FLUIDIC OSCILLATOR DEVICES BASED ON THE "AERODYNAMIC PARADOXON"

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ABSTRACT

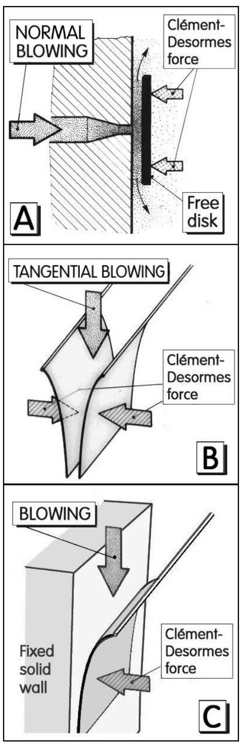
An unusual flow-induced oscillation mechanism is based on an old but nearly forgotten phenomenon: aero-dynamic force acting on a body in a direction contradicting simple logic (in some configurations opposing the direction of incoming flow) and turning down the flowpath. This seemingly paradoxical effect is replaced by usual orientation as the body is moved. The change of direction, together with the body inertia,may lead to self-excited oscillation. The author, as long as 37 years ago, proposed using this mechanism in a number of interesting fluidic devices (Tesař 1971, 1972a-g, 1976). The paper concentrates on observed existence of two different vibration regimes and the fact that the transition between these regimes exhibits a local maximum of Strouhal number Sh*.*

1. INTRODUCTION

The paper discusses an unusual operating principle of fluidic oscillators and other devices, patented by this author considerable time (37 years) ago but currently becoming of increased importance. The devices have elastically supported (or hinged) movable body kept in flow induced vibration by alternating direction of fluid force. While one of the directions is obvious, in agreement with fluid flow direction, the other is contrary to intuitive expectations. This contradictory force direction was described in scientific literature already by Nicolas Clément and his son-in-law Charles Desormes (1827). They called the effect "Aerodynamic Paradoxon" and under this name it may be found in literature, though nowadays only rarely. Of course, like all paradoxes in fluid mechanics, it is easily explained by standard fluid mechanics.

The effect is found in several alternative flow configurations. The basic ones are shown as A, B and C in Fig. 1. Probably the least expected and most "paradoxical" is the case A, with a freely movable disk (see also Fig.2) expected to move by the air flow away from the nozzle but in fat moved back, i.e. in the direction of decreasing distance X. In other words, in a range of distances X the force D is negative (Fig. 2), opposite to the direction of the nozzle exit air flow. When the negative D moves the disk up to the nozzle exit, the air flow must stop. Pressure upstream from the disk is built up and finally moves the disk away from the nozzle Theoretically, the disk may remain in the stable equilibrium point - Fig. 2 - where the force D is zero as it changes its sign. However, this position is almost impossible to attain. Inertia of the disk usually causes it to move beyond the equilibrium. There a force is generated pushing it back. The alternating positive and negative force action causes the disk to oscillate back and forth.

The "paradoxical" Clément-Desormes force is caused by conversion of the pressure energy into kinetic energy under the disk — in the radial flow region where the pressure is lower than atmosphe-



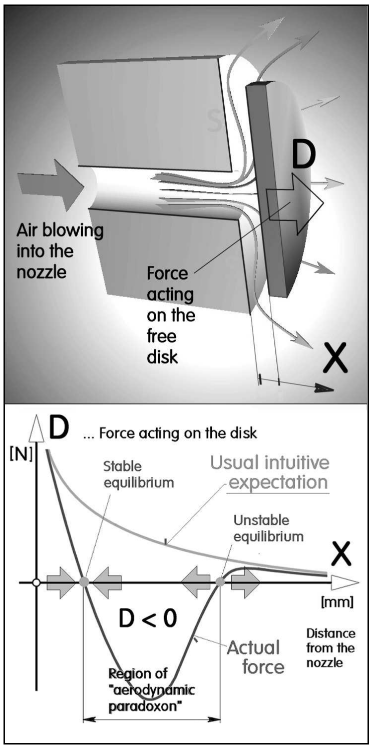


Fig 1 (left)*: Alternative basic configurations on which the «Aerodynamic Paradoxon» phenomenon is usually demonstrated.*

