{Hz} \cdot 2 \cdot 3.14 = 345.4\ \text{rad/s} \tag{2}$$

$$a_{max} = 0.002\ \text{m} \cdot (345.4\ \text{rad/s})^2 = 238.6\ \text{m/s}^2 = 24.3\ g \tag{3}$$

Of course, the same acceleration will not be transferred to the gas meter in every case because it depends on the gas installation layout. However, in old buildings where gas meters are located in houses and not connections directly at the installation, vibrations may even be intensified due to the long arm of the force. The question therefore arises as to what type and what strength of vibrations go beyond vibrations of minor significance, and what elements of the gas meter or counter construction are susceptible to them.

2. First experiments

Building a device that would allow for obtaining target vibrations turned out to be a complex issue. The author planned the following arrangement of two gas meters, connected to an air flow source and a vibration source (Fig. 1).

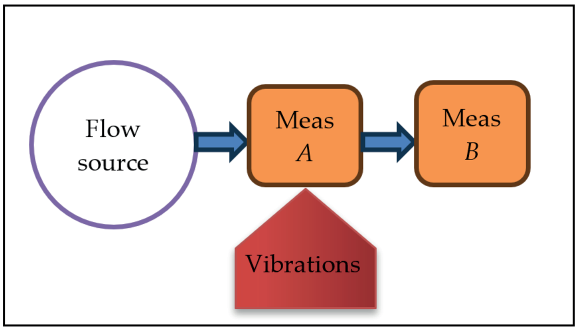

Fig. 1. Measurement schema

The compressed air was to flow first through gas meter *A*, subjected to vibrations, and then be pumped directly from it to gas meter *B* – identical and operating under normal conditions. In this way, the risk of leakage in the measuring system was eliminated (if it occurred, significantly lower readings would be obtained on gas meter *A* than on *B* with the vibration generator switched off) and the system was theoretically ensured to operate synchronously. Since the scope of the study was limited, it was assumed that any difference in the operation of both systems was to be measured in the absence of vibrations, and then it was expected that this difference would be constant despite the activation of the vibration generator. Ultimately, it would be necessary to consider carrying out these studies with a larger number of meters and a stable source of pumping air, however, the aim of the experiment was only to determine whether vibrations affect the operation of the gas meter or not, hence the precise effect of vibrations on the measurement value was not of fundamental importance.

Several vibration generating systems were assembled – using an exercise mat type generator (generating vibrations in two planes with a frequency of up to 50 Hz) and an electric saw (generating vibrations in one plane with a frequency of up to 50 Hz). It turned out that the strength of the test set itself was a rather complex issue, because at a given vibration frequency and mass inertia of the gas meter, very high stresses were obtained on the vibration transfer system. The physical implementation of the measuring system is shown in Figures 2 and 3, and the measurement results are in Table 1.

Fig. 2. Physical implementation of the measurement system based on an exercise mat (2D vibration)

Fig. 3. Physical implementation of the measurement system based on an electric saw (1D vibration)

Table 1. Meter readings during measurements

Type of vibrations	Meas. *A*	Measurements *B*	Delta *A*	Delta *B*	Relative error [%]	Error cum. [%]
No vibrations	0.195	0.231	–	–	–	–
	2.165	2.248	1.970	2.017	102.39	103.83
2D vibrations	3.764	3.886	1.599	1.638	102.44	103.24
	4.764	4.902	1.000	1.016	101.60	102.90
	5.915	6.073	1.151	1.171	101.74	102.67
	9.464	9.655	3.549	3.582	100.93	102.02
	12.954	13.180	3.490	3.525	101.00	101.74
	16.438	16.721	3.484	3.541	101.64	101.72
1D vibrations	17.371	17.671	0.933	0.950	101.82	101.73
	19.047	19.380	1.676	1.709	101.97	101.75
	21.027	21.394	1.980	2.014	101.72	101.75
	21.577	**21.981**	**0.550**	**0.587**	**106.73**	101.87
	22.429	22.855	0.852	0.874	102.58	101.90
	22.538	22.965	0.109	0.110	100.92	101.89
	23.678	24.129	1.140	1.164	102.11	101.90
	24.675	25.142	0.997	1.013	101.60	101.89
	25.995	26.476	1.320	1.334	101.06	101.85

