تحقیقات منابع آب ایران
Iran-Water Resources Research

سال دوم، شماره ۱، بهار ۱۳۸۵
Volume 2, No. 1, Spring 2006 (IR-WRR)
1-9

بررسی میدان فشار دینامیک در پائین دست هواده‌های مستقر در تونل‌های دایروی

محمدرضا کاویانپور [۱] ، الهام طلوعی [۲]

چکیده

صدمات ناشی از کاویتاسیون در سازه‌های هیدرولیکی یکی از مسائل مهم و حساس این ابنیه می‌باشد که گزارش‌های متناوبی از آن قابل مشاهده است. در این ارتباط هوادهی بعنوان یکی از راهکارهای شناخته شده جهت کاهش خطرات و صدمات ناشی از این پدیده معرفی گردیده که به دلیل موفقیت و تاثیر فزاینده آن، کاربردهای وسیعی را در انواع سازه‌ها یافته است. این راهکار به جهت هزینه نسبتا کمتر و سهولت اجرا، مورد توجه طراحان سازه‌های هیدرولیکی واقع شده است. بررسی این مطالعات نشان می‌دهد که علیرغم مطالعات قابل توجهی که در زمینه تخلیه کننده‌های تحتانی و سرریزهای آزاد به شکل مستطیلی انجام گرفته است، متاسفانه اطلاعات بسیار اندکی برای این هواده‌ها در تونل‌های دایره‌ای گزارش و در دسترس می‌باشد. تونل‌های فوق عموما جهت انتقال آب در سرریزهای تونلی و یا تونل‌های نیروگاهها مورد استفاده قرار می‌گیرد که با توجه به میزان اهمیت آن و کمبود اطلاعات پیرامونی، مقاله حاضر با هدف تامین اطلاعات لازم آزمایشگاهی جهت تجزیه و تحلیل فشارهای دینامیک و ارزیابی فرکانس غالب نوسانات آن در سرریزهای تونلی تهیه گردیده است. آزمایشات در یک تونل دایره‌ای به قطر ۲۸/۸ سانتی‌متر در موسسه تحقیقات آب ایران انجام گرفت. هواده‌های مورد استفاده از نوع تخت بوده که ارزیابی اثر هندسه هواده بر میدان فشار، با تغییر ارتفاع و زاویه آن صورت گرفت. همچنین با قرار دادن یک صفحه در بالادست هواده، اثر ضخامت تیغه جریان ورودی به هواده نیز مورد ارزیابی قرار گرفت و در نهایت، تاثیر شرایط جریان ورودی با تغییر سرعت جریان از طریق تنظیم ارتفاع آب داخل هد تانک بالادست تونل مورد ارزیابی قرار گرفت. هوا از طریق یک هواده دایره‌ای در پائین دست هواده‌ها به داخل مجرا وارد گردید و با تغییر شرایط هندسی هواده و شرایط هیدرولیکی جریان ورودی به آن، به اندازه‌گیری میدان فشار در پائین دست اقدام و سپس با تجزیه و تحلیل اطلاعات، ارزیابی میدان فشار و طیف غالب نوسانات صورت گرفت که نتایج حاصل از آن می‌تواند راهگشای طراحان این سازه‌ها قرار گیرد.

کلمات کلیدی: نوسانات فشار، هوادهی، طیف انرژی، کاویتاسیون

Pressure Fluctuations Downstream of Aerators in Circular Tunnels

M. R. Kavianpour[1], E. Tolooei[2]

Abstract

Serious damages have been reported in hydraulic structures due to cavitation. It is known that introducing air into the flow will considerably reduce cavitation risks. Thus, aerators are used in many situations to introduce air into the flow and to eliminate cavitation tendency. Although many works have been reported for flow aeration in outlet conduits of rectangular sections, less information can be found for circular tunnels. These structures are commonly used to supply water for hydroelectric power plants or drinking and irrigation systems. In this paper, experimental information regarding the intensity of pressure fluctuations and its dominant frequency downstream of rectangular aerators in such structures are provided. Experiments were performed in a circular pipe of 28.8 cm diameter. Rectangular aerators of different heights and angles were fixed inside the tunnel and air was supplied through aerator to check its effect on the intensity of hydrodynamic pressures. This information is useful for the structural design of such outlet tunnels.