Fig 2 (right)*: The moving component, such as the disk from Fig. 1 A, oscillates because it is prevented by its inertia to stay in the stable equilibrium position.*

ric. Essentially, the fluid need not come towards movable body in the perpendicular direction (A in Fig.1). In the configurations B and C in Fig. 1, fluid enters the low-pressure region under the movable (or deformable) body tangentially. The final negative feedback effect of closing the flow channel is the same.

2. USES IN FLUIDICS

This mechanism of generating self-excited oscillation has been used in a number of interesting fluidic devices, mainly oscillators and sensors (or transducers) operated in periodic flow regimes (Tesař 1971, 1972a-g). Another interesting application was an extremely simple pneumatic low-power motor (Tesař, 1976). Unfortunately, experimental results obtained with these devices and their scaled-up models were never properly published. Recently renewed interest in new principles of fluid flow handling and control, mainly associated with the emergence of microfluidics (Tesař, 2007), has led to considering this mechanism again, mainly in biosensors.

2.1 Oscillators

It is advantageous to use in fluidics devices containing no moving parts. They are much more robust in operation and easier to manufacture. However, there is an important class of oscillator devices which in the no-moving-part version, dependent on purely aerodynamic mechanisms, exhibit the typical dependence of their oscillation

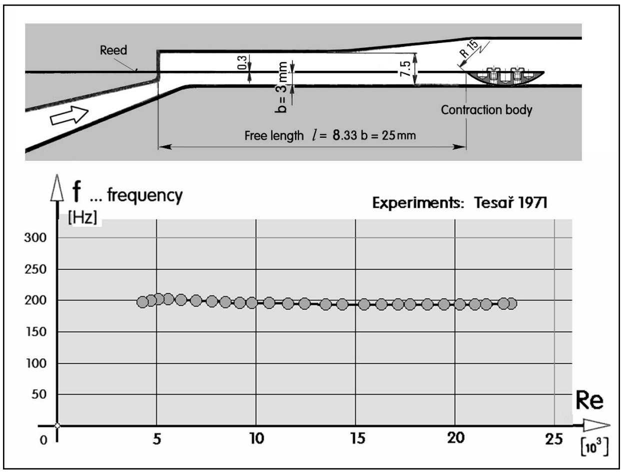


Fig 3: *Results obtained with a laboratory model of fluidic oscillator based on the idea corresponding to* C *in* Fig.1. *In contrast to no-moving-part fluidic oscillators with their typical frequency increase with flow rate (and hence with Reynolds number* Re*), here the frequency tends to be almost constant.*

frequency on flow rate (characterised by constant or nearly constant Strouhal number Sh). This may be useful in some sensor applications but in other cases it is a distinct disadvantage. It demands close control of the supply flow rate and this complicates the fluidic circuitry. Solution are sought in locking-in the oscillatory process to a mechanical oscillator -- such as, e.g., a tuning fork. Practical realisations are complicated and difficult to manufacture. In particular, it requires mutual crossing of the feedback channels, which necessitates making the device as a three-dimensional structure.

The extremely simple and elegant solution, Fig. 3, with the vibrating reed driven by the Clement-Desormes force acting on the contraction body (essentially the mechanism C in Fig.1.) is easily produced in a two-dimensional (planar) layout. The reed with the body at its end may be made by etching in a single manufacturing operation togethar with all the cavities for fluid flow. In the author's laboratory tests the reed was operated for ~ $28 .10^6$ cycles with no signs of any problems with material fatigue. Strictly speaking, the frequency is not perfectly constant across the whole operating range (Fig. 3), but the deviations are practically negligible for absolute majority of engineering applications.