The measurement results indicate that meter *B* measured 2.39% more gas volume than meter *A* in the test without vibrations – this is surprising in itself, because this meter was connected in serial connection after meter *A*, and therefore it was to be expected that the measurement on this meter would be rather smaller (due to possible leaks). This may indicate a difference between the meters themselves, which, although purchased from the manufacturer's distribution network, were nevertheless delivered in a way that did not protect them from vibrations during transport. However, since the measurement difference in this direction could not have resulted from a leak in the system, it was decided to continue the study (Fig. 3, 4).

Subsequent measurements indicated a fluctuating value of the relative error from 0.92% to 2.44% of the measured volume, while one of the measurements indicated an error of 6.73%. The measurements do not indicate what the relationship was between specific vibrations and a specific error value, but it was certainly possible to demonstrate that vibrations of the order of 50 Hz disturb the operation of the meter.

Interestingly, the phenomenon of waving the digits of the abacus was observed – during single-plane horizontal vibrations from the direction shown in Figure 4 and when the vibrations were transferred in such a way that the abacus was subject to vibrations, the drums of the abacus moved up and down by about 3 mm on their own – this did not cause the drums to jump, but indicated that the jump would have occurred if the drum had not been stopped by the decade flip-flop.

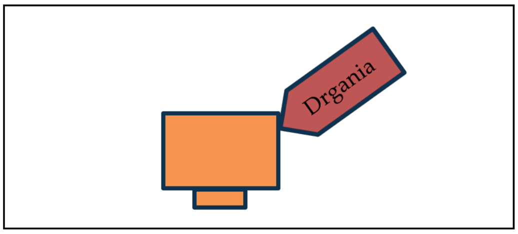

Fig. 4. Direction of vibrations at which the "waving" phenomenon of the counter drums was observed

The results of the above experiments and measurements are of course not definitive, therefore it was decided to conduct further analyses after dismantling the counter.

3. Dismantling the counter

The dismantling of the abacus was done in a non-standard way – it was decided to cut out the abacus glass and cut the fasteners using an angle grinder to ensure that the abacus could be removed without any shifting that could change its condition during dismantling (Fig. 5).

Immediately after cutting off the abacus, the phenomenon that we tried to demonstrate was observed, namely – almost all of the abacus drums could be turned freely. The protection in the form of decade flip-flops did not hinder this rotation in any way. After a preliminary analysis of the phenomenon, it was recorded on film.

It was therefore necessary to explain the cause of this phenomenon – as a reminder, it should be added that the counter was working properly just before dismantling (apart from a momentary deviation during one measurement), but after dismantling the counter, it turned out that the protections for the free rotation of the drums did not work.

After analyzing the condition of the counter, the pin on which the counter drums are mounted was observed to have been pushed out.

