Vladimir Jordan – industrial water-hammer engineer and researcher

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ABSTRACT

Vladimir Jordan was an adherent of post-WW2 hard working European engineering community. In 1947 he established and headed the design office of a newly founded manufacturer of turbine and industrial equipment: Litostroj. As a natural born artist, he 'fell in love' with the graphical method which he applied in conjunction with analytical methods for water-hammer analysis to a range of industrial problems. In particular, his original papers on the treatment of distributed vaporous cavitation along pipelines, shut-off valve induced hydraulic oscillations, and water-hammer effects in Kaplan turbine draft tubes, attracted wide interest in the seventies. Jordan's life and work are reviewed. Special attention is paid to a few highlights which may not sink into oblivion.

1 NOTATION

A	pipe cross-sectional area
a	water hammer wave speed
D	pipe internal diameter
GD^2	polar moment of inertia
g	gravitational acceleration
H	pressure head (head)
H_b	barometric head
h_{loss}	head loss
L	pipe length
n	rotational speed
n_q	specific speed of turbomachine (pump, turbine)
Q	discharge
t	time
t_r	flow reversal time
β	check valve opening angle
φ	pipe slope
Subscripts:	
chv	check valve
max	maximum
p	pump
wcs	water column separation
0	initial conditions

2 INTRODUCTION

Water hammer knowledge is based on more than two centuries long endeavours of fellow engineers and scientists from academia, institutes and industry. The life and work of a number of prominent pioneers in water-hammer research have been presented and discussed at past and present Pressure Surges Conferences to pay gratitude and tribute for their discoveries and efforts, and to inspire younger engineers to continue and foster their work. These are the men to whom the renowned water-hammer specialists prepared and presented their tributes (from the oldest contribution onwards):

(i) Johannes von Kries (1853-1928), a German scientist who derived and validated the 'Joukowsky formula' before Joukowsky did (Tijsseling and Anderson 2004).
(ii) Thomas Young (1773-1829), an English scientist and medical doctor who made significant discoveries in physics, medicine and linguistics. In the water-hammer area he derived the pressure wave speed in an incompressible liquid contained in an elastic tube and he made a study of hydraulic rams (Tijsseling and Anderson 2008).
(iii) Adriaan Isebree Moens (1846-1891) and Diederik Johannes Korteweg (1848-1941), Dutch scientists known for the Moens-Korteweg formula for the wave propagation speed (Tijsseling and Anderson 2012).
(iv) Victor Lyle Streeter (1909-2015), an American engineer and scientist was a major contributor to the early application of digital computers for solving water-hammer problems in a wide range of engineering disciplines, from unsteady flow in pipe networks to blood flow in arteries (Wylie and Wiggert 2012).
(v) John A Fox (1923-2012), UK's pioneer in modern approaches to the numerical analysis of unsteady flows in pipelines and blood vessels (Vardy 2012).
(vi) Piotr Szymański (1900-1965), a Polish scientist who developed an analytical solution describing the instantaneous acceleration of a viscous fluid at rest (Urbanowicz and Tijsseling 2015).
(vii) Leonhard Euler (1707-1783): see Hamouda and Tijsseling paper at present conference (Hamouda and Tijsseling 2022).

In this paper we would like to pay a gratitude and tribute to European engineers who were drawn into World War II (WW2) hostilities and who helped to rebuild torn-down European countries. The paper in a way reflects to current pandemic and war time in Europe too. This paper reviews the life and work of Slovenian research engineer Vladimir (Vlado) Jordan, born in 1913, a year before WWI started, in then Duchy of Carniolia, a part of the former Austro-Hungarian Empire. His original papers on the treatment of distributed vaporous cavitation along pipelines (Jordan 1975d), shut-off valve induced hydraulic oscillations (1973c), and water-hammer effects in Kaplan turbine draft tubes (1975e), attracted a wide interest in the seventies. In the early eighties, he wrote a book on water hammer (Jordan 1983) which combines his research and practical work on hydraulic transients in hydropower and pumping systems. The book was published in 1983, three years before his death.