Keywords: Pressure Fluctuations, Aeration, Dominant Frequency, Cavitation

۱- استادیار، بخش مهندسی عمران دانشگاه خواجه نصیر طوسی، تهران، ایران
۲- کارشناس ارشد، شرکت مشانیر

1-Assistant Professor, Civil and Structural Engineering Department, Khajeh Nasir Toosi University of Technology, Tehran, Iran, (kavianpour@yahoo.com)
2- Moshanir Consulting Engineers, Tehran, Iran.

Introduction

The human life is largely affected by the new technological achievements in the recent decades. Construction of huge and massive structures, such as offshore structures, skyscrapers, and high dams are some examples of these developments. High dams do play an important role in sustainable developments. Therefore, a great amount of investment and resources are usually spent to complete these huge structures. Accordingly, the design of the related structures such as, spillways, tunnels and hydro-mechanical equipments have been the main subjects for many investigations. Cavitation tendency, hydrodynamic forces, and aeration of flow are the main aspects of these studies. In high dams, high flow rates and the resultant velocities can be experienced over the spillways or through the outlet tunnels. Accordingly the threat of damage due to cavitation erosion increases. Once damage is initiated on the surface, catastrophic damage is accelerated by the combined action of cavitation and impingement attack.

The high velocity flows on the surface of spillways and inside outlet tunnels, associated with intense pressure fluctuation, may cause the local pressures to drop significantly (Kavianpour, 2003; Khosrojerdi and Kavianpour, 2003). As a result, the cavitation may tend to occur (Kavianpour, 1997; Narayanan and Kavianpour, 2000). A dimensionless similarity index, called index of cavitation or cavitation number is usually used to quantify the level of cavitation and its tendency of occurrence. The cavitation number (σ) is defined by:

$$\sigma = \frac{P - P_v}{0.5 \rho U^2} \tag{1}$$

where P, ρ and U are respectively the pressure, the fluid density and the flow velocity, and P_v is the vapor pressure of fluid. Accordingly, cavitation will occur, if the index σ is lower than a critical value σ_{cr}. The critical value for conduits and spillways has been suggested as 0.2-0.25 (Falvey, 1990).

Literature Review

Research on pressure fluctuations has been conducted by many investigators. It is known that the injection of air into the flow will reduce the cavitation damage. Peterka (1953) used venturi-type cavitation apparatus to show that for 2 percent air concentration, adjacent to the boundary, cavitation damage was greatly reduced. He also realized that for 6 to 8 percent, it was virtually eliminated (Peterka, 1953). Based on laboratory measurements, Peterka also suggested that entrained air increases the minimum pressure, which occurs in the otherwise cavitating region. It was after publishing his results that the use of deflectors in spillway of high dams for flow aeration was rapidly increased. The results of pressure measurements made on the Libby dam sluiceway presented by McGee (1988) appear to corroborate Peterka's conclusion (McGee, 1988). McGee's results showed reduced pressure fluctuations and increased minimum pressures with forced aeration.

Aeration of flow will reduce the fluid density and increase its compressibility. Injection of air also increases the mean pressure and reduces the intensity of pressure fluctuations, resulting in reduction of cavitation risks (Kavianpour, 1997; Kavianpour, 2000; Nakhaei and Kavianpour, 1999). In the near field of the aerators, cavitation risk reduces due to the increase in the mean pressure and reduction of the intensity of pressure fluctuations. Therefore, aeration of flow in outlet works such as, spillways of high dams and bottom outlet conduits is recommended as an effective and relatively easy way to eliminate cavitation damages.

