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POLISH ACADEMY OF SCIENCES

TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

114

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Aims and Scope

Transactions of the Institute of Fluid-Flow Machinery have primarily been established to publish papers from four disciplines represented at the Institute of Fluid-Flow Machinery of Polish Academy of Sciences, such as:

- Liquid flows in hydraulic machinery including exploitation problems,
- Gas and liquid flows with heat transport, particularly two-phase flows,
- Various aspects of development of plasma and laser engineering,
- Solid mechanics, machine mechanics including exploitation problems.

The periodical, where originally were published papers describing the research conducted at the Institute, has now appeared to be the place for publication of works by authors both from Poland and abroad. A traditional scope of topics has been preserved.

Only original and written in English works are published, which represent both theoretical and applied sciences. All papers are reviewed by two independent referees.

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Editorial

These Special Issues of the *Transactions of Fluid-Flow Machinery*, Nos. 113 and 114 contain selected papers from the International Conference on *Turbines of Large Output* devoted to commemorate 100$^{\text{th}}$ Birthday Anniversary of Prof. Robert Szewalski. The conference was held in Gdańsk, Poland on September 22-24, 2003.

The Conference is a continuation of previous conferences held at the Institute of Fluid-Flow Machinery PAS in former years dedicated to technology of steam turbines. Series of conferences bearing the same name took place in the years 1962, 1965, 1968, 1993. In 1997 organised has been a conference on steam turbines and related topics, but with a slightly amended title – *Problems of Fluid-Flow Machinery*. At present at the Institute of Fluid Flow Machinery there are conduced research of fundamental character encompassing both the issues related to steam turbines and fundamentals of power engineering.

Organisers of the present conference have returned to the traditional name, i.e. Conference on *Turbines of Large Output* to mark the respect to the memory of Professor Robert Szewalski (1903-1993), the founder and a director of the Institute of Fluid-Flow Machinery for several years, and initiator of the conference series devoted to the problems of steam turbines.

The Editors are very grateful to the referees of the papers presented in this issue of the *Transactions of Fluid-Flow Machinery*: J. Badur, W. Batko, E. S. Burka, J.T. Cieśliński, P. Doerffer, A. Gardzilewicz, B. Grochal, J. Kiciński, G. Kosman, T. Król, J. Krzyżanowski, J. Mikielewicz, A. Neyman, W. Ostachowicz, R. Puzyrewski, R Rządkowski, J. Świrydczuk, M. Trela, T. Uhl and Z. Walczyk.

We appreciate cordially the manifested authors interest in our conference. Special thanks are conveyed to Ms 'Maya' Bagińska, for her fruitful editorial help related to directing the papers to reviewers and correspondence with the authors of contributions.

Prof. Jarosław Mikielewicz
Editor-in-Chief

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Hydrodynamic and strength analyses of high-pressure hydraulic conduits

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Abstract

The paper presents a review of the methods for determining the pressure shock wave propagation velocity and water hammer pressure in high-pressure thick-walled conduits, taking into account the geometry and the ways of hydraulic installation mounting, as well as the physical properties of materials. To simplify the calculations, characteristics determining the effects of material and conduit relative thickness on the pressure shock wave propagation velocity were made. The paper also describes a method of strength analysis of conduits that are part of high-pressure hydraulic systems, based on the material minimum criterion.

Keywords: Water hammer; Propagation velocity of a pressure shock wave; Water hammer pressure; Strength of hydraulic conduits

Nomenclature

c – mean instantaneous fluid velocity, m/s
c_o – mean fluid velocity in a steady flow, m/s
d – internal diameter of a hydraulic conduit, mm
E – modulus of wall elasticity, MPa
K – modulus of fluid elasticity, MPa
m – relative thickness of the conduit wall
p_o – fluid pressure in a steady state, MPa
p – fluid total pressure at the moment of water hammer occurrence, MPa
R_e – yield point, MPa
u – propagation velocity of a pressure shock wave, m/s
ν – Poisson ratio of the conduit wall
δ – thickness of the conduit wall, mm

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Δp	–	water hammer pressure, MPa
ρ	–	hydraulic fluid density, kg/m^3
σ_l	–	longitudinal stresses, MPa
σ_r	–	radial stresses, MPa
σ_t	–	circumferential stresses, MPa
σ_z	–	reduced stresses, MPa.