3 HIS LIFE

Vladimir Jordan (Fig. 1; his colleagues always called him Vlado) was born on 2 January 1913 in the small village of Ihan in then Duchy of Carniolia, part of the former Austro-Hungarian Empire, now Slovenia. By coincidence the village of Ihan is the neighbouring village of Vir and Študa, places where the first author has been living most of his life. His father Franc Jordan, youth writer and translator, was a headmaster at the local primary school (Stražar 1974). The family moved to Ljubljana in 1923 where his father Franc took a new teaching position. His parents passed away before World War II.

Fig. 1 Two photos of Vladimir Jordan (1913-1986)

In the autumn of 1931 he enrolled at the Technical Faculty of the University of Ljubljana. The syllabus of the Department of Mechanical Engineering, where he studied, had a two-years programme at that time. That is why Vladimir Jordan completed his four-years BSc studies in mechanical engineering at the University of Belgrade in 1940. Then he served compulsory military service in the army of the Kingdom of Yugoslavia. On 6 April, 1941 the nazi Germany and the fascist Italy, and their allies attacked and occupied Yugoslavia. Large parts of today Slovenia were occupied and annexed by Germans and Italians, and small parts by their allies Hungary and new-born German satelite Croatia (a number of villages in the south-east). Vladimir and his younger brother Bogdan (1917-1942), who graduated geography just before the aggression, joined the resistance movement in Ljubljana which was occupied by the Italians. Loyal and devoted to his country, Bogdan was killed as a hostage on 21 July, 1942 in the Ljubljana Gravel Cave (Malovrh 1945). Vladimir was greatly affected by his brother's death. In September 1943, Vladimir joined the partisan units. In December of the same year, he was already at Goteniški Snežnik in southern Slovenia, where there was an important partisan printing house Triglav (Krall 1972). There, his task was to prepare woodcuts and linocuts and to take care of the technical aids of the printing machines. As an excellent draftsman, he crafted drafts of propaganda material and even drafts of partisan banknotes and bonds. His professor of arts at the highschool was the academic painter Božidar Jakac, who already noticed his talent for fine arts (Fig. 2), invited him to the Academy of Fine Arts after the war; however, he decided to continue his career as an engineer.

Vladimir Jordan joined Litostroj, the manufacturer of turbine and industrial equipment established in 1946, on 1 January 1947. First, he helped in the organization of the construction company, then immediately he became an independent designer and chief designer. He was also the head of the design department for several years. With his thorough knowledge and deep understanding of engineering design, he established himself in the design of water turbines and cranes. Among its resounding unique works of that period are the tunnel for aerodynamic testing of aircraft and aircraft profiles at the Žarkovo Aviation Institute near Belgrade, Serbia, and the pumping system for the supply of fresh water from the Radovna River to Lake Bled, Slovenia (Kramar 2010). As an open expert, he passed on his rich knowledge to younger colleagues, who then took on construction and design tasks independently.