2.2 Sensors, transducers and other devices

The presence of the moving component in the device offers an opportunity for acting on it by various non-fluidic forces, which then influence the oscillatory motion. This changes the device into a conversion device (Chapter 5 in Tesař, 2007). Tests already made included sensors of mechanical input variables (force, motion) with frequency changed by the input force stressing the elastic reed (Tesař 1972c). Other M/F (= mechano/fluidic) sensors with the mechanical input vary the geometry of the channel in which the reed vibrates (Tesař 1972e, 1972g). The advantage of this form of sensing is the frequency-modulated character of the output signal, not influenced by inevitable losses in the transmission and eminently suitable for subsequent digital processing. This advantage also applies to the temperature (T/F) sensor with bimetallic reed described in Tesař (1972f) and the electric and/or magnetic E/F transducer (actually using conversion chain E/M/F) with electric input and fluidic output using magnetic force on a ferromagnetic vibrating body (Tesař 1972b). Other transducers involve the inverse F/E conversion with interrupted contact pair (one of the contact being the reed, Tesař 1971).

Perhaps the most interesting case among the tested conversion devices was the extremely simple low-speed, low-power pneumatic or hydraulic motor (Tesař 1976) at one time tested for bomb activation (removal of a mechanical stop in front of the firing pin).

3. COMPLEXITY: TWO-REGIMES

Results of the experiments performed in the earliest history of investigating this phenomenon were never properly published. The most interesting fact following from them was an indication that the underlying mechanism of the oscillation is complex and non-monotonous: there were two different clearly distinguishable regimes.

3.1 Hinged foils early experiment

The first of he author's feasibility experiments used the configuration B in Fig. 1, with two symmetrically arranged foils between which the air was blown. The foils made from 0.6 mm thick (and therefore practically inelastic) duraluminium sheets were arranged according to Fig. 3. They were rather large (note the 70 mm span in relation to d = 1 mm nozzle diameter), with top ends formed into hinges (could be freely rotated on the 4 mm dia. pins). There was no elastic member in the body system, but the foils hanging down from the hinges were forced into the "open" position by gravity. Air flow from the downwards oriented vertical air jet, issuing between them, pushed the foils together into the "closed" position by the Clément-Desormes force. Their metallic contact was detected as an electric pulse passing between the hinge pins. The flow rate supplied into the nozzle was measured by a rotameter.

The dependence of oscillation frequency on the nozzle flow rate, Fig.5, indicated an existence of two different regimes, M and N. Neither one of the quite plausible linear fits through the data points passes in Fig. 5 through the origin, so that this not a case of a constant Strouhal number Sh law, so typical for no-moving-part aero-dynamic oscillation.

3.2 Local Strouhal number maximum

When re-plotted in Fig. 6, another set of linear fits in logarithmic co-ordinates indicate possible fitting a power-law dependences to the Sh = *f(*Re*)* dependence in each of the two regimes. The characteristic dimension used in evaluating Sh and Re in Fig. 6 was the nozzle diameter d. At the transition Sh reaches the maximum. This takes place at Re values that may be reasonably associated with transition into turbulence in the jet issuing from the nozzle. This was initially conside-

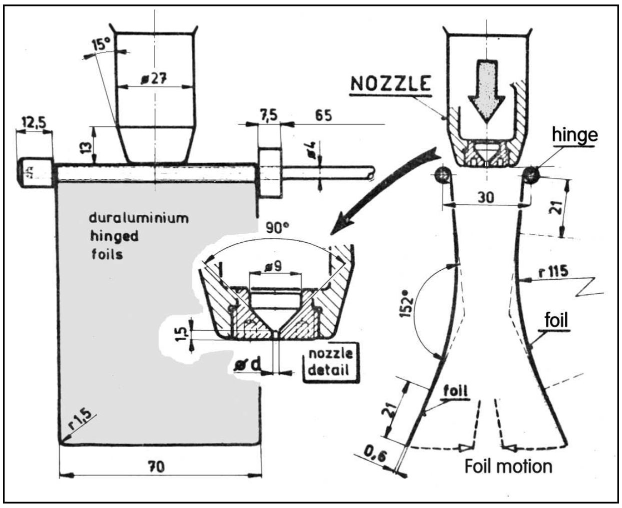


Fig 4: *The earliest experiment performed by the present author in 1971. Two thick and therefore essentially inelastic foils correspond to the configuration* B *in* Fig. 1. *Air is blown between them through the* 1 mm *dia. nozzle.*