1 Introduction

Our knowledge about unsteady flows observed in hydraulic systems of machines and devices has to be updated on a regular basis. This concerns first of all the application procedures, closely connected with the operational safety and reliability of hydraulic installations. Water hammer is a non-stationary phenomenon occurring frequently during fluid flow. Such phenomena cause an increase in the dynamic load of installations and particular units of hydraulic systems. Pressure fluctuations accompanying the water hammer phenomenon result from quick changes in the velocity and direction of fluid flow. Changes in velocity, e.g. during adjustment (of a valve, regulator, etc.), cause an increase or a decrease in pressure and produce positive or negative water hammers.

In hydraulic systems, especially high-pressure ones, the time of adjustment is usually shorter than the time of shock wave transition, and water hammer pressure reaches its maximum value. This phenomenon, referred to as simple water hammer, is more dangerous to installations (from the perspective of strength analysis) than complex water hammer. Therefore, we should aim at precise determination of the water hammer pressure Δp and total p, as well as reduced stresses σ_z, occurring at that time in the walls of a hydraulic conduit.

2 Determination of water hammer pressure

The maximum total pressure of a simple water hammer may be determined from the Żukowski-Allevi formula [1]:

$$p = p_o + \rho\, u\, c_o, \tag{1}$$

which shows that the water hammer pressure is affected by the propagation velocity of a pressure shock wave u. In most cases it is determined from a commonly known formula, reported for the first time by Kortewega [2]:

$$u = \sqrt{\frac{\frac{K}{\rho}}{1 + \frac{K}{E}\frac{d}{\delta}}}. \tag{2}$$

The dependence (2) was derived assuming that during the water hammer phenomenon only simple stresses occur in the conduit walls, so it may be applied only in the case of thin-walled conduits, e.g. derivation ones. Hydraulic conduits are considered thin-walled it they fulfill the conditions of a membranous shell. The state of stress and strain of a membranous shell may be described by means of the Laplace equations, and its relative thickness as [3]

$$m = \frac{\delta}{d} \leq 0.025.$$

In the case of hydraulic installations employed in control and high-pressure hydraulic systems, the relative thickness m usually exceeds considerably the limit value 0.025. Because of that the application of the formula (2) to hydrodynamic analyses of thick-walled hydraulic conduits may lead to erroneous results [4]. Due to that an attempt was made to devise new formulas describing the propagation velocity of a pressure shock wave in thick-walled conduits, employing the shell theory for thick-walls [5-7]. The following factors were taken into account:

- physical properties of the conduit and hydraulic fluid,
- relative thickness m of a hydraulic conduit,
- relationships between the state of stress and state of strain in a hydraulic conduit.

The following dependences describing the pressure shock wave propagation velocity were derived for three main variants of conduit mounting in hydraulic systems:

- conduit mounted on both sides, without dilatation

$$u = \sqrt{\frac{\frac{K}{\rho}}{1 + \frac{K}{E}\left[\frac{1-\nu^2}{m+m^2} + 2(1+\nu)\right]}}, \tag{3}$$

- conduit mounted on both sides , with dilatation

$$u = \sqrt{\frac{\frac{K}{\rho}}{1 + \frac{K}{E}\left[\frac{1}{m+m^2} + 2(1+\nu)\right]}}, \tag{4}$$

- conduit mounted on one side

$$u = \sqrt{\frac{\frac{K}{\rho}}{1 + \frac{K}{E}\left[\frac{1.25-\nu}{m+m^2} + 2(1+\nu)\right]}}. \tag{5}$$

Table 1.

No.	Type of material	Modulus of elasticity E	Poisson ratio
		10^5 MPa	
1	steel	2.1	0.30
2	copper	1.1	0.34
3	aluminum	0.7	0.36
4	polyamide	0.021	0.39
5	hard rubber (78° Sh)	0.0008	0.49

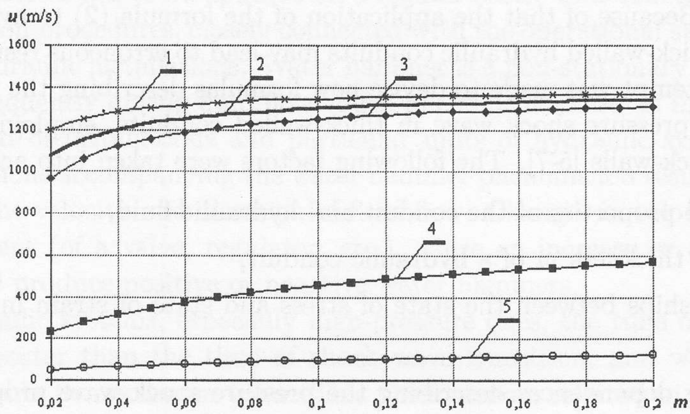

Figure 1. Characteristics $u_1 = f_1(m)$ of conduits mounted on both sides, without dilatation.