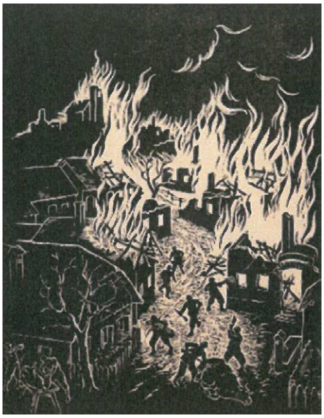

Fig. 2 Jordan's war art – War; graphics, woodcut, 1950

In his engineering work, in addition to designing and constructing, he has been increasingly involved in stress and hydraulic analyses of hydraulic turbomachines and its auxiliary equipment. When monitoring the operation of water turbines and pumps, he noticed that he should deepen the understanding of physical phenomena associated with the transient states of operation of these machines. These include water turbine and pump start-up, load increase or decrease, stoppage of its operation, etc. (Jordan 1983; Chaudhry 2014; Li *et al.* 2019). Any change in the liquid flow velocity is accompanied by inertial forces, followed by a temporal change in the internal pressure. Excessive internal pressure, however, can lead to failure of the walls of the pipeline, shut-off valves or even failure of the turbine itself (Li *et al.* 2020). Engineer Jordan was looking for the literature that would address water-hammer problems. He found physically explained basics in the French language, namely in Bergeron's book *Du coup de bélier en hydraulique - au coup de foudre en electricité* (*Waterhammer in hydraulics and wave surges in electricity*) (Bergeron 1950). As a natural born artist, he 'fell in love' with the graphical method (in Central Europe known as a Schnyder-Bergeron graphical method) which he applied in conjunction with analytical methods for hydraulic transient analysis to a range of industrial problems.

In the late 1950s, Vladimir Jordan established a research and development department. He became the head of the department, where he has been mainly involved in the study of the water hammer in hydropower and pumping systems, an important issue for the safe operation of these systems. He has greatly expanded the application range of the graphical method by taking into account a number of internal and boundary conditions. He considered line and local head losses, pipe junctions, valves, pumps and turbines, surge suppression devices and in particular, water column-separation effects. His broad knowledge was used to tackle water-hammer problems in a number of hydropower facilities and water supply networks in all former republics of Yugoslavia and worldwide, where Litostroj supplied turbines, pumps and its auxiliary equipment. In 1965 he successfully defended his doctoral thesis on water hammer with column separation in pumping systems (Jordan 1965b). Due to the need to buy a smaller apartment, he decided to terminate his employment at Litostroj from 1967 to 1970 (Kramar 2010). He went to Andritz in Graz, Austria, where he developed water-hammer computer programs in Fortran language. After that he returned back to his home country, he continued to work in Litostroj till his retirement in 1977. During the sixties and seventies he published his research and development achievements in 26 technical papers; 13 papers in Slovenian language in mechanical engineering journal Strojniški vestnik and 13 publications in English, German and Serbian languages (please see a list in Bibliografy at the end of this paper). The publications dealt with column separation, resonance, check valves, shut-off valves, pumps and turbines, etc. In this period he developed new computer codes for water hammer and analysis in hydropower systems (Jordan 1973a) that were based on the graphical method. Finally, during his retirement in the early eighties, he published a well-written book on hydraulic transients in hydropower and pumping systems (Jordan 1983). The book brings together his research on water hammer and practical work experience on a number of industrial projects. He dedicated the book to engineers at the beginning of their career. Vladimir Jordan died on 28 September 1986 (Fašalek 1986) in Ljubljana due to head injuries in an accident.

4 HIS WORK ON COLUMN SEPARATION AND OTHER WATER HAMMER PROBLEMS

Jordan presented his first technical paper on water hammer at the *II. Meeting of the Yugoslav Experts on Hydraulic Research* in Bled, Slovenia, in the late fifties (Jordan 1958). The paper deals with the closure of shutoff valves and gates in pipelines. He presented simple relations for self-closing types of valve and gate actuators (passive actuators). In this case the device's closing time strongly depends on flow conditions acting on the device's body (Ellis and Mualla 1984), i.e. the closing time is not known in advance; it is a result of water hammer analysis. In 1961 he published his first paper on water hammer in the Slovenian mechanical engineering journal Strojniški vestnik (Jordan 1961a). This paper is actually a review paper on water hammer in hydroelectric power plants and pumping systems. The physical foundations of water hammer as well as its importance in the design and operation of hydraulic systems were described. The principle of the Schnyder-Bergeron graphical method for solution based on Joukowsky's equation was explained and applied to hydraulic systems with different boundary conditions including water turbine (action and reaction type) and pump. Among others, he presented an interesting example of pump-power failure with column separation at the pump followed by a large pressure head after the check valve closure at full reverse flow (Fig. 3). He noted the importance of the time of flow reversal t_r at the pump on the maximum water hammer head which can be approximated by the following equation:

$$t_r = \frac{2\left(Q_0 - Q_{p,wcs}\right)}{gA\left(H_0 + H_b\right)} \tag{1}$$

The symbols are declared in Section 1. In addition, devices to reduce water hammer in hydraulic systems were considered as well. He quoted works of Joukowsky, Allievi, Schnyder, Bergeron, Fabritz, Jaeger, Lein, Stepanoff, Pavluch, Parmakian and Viti, all pioneers on water hammer theory and solution models, and their applications in engineering practice. Jordan published a similar review paper on water hammer in pumping systems in Serbian Language (Jordan 1962c).

Soon after that, Jordan published a special paper on the influence of check valves on water hammer after pump-power failure (Jordan 1961b). He presented the following simple formula for the optimal position of the check valve in the case of column separation at the pump or at some point along the pipe:

$$L_{chv} = \frac{LQ_0^2}{2gA^2\left(H_0 + H_b + 0.25h_{loss}\right)} \tag{2}$$

Jordan's two 1961 papers can be considered as the starting point for his interest on water hammer with column separation (Wylie and Streeter 1993; Bergant et al. 2006).

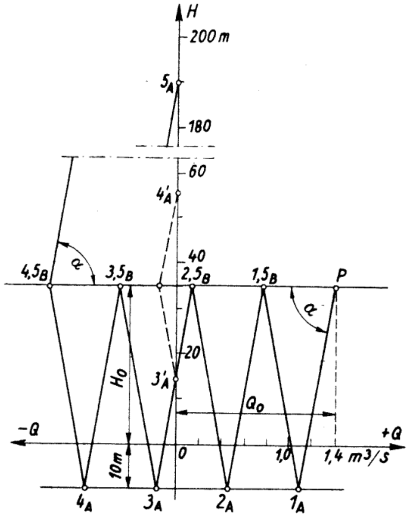

Fig. 3 An example of graphical determination of water hammer after pump-power failure (Point 4'$_A$ gives maximum head in the case of no flow reversal) (Jordan 1961a)

At that time several pumping systems had been equipped with swing check valves and they experienced valve slam (Thorley 2004). Check valve slam occurs at an unfavourable ratio between the closing body mass and pipe flow deceleration due to pump power-failure. Jordan (1962a, 1964c) presented a graphical procedure for the coupled solution of the closing body equation of rotating motion and the water hammer equations. He assumed small pump inertia in his investigations and noted that the check valve should be closed before flow reversal. Figure 4 depicts an example of rotational speed and acceleration of the closing body during pump power failure. Jordan further investigated surge suppression devices in pumping systems. In his 1964 paper (Jordan 1964a) he investigated oscillations of water masses in systems with air vessel and, two years later, the effect of the pump flywheel on attenuation of flow deceleration in pipelines after pump failure (Jordan 1966a). In the latter paper he presented a graphical-analytical procedure for approximate estimation of the flywheel inertia that is based on the fact that during the deceleration period the pump rotational speed does not drop below a critical value defined by the allowable water hammer head at the pump. In 1964 he published a 293-page manual on the graphical method: *Hidraulički udar u hidroelektranama i crpnim postrojenjima. Primena Schnyder-Bergeronove grafičke metode. (Water hammer in hydroelectric power plants and pumping systems. Application of the Schnyder-Bergeron graphical method.)* (Jordan 1964b). He presented numerous applications of the graphical method for solving water hammer problems in hydropower and pumping systems. Among others, he presented a case study on how to attenuate water column separation in pumping systems by the installation of several check valves along the pipeline (Karney and Simpson 2007). The manual served as a guideline for engineers in Yugoslav hydraulic institutes, and turbine and pump manufacturers.