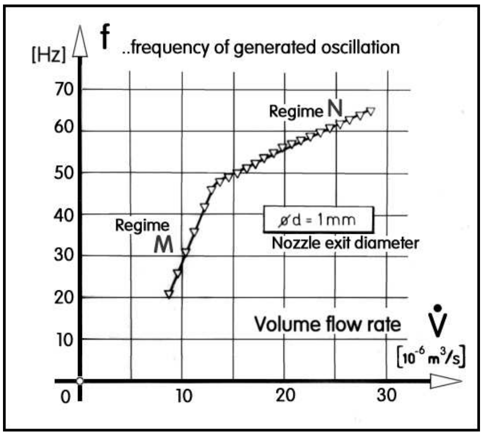


Fig 5*: Results of the experiment shown in Fig. 4. The dependence of the frequency on the supplied air flow rate exhibits a transition from the initial regime* M *at higher flow rates into another regime* N*.*

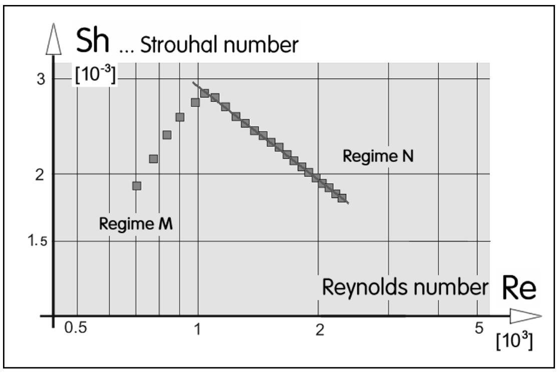


Fig 6*: Results from Fig. 5 re-plotted as a dependence between Reynolds and Strouhal number (using the nozzle diameter as the reference dimension). There is a local maximum of the Strouhal number at the transition. The Re values suggest the change from regime* M *into* N *is associated with transition into turbulence in the jet.*

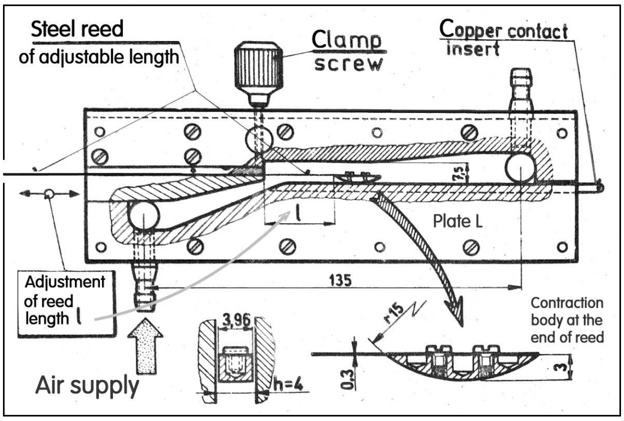


Fig 7: *Model used in investigations (see also Fig. 3) of the influence of the natural frequency of the vibrating body fixed to the end of the reed with free lengths l.*