3 Characteristics of the propagation velocity of a pressure shock wave

To make it easier to determine the total pressure p, characteristics describing the effects of material and the relative thickness m of thick-walled hydraulic conduits on the pressure shock wave propagation velocity were made. They concern commonly applied hydraulic fluid, i.e. hydraulic oil L-HL-46 with the elasticity modulus $K = 1.72103$ MPa and density $\rho = 869.61$ kg/m^3 Table 1 presents the materials of which hydraulic conduits were made, their moduli of elasticity E and Poisson ratios ν. The characteristics were made on the basis of dependences (3)÷(5), for three variants of hydraulic conduit mounting.

The characteristics presented in Figures 1÷3 (the numbers of the characteristics correspond to the ordinal numbers from Table 1) show that an increase in the relative thickness m of hydraulic conduits is accompanied by higher propagation

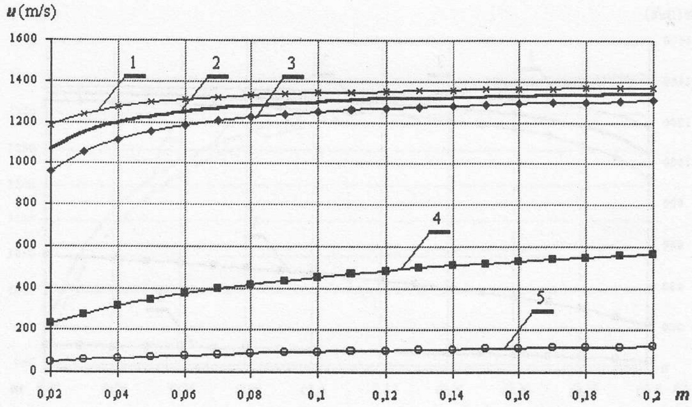

Figure 2. Characteristics $u_2 = f_2(m)$ of conduits mounted on both sides, with dilatation.

velocity of a pressure shock wave u. The increment in the velocity u decreases with increase in the relative thickness m. After reaching a certain value of m (depending on the material of which the conduit was made), the velocity u approaches asymptotically the constant value.

To determine the effects of the variant of hydraulic conduit mounting on changes in the propagation velocity of a pressure shock wave u, characteristics $u_4 = f_4(m)$ were made for aluminum conduits (Fig. 4). All three variants of conduit mounting were taken into consideration.

The characteristics show that the propagation velocity of a pressure shock wave, as well as water hammer pressure, depends first of all on the type of material and relative thickness of a hydraulic conduit. In the case of conduits with identical geometry, made of the same material, the influence of the mounting variant is insignificant.

4 Strength analyses of high-pressure conduits

Strength analyses of thick-walled high-pressure conduits where the water hammer phenomenon occurs must be preceded by hydrodynamic calculations. The propagation velocity of a pressure shock wave should be determined from formulas (3), (4) or (5), and the maximum total pressure accompanying a simple water hammer – from dependence (1).

Thick-walled conduits are characterized by a triaxial state of stress, i.e. longitudinal (σ_l), radial (σ_r) and circumferential (σ_t) stresses. The distribution of longitudinal stresses is uniform all over the conduit section, whereas radial and

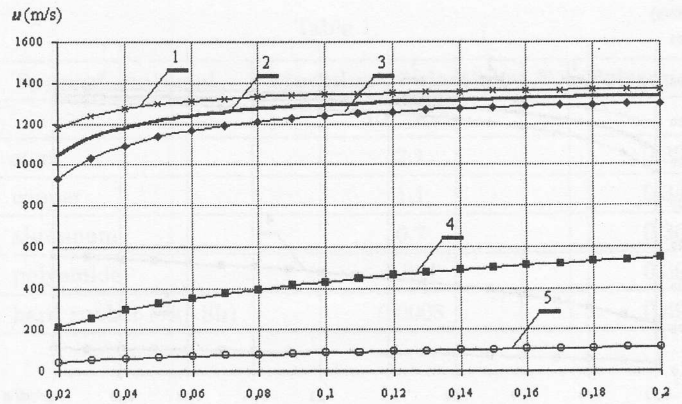

Figure 3. Characteristics $u_3 = f_3(m)$ of conduits mounted on one side.

circumferential stresses reach their maximum on the inner surface (Fig. 5). Due to that, as the result of excessive material effort, inner extreme fibers are damaged first.