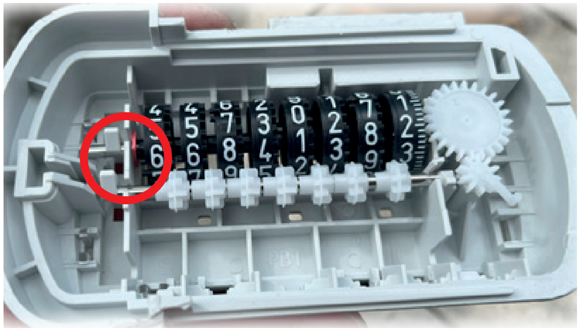

Fig. 6. Extension of the pin on which the counter drums are mounted

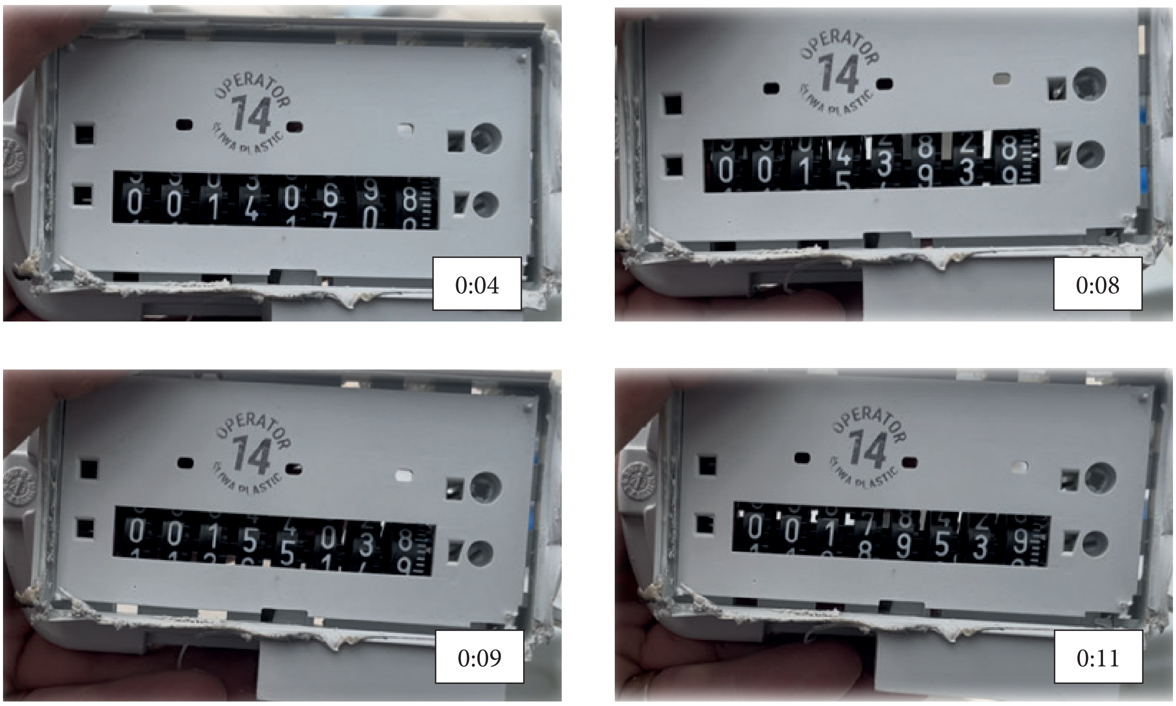

Fig. 5. Selected frames of a film showing the free rotation of the abacus drums

The pin in this position prevented the drums from adhering to the decade flip-flops and allowed them to rotate freely. It should be added that the greatest impact of the extension has on the drums located on the opposite side of the counter (the liter digit), while in relation to the drum located at the very extension, the distance from the decade flip-flop is too small to be able to rotate freely. In other words, all drums are subject to free rotation, up to and including the hundreds-cubic-meter digit, while the thousands-cubic-meter digit already shows elements of resistance, while the tens of thousands-cubic-meter digits cannot be rotated freely (Fig. 6).

After setting the pin in its correct position, the counter continued to work correctly, but there were no traces of mechanical skipping anywhere on it, because it took place on the principle of the free rotation of the drums. What is also important – all the movable drums could be rotated freely forwards, while the drums on the far right (located farthest from the extension) could be rotated in both directions. This way, if the phenomenon occurred under actual operating conditions, it would be more likely to result in an overestimated reading.

4. The jump of the abacus

Taking into account the influence of the extended pin of the counter drums on the correctness of the work, it was decided to investigate what force (acceleration) is sufficient to extend it. For this purpose, an Extech VB300 vibrometer was used, which allows for measuring acceleration in 3 planes (Fig. 7).