Experimental Investigation

In order to study the effects of inflow condition on the magnitude and distribution of hydrodynamic pressure fluctuations, a set of experiments was performed at Water Research Institute of Iran. Figure 1 shows a schematic view of the experimental setup. Water was supplied by a pump with the capacity of 150 liter per second into a head tank (2.4m×1.8m×2.65m), placed on a stand of 1.3 meter height. The depth of water within the head tank was controlled using a by-pass valve. The test section consisted of a circular pipe, 28.8 centimeter in diameter and 7 meter long, which was connected to the tank. Within this pipe, aerators in the form of ramps of different heights and angles were fixed to check the effects of their geometry. Upstream of the ramps, a set of plates were also placed inside the pipe to provide the required depth for the entering flow to the ramps. They were made of plexy-glass to visualize the flow condition. It should be noted that the flow velocity inside the pipe was a function of the depth of water within the head tank, which was controlled by the by-pass valve. Therefore, by adjusting the by-pass valve and by fixing the plates to manage the depth of flow entering the ramps, it was possible to determine the Froude number of flow. Table 1 shows the flow depths and the geometry of the ramps used in this study.

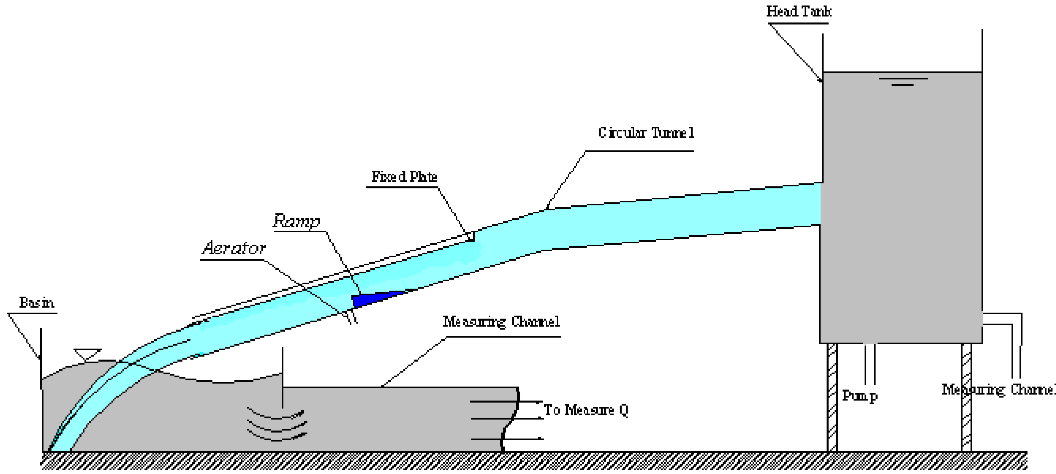

Figure 1- A schematic view of experimental setup.

Table 1- Characteristics of flow depth and aerator geometry

Water Depth (Cm)	Angle of Ramp					
	5 Degree			10 Degree		
	Height of Ramp (Cm)			Height of Ramp (Cm)		
	1 cm	2 cm	3 cm	1 cm	2 cm	3 cm
4 cm	4.46	3.6	2.07	11	8.71	7.4
7 cm	3.33	3.05	1.14	7.14	6.25	6.45
10 cm	1.8	1.31	1.2	3.15	3.5	5.58

Downstream of the test section, the exiting jets were discharged into a basin, 7.2 meter long. At the end of the basin, a control valve directed the water into a collecting channel, 1 meter wide, at the end of which, a sharp-crested weir was fixed to measure the discharge.

Pressures fluctuations were measured using pressure transducers (type: PDCR800, 750mbar) with effective diameters of 10 millimeter. A set of pressure taps was fixed along the centerline and on the wall of the pipe, just downstream of the aerator (Figure 2). The pressure taps were arranged in four rows along the centerline of the pipe with a vertical and longitudinal distance of 15 millimeter. The pressure taps were then fixed to the pressure transducers, using plastic tubes (PVC) with an internal diameter of 8 millimeter and maximum length of 2 meter (Lopardo et al., 1987). The output signals of the pressure transducers were then collected by a set of data acquisition system. By controlling the head of water within the tank and the depth of flow entering the ramps, the experiment was repeated for different flow and geometry conditions.