The maximum values of component stresses, determined from the Lame function [8] and relating to the relative thickness of a conduit, are as follows:

$$\sigma_l = p\,\frac{1}{4\,(m + m^2)}; \quad \sigma_r = -p; \quad \sigma_t = p\left[1 + \frac{1}{2\,(m + m^2)}\right]. \tag{6}$$

The degree of material effort of the conduit walls is defined by the reduced stress σ_z, determined on the basis of the hypothesis of the highest unit strain energy of distortion. Employing the minimum material criterion, the value of reduced stress should be compared with the yield point R_e [3, 9], thus

$$\sigma_z = \sqrt{\sigma_l^2 + \sigma_r^2 + \sigma_t^2 - \sigma_l\sigma_r - \sigma_l\sigma_t - \sigma_r\sigma_t} \leq R_e\,. \tag{7}$$

After introducing dependence (6) to expression (7), the strength condition for thick-walled conduits where a simple water hammer occurs assumes the following form:

$$\sigma_z = p\,\frac{\sqrt{3}}{4}\,\frac{(1 + 2m)^2}{m + m^2} \leq R_e. \tag{8}$$

The strength condition (8) ignores the Poisson feedback mechanism, which can affect the state of stress and strain, i.e. cause an increase or a decrease in reduced stresses in the conduit walls [7]. In order to investigate the phenomenon in detail, studies on wave problems connected with water hammer should be continued.

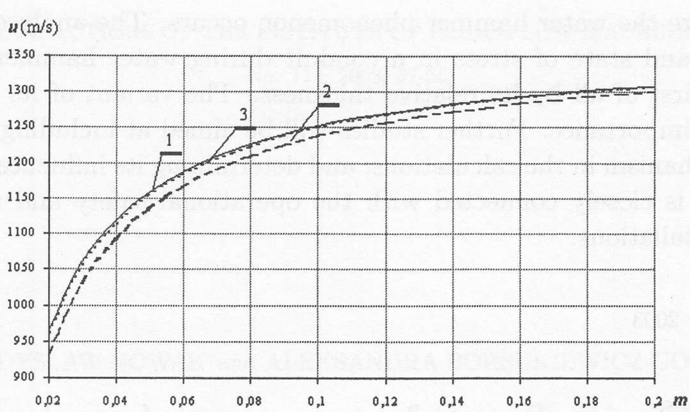

Figure 4. Curves $u_4 = f_4(m)$ of aluminum conduits, taking into account the mounting variants: 1 – on both sides, without dilatation, 2 – on both sides, with dilatation, 3 – on one side.

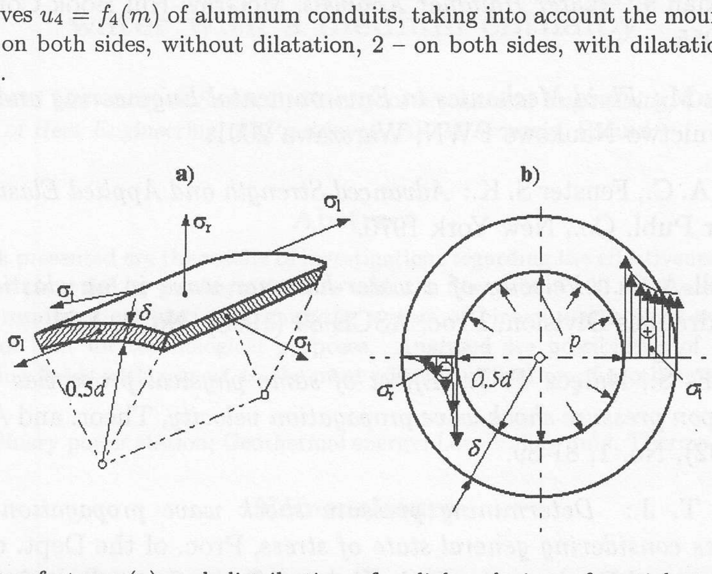

Figure 5. State of stress (a) and distribution of radial and circumferential stresses (b) in a thick-walled hydraulic conduit.

Numerical and empirical researches should be carried simultaneously, despite the fact that empirical tests require expensive equipment and high frequency of sampling.

5 Conclusions

The method of making hydrodynamic and strength analyses presented in the paper allows to determine in the best possible way the wall thickness in mono-ply conduits where the water hammer phenomenon occurs. The analyses show that the pressure and state of stress in a conduit during water hammer occurrence are affected first of all by its relative thickness. The variant of its mounting is of secondary importance. Further studies will be aimed at including the Poisson feedback mechanism in the calculations, and determining its influence on material effort, which is closely connected with the operational safety and reliability of hydraulic installations.

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