The cut off counter, with the pin inserted into the correct position, was placed on a plane, and then the vibrometer was struck on the counter with a small force. As a result of the impact, the pin extended by 0.5 mm.

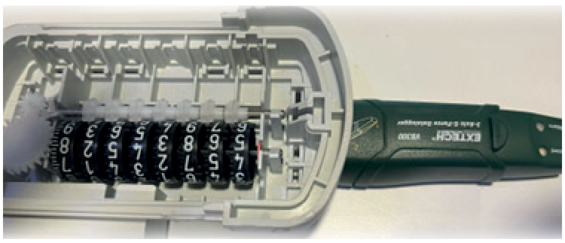

Fig. 7. Extension of the pin on which the counter drums are mounted

An acceleration of around 8 g may seem large, but it is an acceleration of impact. Comparable experiments were performed and a pen falling from a height of about 60 cm caused an acceleration of around 6 g to be recorded. It should also be remembered that when a vibrating cylinder is working, at a frequency of 50 Hz and a forcing of 2 mm, the acceleration is 24 g. The author therefore considers that an instantaneous acceleration at the moment of impact of around 8 g indicates a rather small force of impact (Fig. 8).

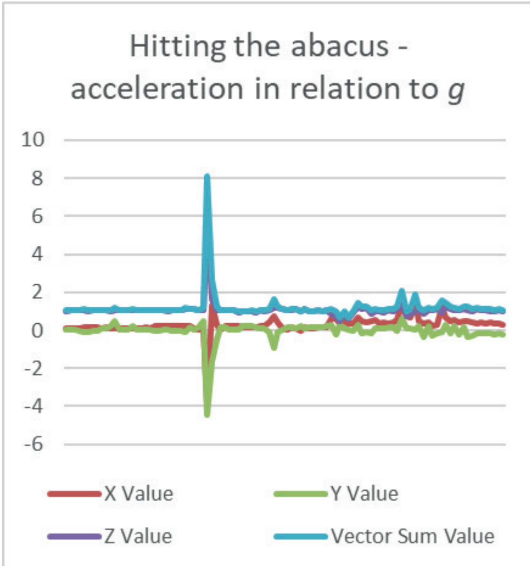

Fig. 8. Acceleration value at the moment of impact – readings every 50 ms

Using Newton's second law of dynamics and assuming that the drum pin weighs 2 g, an acceleration of 8 g is obtained with a force of $F = 0.14$ N. This force is sufficient to extend the pin by about 0.5 mm. This is a surprisingly small value – it is a force comparable to the force of gravity acting on an AAA battery.

Further experiments have shown that when the pin is extended by 2 mm (i.e. after four similar strikes), the first drums are moved away from the decade flip-flops, which can also be manifested by the lack of contact between the drum teeth and the gear wheel driving the counter (Fig. 9).

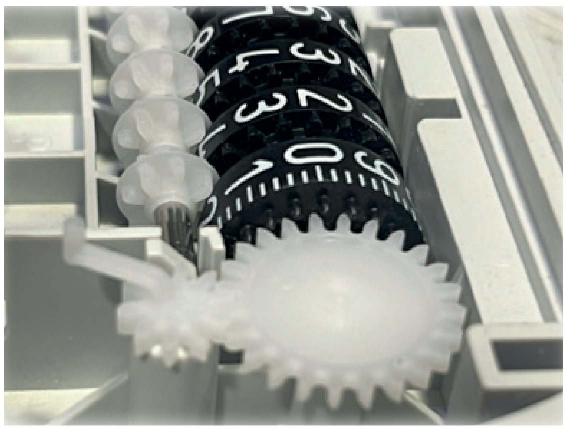

Fig. 9. Deflection of the drums after extending the pin by 2 mm

When the pin is fully extended (above 5 mm) all the drums can be turned freely (apart from the ones closest to the point of extension, which was discussed earlier). Of course, once the pin is pushed back into place, the counter works properly again and there is no trace of the skip on the drums.