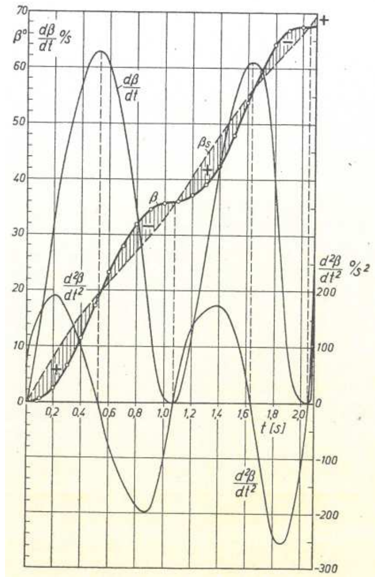

Fig. 4 An example of graphical determination of rotational speed and acceleration of the closing check valve body during pump-power failure (Jordan 1962a)

Then he published a paper on non-classical methods in the sixties (Jordan 1965a): (i) by-pass at the pump, (ii) one-way surge tank along the pipeline, (iii) control valve and (iv) vessel with air valve at the top and pierced check valve at the pipe T-section. According to Jordan the classical methods include pump flywheel, surge tank and air vessel (air chamber). It should be noted that in the first part of his paper he presented basic principles on how to model distributed vaporous cavitation zones along the sloping pipeline within the graphical method (he neglected pipe-wall friction losses). This was the topic of his doctoral dissertation entitled *Određivanje hidrauličkog udarca pri isključenju crpke bez ublaživača udarca pod uslovima raskidanja vodenog stuba* (*Prediction of water hammer at pump failure without surge protection under water column separation conditions*) that he submitted and defended at the University of Belgrade, Belgrade, Serbia (Jordan 1965b). In his dissertation, he investigated column separation and distributed cavitation in pumping systems with horizontal, upward and downward sloping pipe sections and he studied analytically the effect of hydraulic grade line (HGL) and pipe slope on the formation of cavitation zones. A cavitation zone may result from the passage of a negative pressure wave traveling in the direction of decreasing steady-state pressure. In his thesis he has developed a new column separation consolidation model that treats distributed cavitation regions along the pipeline by using graphical-analytical solutions for equations describing distributed cavitation zones at vapour pressure and the condensation of these zones back to the liquid phase. Pressure waves do not propagate in distributed vaporous cavitation regions, because the local pressure remains constant at vapour pressure. He assumed that small separated liquid columns move along the pipeline. As soon as a rarefaction wave arrives at the reservoir at the downstream end, the reservoir pressure induces condensation of the distributed cavitation zone next to the reservoir and vapour (or vacuum) turns back to liquid. Similar phenomena occur at the pump after rapid closure of the protecting check valve. He gives a step-by-step example for the pump failure in an $L = 1500$ m long upwards sloping steel pipe of $D = 578$ mm internal diameter. The pipe slope is constant at $\varphi = 2.1^{\circ}$

and the wave speed is a = 1000 m/s. The static head H_0 = 60 m and the initial discharge Q_0 = 0.5 m^3/s. In addition to consolidation model results (see Fig. 5; Fig. 40 in Jordan's thesis), he presented also a solution with a discrete vapour cavity at the pump only and a solution with discrete vapour cavities at selected locations along the pipeline by using the Schnyder-Bergeron graphical method. In Fig. 5 the operating point N_0 is calculated by the consolidation method. Hatched areas in Fig. 5 depict vaporous cavitation regions and the resulting maximum water hammer head at the pump is H_{max} = 260 m obtained from the graphical method (liquid region). He also compared calculated and measured maximum water hammer heads at upstream-end valve after its rapid closure in an upwards sloping pipeline from Smirnov's (1954) and Jordan's pipeline apparatuses. The main system data and results are given in Table 1. In addition, Jordan presented his column separation consolidation method in two German-language papers (1966b, 1975d) and later on in detail in his 1983 book.