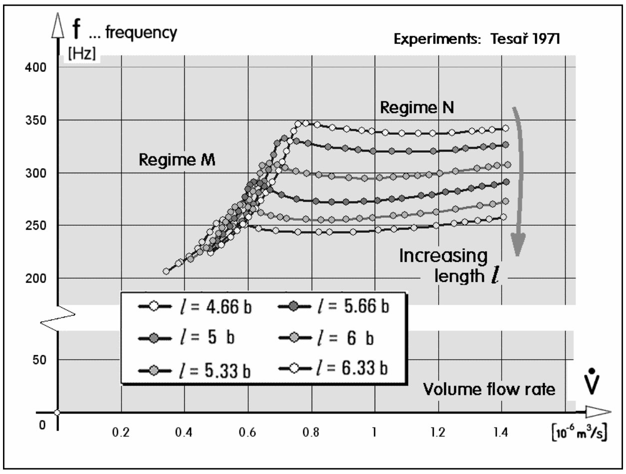


Fig 8: *Dependences of oscillation frequency on the supply air flow rate obtained with the model from Fig. 7 for different reed lengths l. There is again a transition between two different regimes,* M *and* N *, similar to the spring-less case in Fig. 4.*

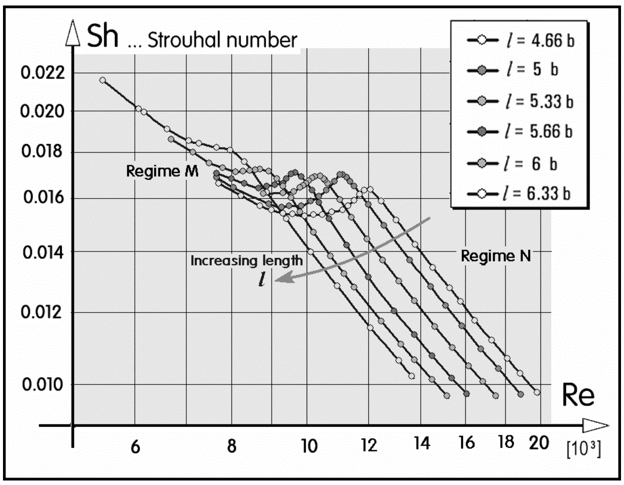


Fig 9: *Results from Fig. 8 converted into the dependence between Strouhal and Reynolds number. The conspicuous feature again is the local maximum of values at the transition between* M *and* N.

red to be the explanation. However, transition into turbulence in jets takes place gradually: the turbulence prevails at larger distances from the nozzle, towards which it gradually propagates as Re is increased. The change is therefore hardly so sudden as suggested by Figs. 5 or 6.

The fact that the electric current passed through the foil hinges indicated an absence of a continuous oil film in the hinges (despite the hinges being well oiled before the test). A possibility thus existed of the hinge friction (certainly not a simple process) being a factor behind the observed complexity. Next investigations were therefore made with the hinges replaced by an elastic strip — the reed that supports the body. The configuration used in this next laboratory model (Fig. 7) was asymmetric, with only one body, according to C in Fig. 1. The vibrating parts were located in the constant-depth channel. The free length l of the reed could be adjusted. As before, the frequency of the self-excited vibration was measured by counting the interruptions of electric contact between the end body and channel wall.

Two different regimes at least seemingly corresponding to M and N from Fig. 5 were found again, as seen in the results plotted in Fig. 8. Obviously, also here a linear fit to the points in the regime M does not pass through the origin, so that the Sh vs. Re dependence in Fig. 9 again exhibits (at least in most cases) the remarkable local maximum of the Strouhal number.

4. LATER DEVELOPMENTS

The period since the author's first demonstration in 1971 of the oscillation based on the "Aerodynamic Paradoxon" has witnessed progress in understanding some aspects of the phenomenon. There were investigations of the Clément-Desormes force acting on a free disk, though only in steady states. Paivanas and Hassan (1981), represent the first paper from among a number of several others. Also the case of a tangential blowing on a curved reed in a channel became a subject of investigations, this time actually concerned with oscillation. Shapes similar to those discussed in Tesař (1971, 1972a) became of concern for application to vocal cord total prostheses – a typical one among many papers by Horáček and collaborators on this subject is Horáček and Švec (2000). The "reeds" used in these investigations, however, were inelastic, of polymeric materials. Very recently, an interest into the Clément-Desomes force has led to interesting stability studies, cf. e.g. Antoine M. et al., 2008.