5. Spreading the drums

The above analyses, although indicating that the meter is not adapted to work in vibration conditions, do not indicate the possibility of overestimating the gas reading, but rather underestimating it. Is there therefore a mechanical possibility of overestimating the reading?

Further analyses were carried out and it was determined that the nominal distance between the drums is 2 mm, the width of the tooth in the drum is about 1.3 mm, and the decade flip-flops have alternating teeth of 3 mm and 4 mm width. The principle of operation is such that the wider tooth of the decade flip-flop comes into contact with the protruding tooth of the lower digit, which rotates it by the distance of the larger and smaller tooth, which in turn causes the "older" drum to move by two teeth, i.e. exactly the distance needed to move by one digit (Fig. 10–14).

However, the drums have some freedom to deviate from the plane of rotation (due to the clearances between the pin constituting the axis of rotation and the inner diameter of the drum). In the tested abacus, a distance of 3 mm (1 mm more than the nominal distance) can be obtained without using any significant force.

It should be noted that in the case of this new distance increased by the depth of the tooth in the drum (1.3 mm) gives a total of 4.3 mm, which is enough space for the larger tooth of the decade flip-flop to fall into this space and then move the drum regardless of the fact that the number 9 has not yet appeared on the "younger" drum. Interestingly, this phenomenon can only occur for drums whose "younger" drum is set to at least the number 1 (it will not occur on drums whose "younger" drum is set to the number 0, due to the position of the protruding tooth of this "younger" drum).

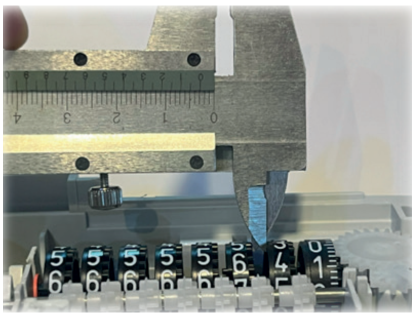

Fig. 10. Possible opening of the drums is 3 mm

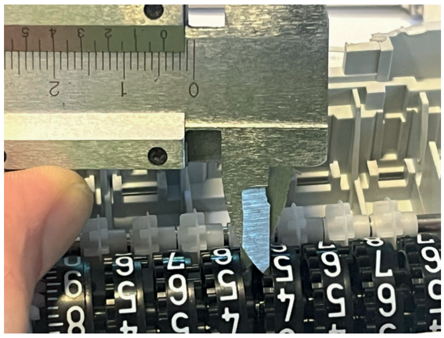

Fig. 11. The distance from the drum to the tooth cavity (4.30 mm)

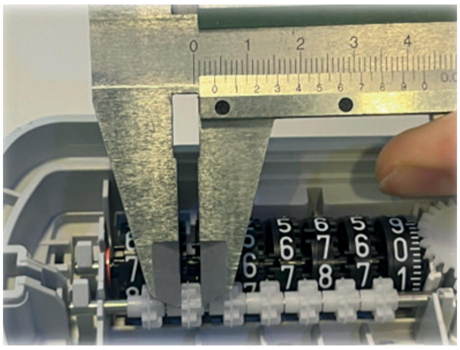

Fig. 12. The width of the wider tooth of the decade flip-flop (4 mm)

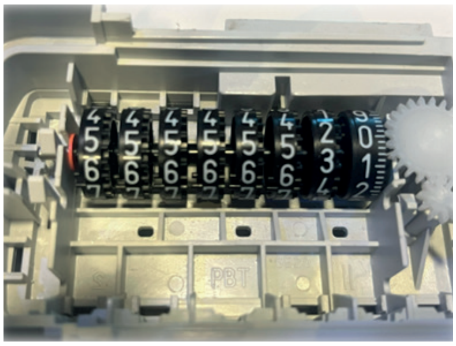

Fig. 13. The position of the teeth initiating the shifting of the "older" drum for drums indicating the number 0