Table 1. Apparatus data and comparison of maximum heads at the valve

	Jordan's 1965 apparatus	Smirnov (1954)	Smirnov (1954)
Static head (H_0)	10.4 m	21 m	4 m
Initial head losses (h_{loss0})	3.9	70.5	86 m
Initial discharge (Q_0)	0.00145 m^3/s	0.00165 m^3/s	0.00175 m^3/s
Pipe internal diameter (D)	50 mm	50 mm	50 mm
Pipe length (L)	202 m	1160 m	1160 m
Pipe slope φ	15.7° - from 0L to 0.125L 1.1° - from 0.125L to L	2°	2°
Water hammer wave speed (a)	1340 m/s	1260 m/s	1260 m/s
Measured max. head (H_{max})	87 m	91 m	47 m
Calculated max. head (H_{max})	87.5 m	103 m	41 m

Jordan has made important contributions on water hammer in hydropower systems as well. In his early hydropower paper (Jordan 1962b) he discussed specifications of control guarantees for water turbines (IEC 60041 1991; IEC 60308 2005) including the maximum momentary over-speed and maximum/minimum momentary pressure during transient events in hydropower plants. These two data are very important for designing control strategies to suppress unwanted water hammer effects that may disturb overall operation of the plant and damage the system components. One of the key control devices is the turbine-unit inertia (Jordan 1967). Jordan presented a simple approximate formula for prediction of sufficient unit inertia (flywheel effect) taking into account allowable values of speed rise and water hammer head in the penstock. Similar procedures can be found elsewhere (Warnick 1984). In addition, he presented methods on how to measure the inertia of rotating mass in a workshop (Jordan 1975c). The introduction of modern methods in the seventies contributed to a significant reduction in the weight of the turbine and valve parts, something that may lead to severe pulsations and vibrations (Dörfler *et al*. 2013). Fluid-structure interaction played an important role. Jordan investigated auto-oscillations (resonant water hammer) of nominally closed shut-off spherical valves (Jordan 1973b, 1973c). In the case the valve gate is not rigid enough, the gate vibrates and consequently the discharge through the leaking gate seal starts to oscillate and may generate unwanted large pressure oscillations in the penstock. Jordan developed a design chart for proper selection of valve parameters.

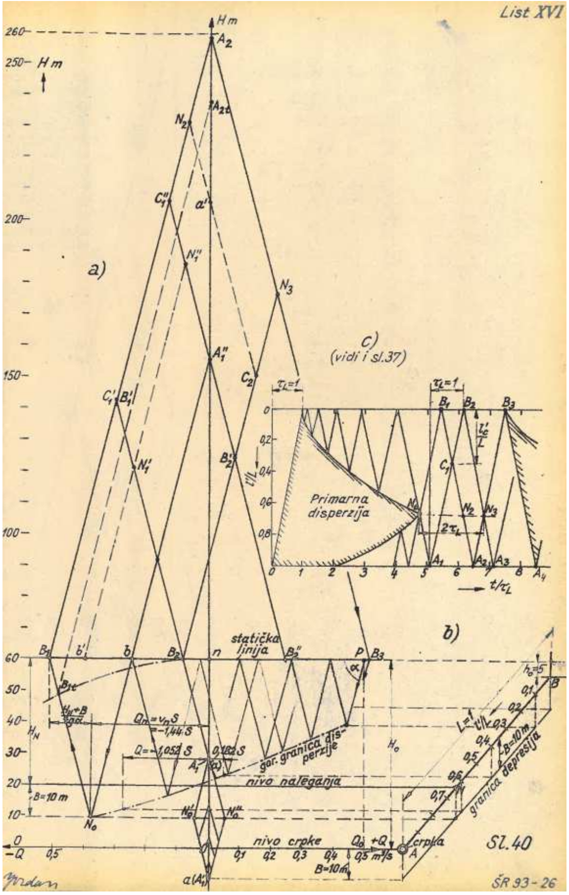

Fig. 5 An example of graphical-analytical determination of distributed vaporous cavitation zones along the pipeline and maximum water hammer at the pump (Jordan 1965b)