Results and Discussion

The statistical parameters such as the mean, the maximum and the minimum values were obtained for pressure fluctuations in each experiment. The procedure was repeated for different velocities and depths of flow entering the ramp. The geometry of aerator in terms of the height and the angle of ramp were also included to this study. The measured pressures were made non-dimension with respect to the mean pressure and the flow velocity in the forms of:

$$C'p^{+} = \frac{p_{\max} - p_{mean}}{U^2/2g} \qquad (2)$$

$$C'p^{-} = \frac{p_{\min} - p_{mean}}{U^2/2g} \qquad (3)$$

$$C'p = \frac{RMS}{U^2/2g} \qquad (4)$$

Where p_{max}, p_{min}, and p_{mean} represent the maximum, the minimum, and the mean values of pressure in meter, respectively. Also, U is the entering mean flow velocity to the ramp and *RMS* (m) is the root mean square value of pressure fluctuations.

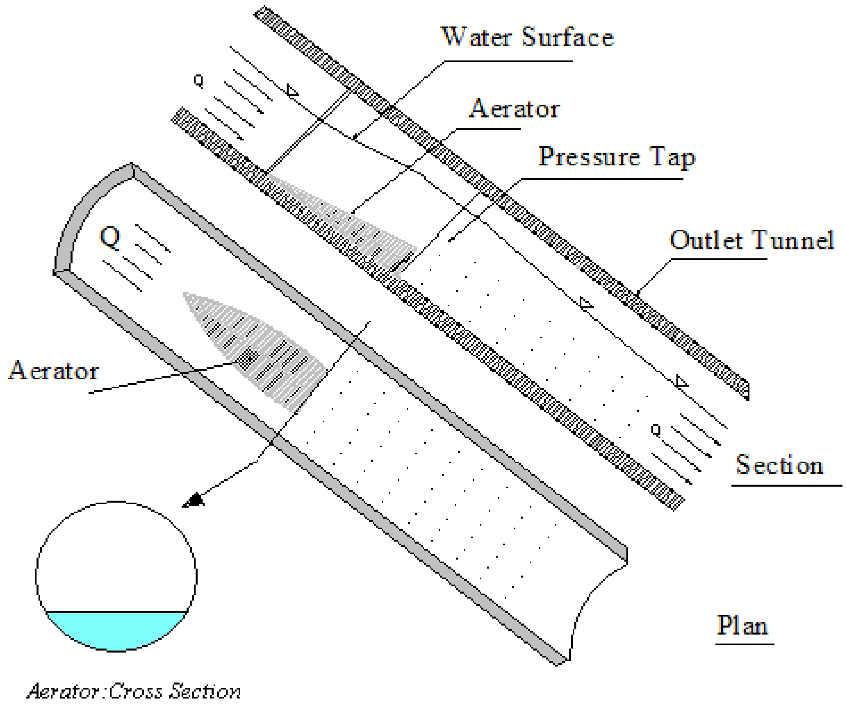

Figure 2- The arrangements of aerator and pressure taps.

Figure 3 shows typical results of the measurements for a ramp 1 centimeter in height with two different Froude numbers; $Fr = U/\sqrt{gh}$, where h is the depth of flow entering the ramp. The vertical axis represents the root mean square value of pressure fluctuations $C'p$, and the horizontal axis stands for the relative distance, Lp/Lj. In this figure, Lp denotes the distance from the aerator. Also, Lj is the length of the reattaching zone just downstream the aerator, which was measured by direct visualization (Figure 5). According to figure 3, the maximum value of $C'p$ for Froude numbers of 4.7 and 8.6 are equal to about 0.035 and 0.015, respectively. Therefore, it is concluded that the maximum value of $C'p$ reduces as the Froude number increases. The same results can also be achieved from the Equations 2 to 4. Equation 3 indicates that $C'p$ is a function of flow velocity and thus, increasing the flow velocity will result in reducing $C'p$. Similar conclusions have been reported in previous investigations (Kavianpour, 1997).

Figure 4 shows the variation of the maximum root mean square values of pressure fluctuations ($C'p$) with aeration ratio $\beta = \frac{Q_a}{Q_w}$, where Q_a and Q_w are the air and water discharges, respectively. The figure contains the results of previous investigations (Kavianpour, 1997 and 2000). A wide range of experiments were performed inside a high pressure conduit as shown in Figure 5, with and without aeration (Kavianpour, 1997). In his experiments, air was only forced to enter the flow through lower nappe of the jet by fixed aerators (Figure 5). Further experiments, were conducted on a chute spillway, so that, air was allowed to enter the flow through upper nappe or free surface aeration and also by lower nappe through fixed aerators (Kavianpour, 2000).