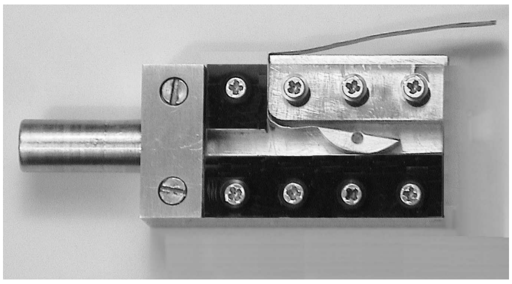


Fig 10: *Repeated verification tests after 36 years since the original proposal were made with the simple model shown in this photograph.*

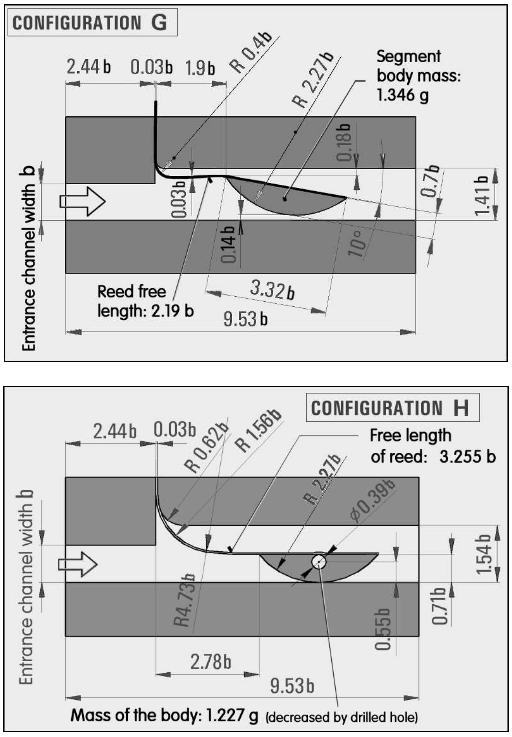


Fig 11: *The two configurations investigated recently in the verification tests.*

Recently, repeated verification tests were performed with the models as shown in Figs. 10 and 11. In one of them (configuration G), small-amplitude oscillation could be detected around the stable equilibrium point (Fig. 2) with the contraction body not contacting the wall. This, of course, made impossible to measuring the frequency just in the range where the interesting M -N could be expected. Nevertheless, the existence of the transition (Fig. 10) as well as the existence of the local extreme (Fig. 11) could be clearly demonstrated with another, slightly changed configuration H.

5. CONCLUSIONS

The "Aerodynamic Paradoxon" effect of the aerodynamic force moving a body (free or flexibly supported - or a flexible reed) in a direction