In the late seventies, close to and in his early retirement, Jordan investigated water hammer in an elbow-type draft tube with or without the connecting long tailrace tunnels in hydropower systems (Jordan 1974-1975, 1975e, 1977a, 1980). After turbine shut-down, column separation may occur in the outlet system due to rapid deceleration of the flow and, as result, subsequent reverse flow with cavity collapse and large water hammer pressure at the turbine outlet. In the case of limited control of the turbine closing devices (turbine-unit inertia) Jordan recommended the installation of air valves at the turbine head cover or the outlet surge tank in the case of systems with long tailrace. In any case, a two-speed wicket gate closing time function (adding a cushioning stroke) was recommended for safer operation of the plant. The opening of runner blades during the turbine shut-down (normal, mechanical quick-stop, emergency) is a favourable blade manoeuvring, which improves over-speed performance and reduces negative axial hydraulic thrust. In addition, he wrote two papers on trapped air pockets in hydraulic systems (Jordan 1975a, 1975b) and a paper on water hammer in bulb turbine systems with sluice gate in the outlet system (Jordan 1977b).

5 HIS 1983 BOOK

In 1983, his excellent book in Slovenian language *Prehodni režimi v hidravličnih cevnih sistemih (Transient regimes in hydraulic piping systems)* was published (Jordan 1983), summarizing all his professional and scientific findings on water-hammer problems and solutions. The 331-page book is still used by practicing engineers today and can serve as a textbook to engineering students. Jordan's book is divided into four parts: (i) introduction to physical basics, (ii) pumping systems, (iii) hydropower systems and (iv) Appendix.

In the first part he presents the theory of steady flow in piping systems and the principles of water hammer including rigid and elastic column theory and the basics of the Schnyder-Bergeron graphical method. One of the numerical examples considers column separation at a high point in a gravity pipeline. The transient event is triggered by the opening of a downstream-end valve (valve opening time $2L/a$; high point at $L/3$ upstream of the valve).

The second part describes water hammer and column separation in pumping systems. He first presents pump system characteristics (a graph of low specific-speed pump four-quadrant characteristics is included; n_q = 25 min^{-1} ($n_q = nQ^{0.5}/H^{0.75}$)). Then he presents water hammer and column separation phenomena due to pump failure in a simple low-inertia pump upward-sloping pipe-reservoir system by using his column separation consolidation model (Jordan 1965b). He gives a step-by-step example for a pump failure in an L = 1500 m long upwards sloping steel pipe of D = 578 mm internal diameter, the very same system as presented in his thesis. In addition to consolidation model results (Fig. 5), he presented a solution with two discrete vapour cavities along the pipeline by using the Schnyder-Bergeron graphical method as shown in Fig. 6. Then he addresses the differences between ideal and practical pumping systems and explains their influence on water hammer. One should consider changing pipe diameter, pipe slope, check valves at the pump and along the pipeline, parallel pumps, pump and valve characteristics, high points, just to mention a few. The most important surge control is appropriate deceleration of the flow after pump failure and Jordan gives sample calculations for systems with increased pump inertia, pump by-pass system, control valve, air vessel and surge tank.

Water hammer and column separation in hydropower systems is presented in the third part of his book. He starts with the description of turbine performance characteristics, which are traditionally presented in a hill chart. He clearly explains turbine generating and dissipating modes (Chaudhry 2014, Chapter 5). He reviews and updates his early work on the estimation of turbine-unit inertia (Jordan 1967) and the effect of turbine governors on transients. Apart from transient events caused by the turbine, he considers active and passive closure of shut-off valves, a topic of his first publication on water hammer (Jordan 1958). He gives an example of accidental simultaneous closure of intake safety gate and turbine shut-off valve. He discusses possible accumulation of air along the pipeline and resulting large water hammer due to movement of trapped air pockets in liquid-filled pipelines. Then he presents auto-oscillations of closed shut-off spherical valve based on the previous published work (Jordan 1973b, 1973c). He gives numerical examples of turbine load rejection in a simple reservoir-penstock-Francis turbine system. The second half of the third part concerns the treatment of the following water hammer control devices: turbine regulating valves, surge tank in the inlet and outlet water-conveyance systems, and air valves. A number of sample calculations are given for each control device.