In the present investigation, the distance between the upstream plates, which are used to fix the depth of flow entering the ramp, and the position of ramps was quite small (Figure 2). Therefore, it was reasonable to accept (as observed) that the process of surface aeration was significantly small compared to the previous experimental investigations for a chute spillway (Kavianpour, 2000). Therefore, it can be concluded that the present results is located between the previous two investigations. According to Figure 4, the maximum value of $C'p$ downstream of ramps in a closed conduit and on a chute spillway, are respectively 0.065 and 0.02. However, the present result shows a maximum value of 0.045 for $C'p$, which is about 2.2 times of that reported for a chute spillway and 0.7 times of that reported in a closed conduit.

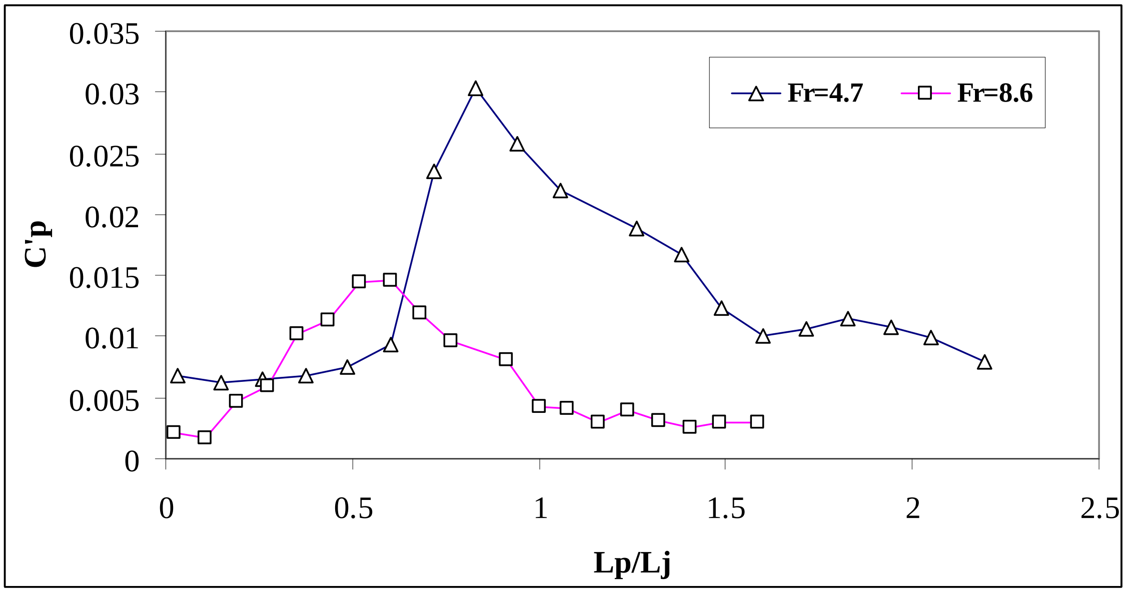

Figure 3- Variations of pressure fluctuations with Froude number on the centerline of the tunnel (B=1 cm).