Fig. 14. Indication of the abacus at the beginning of the test

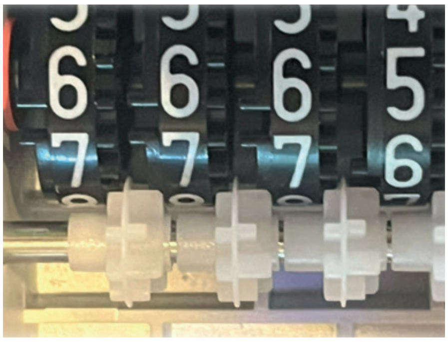

Fig. 15. Correct arrangement of the teeth of the decade flip-flops on the drums

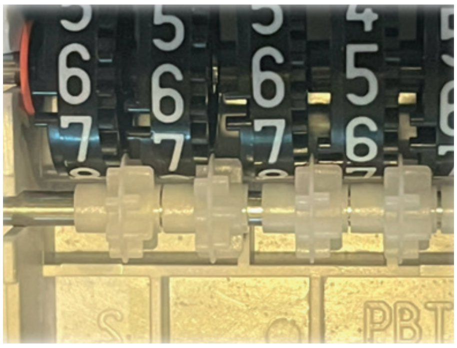

Fig. 16. Possibility of the slip-up of the wider tooth of the decade flip-flop into the space between the drums

Fig. 17. Wider tooth of the decade flip-flop inserted between drums during rotation

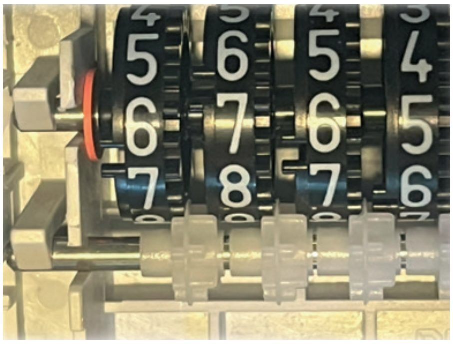

Fig. 18. New position of the drums and no signs of skipping

Fig. 19. New indication of the abacus

It is obvious that the probability of the drums spontaneously moving apart and the wider tooth of the decade flip-flop falling between these drums is negligible. However, taking into account the long time horizon (vibrations lasting for weeks), this probability increases. Importantly, it was possible to demonstrate that the abacus jump is possible. Due to the manufacturer's designed drum clearances and the dimensions of the teeth, at the moment of the drums moving apart there is still 0.3 mm of reserve, and therefore the tooth of the decade flip-flop can fit in the space between the drums and move the "older" drum without using additional force. Importantly, the abacus jump does not leave any mechanical traces on the drums and decade flip-flops (Fig. 15–19).

It should be added that after the experiment was completed, the abacus was also dismantled in the second counter – the one that was not subjected to vibrations. It turned out that in this counter, moving the spindle on which the counter drums are mounted is much more difficult (no precise measurements were made), from which the conclusion is that long-term vibrations can not only be the cause of the spindle displacement itself, but also cause an increase in the clearance between the spindle and the drums, which facilitates any potential displacement.

6. Conclusions

Finally, it was decided to use the conclusions from the analyses from the previous points on the second, undissembled gas meter. It was connected to a system that pumped 0.240 m^3 of air through it in 30 seconds, and then the gas meter was hit several times with a hammer (through pliers, so as not to damage the casing) on the side of the counter from the side of the driving digits. The blows were quite strong – as earlier experiments showed, the extension of the pin occurred at an acceleration of around 8 g. With a mass of the gas meter with a connected cable of around 5 kg, an acceleration of 8 g can be obtained by applying a force of 400 N (corresponding to the force of gravity acting on a weight of 40 kg). The force of the impact was much smaller, although its value was not determined, however, it did not have a significant event, because the purpose of the impacts was to reproduce the effect that vibrations acting for many hours can have on the gas meter, for which, as already mentioned, accelerations of up to 24 g can be expected. It can be assumed that achieving the intended effect rather indicates that in practice much less acceleration than 8 g is needed to extend the stem.