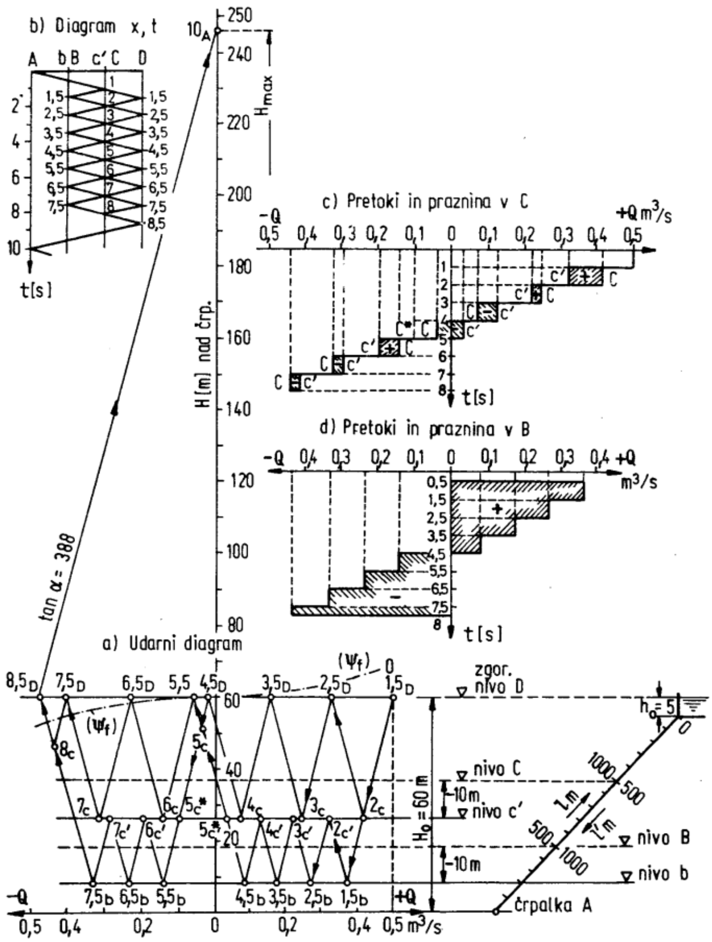

Fig. 6 An example of graphical determination of maximum head at the pump due to pump failure by placing two discrete cavities along the pipe (Jordan 1983)

Finally, the Appendix includes a review of modern solution methods (similar to Wylie and Streeter 1993), accidents in the field (rupture of plant components), computer analysis of hydraulic transients (Jordan 1973b), measurements in the laboratory and in the field (measurement of steady and unsteady quantities), and recommendations for further research of water hammer phenomena (Jordan 1979). Jordan foresees further research in seismic analysis of hydropower systems, measurements of turbine performance characteristics during transient events, consideration of dynamic performance of turbine governors during transient regimes, and application of measurement devices with adequate dynamic response.

6 CONCLUSION

Vladimir Jordan was an adherent of a post-WW2 hard working European engineering community. The paper in a way reflects to current pandemic and war time in Europe too. In 1947 Jordan established and headed the design office of a newly founded manufacturer of turbine and industrial equipment: Litostroj. As a natural born artist, he 'fell in love' with the graphical method which he used in conjunction with analytical methods for water-hammer analysis to a range of industrial problems. In particular, his original papers on the treatment of distributed vaporous cavitation along pipelines, shut-off valve induced hydraulic oscillations, and water-hammer effects in Kaplan turbine draft tubes, attracted wide interest in the seventies. Jordan's life and work have been narrated herein.

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