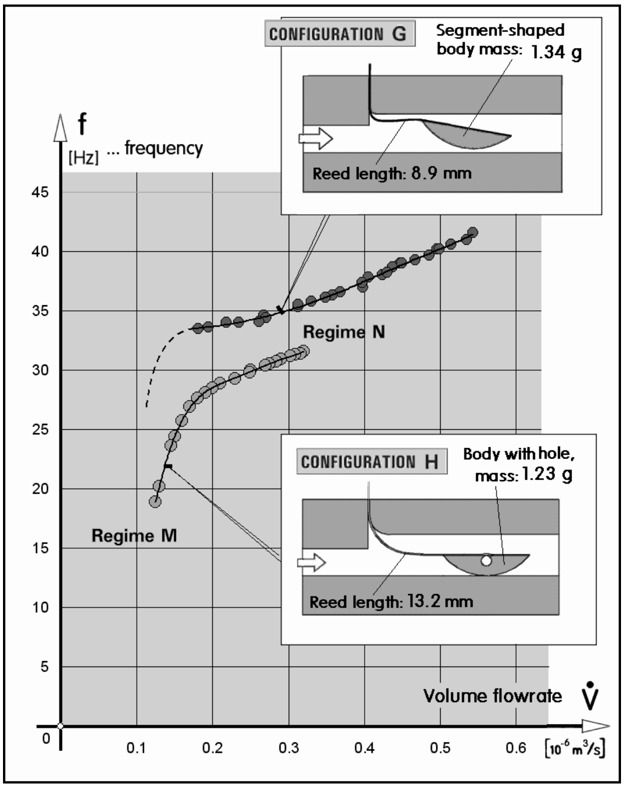


Fig 12: *The transition between the regimes* M *and* N *could be observed in one of the two configurations shown in Fig. 11. In the other configuration, the interrupted-contact measurement method failed just in the region where the transition could be expected.*

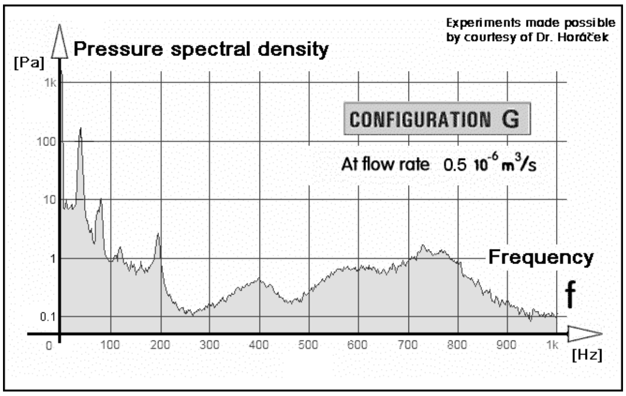


Fig 13: *Frequency spectrum of the acoustic signal generated by the configuration* G *of Fig. 11.*

gradually closing the available flowpath (- opposite to what an uninitiated observer may intuitively expect) may give rise to flow-induced vibration or oscillatory motion of the body. This little known and rarely used mechanism is shown to offer several interesting application opportunities, especially in fluidics. Unfortunately, very little has been so far known about the details of the mechanism of such oscillation. No theoretical analysis has been available, mainly because of the difficulties

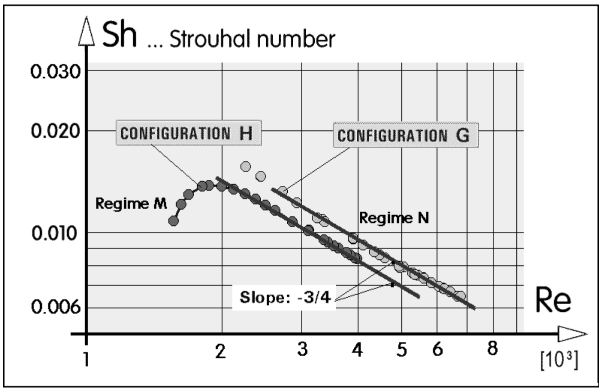


Fig 14*: Demonstration of the existence of the local* Sh *maximum between the regimes* M *and* N *in the configuration* H *of Fig.11.*

associated with taking into account the impacts of the body (impact on the wall or mutual impact of two bodies in the symmetric versions). Also the reed shape variations during an oscillation cycle makes solutions difficult.

Performed experiments lead to the following conclusions:

- Two distinctly different regimes, called here M and N, are distinguishable (of course, unless the transition between is outside of the experimental range).
- The Strouhal number Sh evaluated from the width b of the inlet channel (Fig. 11) at the transition is typically between Sh=0.01 and 0,02
- Characteristic for the M - N transition (though not necessary, cf. the case l = 6.33 b in Fig.7) is the fact that Sh reaches there a local maximum.

In view of the potential usefulness in applications, as well as desirability of gaining insight into an interesting mechanism of this fluid induced vibration (perhaps at least partly present in also other flows with moving bodies), the absence of a deeper understanding is an obvious challenge for researchers.

6. REFERENCES

Several references listed here were included because of their historic importance – they document the beginnings of the research into this problem.

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