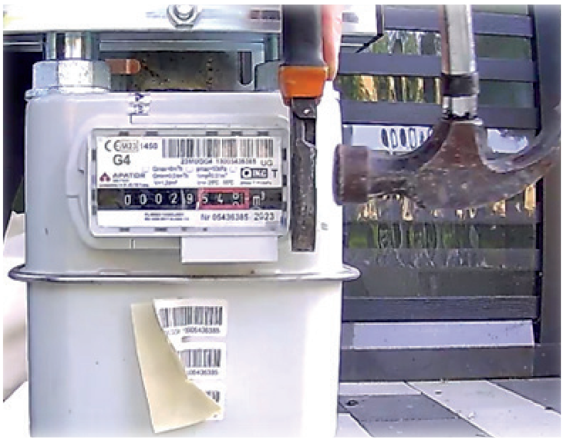

Fig. 20. A hammer blow simulating hours of vibration

As a result of the impact, the pin on which the drums are mounted moved completely. It is to be expected that many hours of vibrations cause the pin to gradually extend, so there are many intermediate states between the correct state and complete extension, but the aim of this final demonstration was to determine how the gas meter will behave after the pin is moved.

It turned out that the impact caused the entire pin with the drums to fall into the counter, and it was set in the correct position using a magnet to reproduce the state that would occur when the pin was gradually extended.

In the event of the effects of gas meter vibrations, the phenomenon of the entire pin retracting will most likely not occur, because the vibrations will gradually extend the pin until it is completely loose, but will still be in a position close to the initial one. As previous analyses have shown, extending the pin by about 2 mm is enough to start observing non-deterministic operation of the meter. What's more, since vibrations are usually oscillatory, the extended pin may reduce its extension as a result of further vibrations (Fig. 20).

A film was then recorded to show how the gas meter works. The film shows that the drums move almost simultaneously, so the counter jumps. This gas meter was not disassembled to leave it in a faulty state, despite having the original seals, but taking into account the description of the causes of the phenomenon in the previous chapters, it should be expected that there are no traces of jumps on the drums and decade flip-flops because they work in conditions of no pressure between these elements (Fig. 21).

Fig. 21. Selected frames showing the counter jumping in a sealed gas meter

The final conclusion is as follows: a jump of the counter of a bellows gas meter with a mechanical counter is possible when used in conditions of intense vibration.

Moreover, even if the gas meter were equipped with an electronic pulse counter, it would still have an incorrect reading, with the mechanical counter indicating an overstated value and the electronic counter indicating an understated value, due to the disconnection of the drive drum from the gear rotating the counter (pulses are counted based on the revolutions of the first drum).

It should also be added that manufacturers of meters can protect them from the effects described in this article. Firstly, by installing an element that prevents the shaft on which the drums are located from moving. Such an element can be installed after the counter is mounted (with a latch), or by extending the elements securing the counter glass. Secondly, it is necessary to ensure that the drums are spread apart, even with the use of a small force, less than the wider tooth of the decade flip-flop. This can be achieved by mounting the drums on rolling bearings, for example (the current mounting method resembles a sliding bearing, hence the need to provide clearances). And thirdly – after making these modifications, full certification tests must be carried out to allow the meters to operate in vibration conditions.

Without the above modifications, readings of gas meters taken in operating conditions that exceed the scope of their certification described in the PN-EN 1359:2017 standard mean that these readings may be unreliable.

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Conflicts of Interest: The authors declare no conflicts of interest.

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