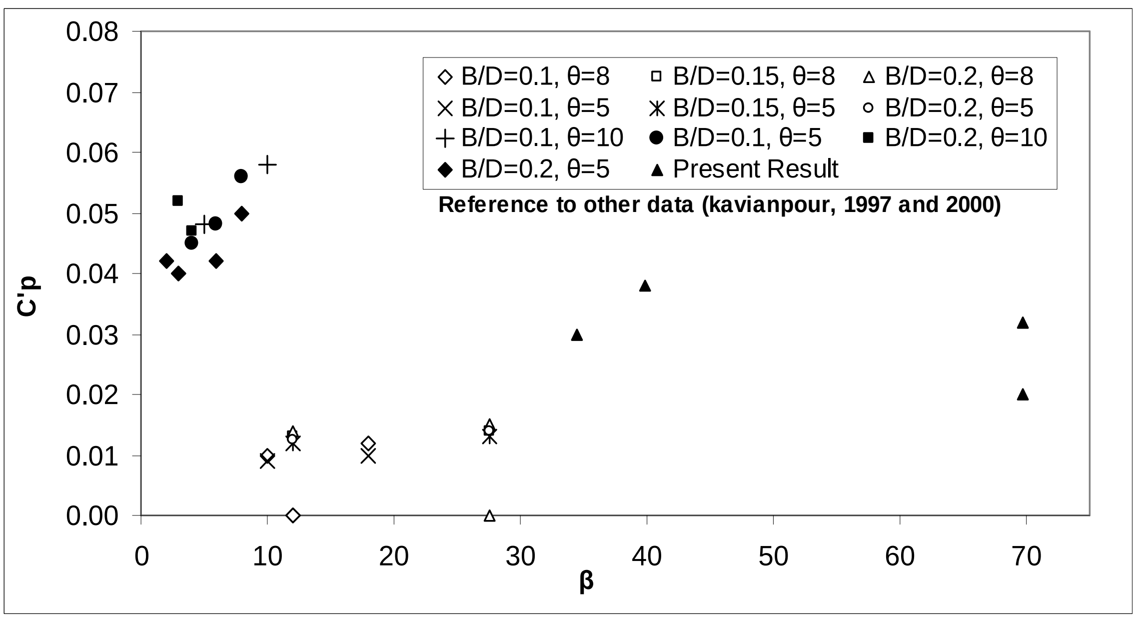

Figure 4- Variations of Maximum pressure fluctuations with aeration ratio.

Figure 6 shows the present results for maximum values of $C'p$, $C'p^-$ and $C'p^+$ along the centerline and on the wall of the circular tunnel. It is observed that the maximum and minimum intensities of pressure fluctuations on the wall are higher than those along the centerline of the conduit. The variations are more pronounced on the wall, especially for low Froude numbers. According to the figure, maximum $C'p^+$ on the wall is about 1.7 times of the minimum $C'p^-$ and about 5 times of the maximum $C'p$. However, on the centerline, the maximum $C'p^+$ is about 1.3 times of the minimum $C'p^-$ and 5 times of the maximum $C'p$. It is also observed that the intensity of pressure fluctuations remains nearly constant for high Froude numbers.

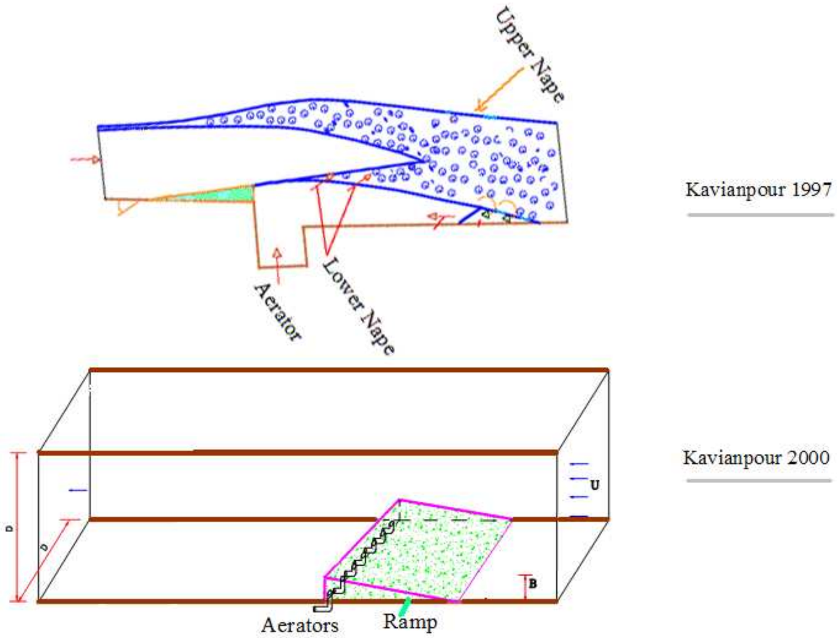

Figure 5- Schematic view of experimental studies (Kavianpour, 1997, 2000)

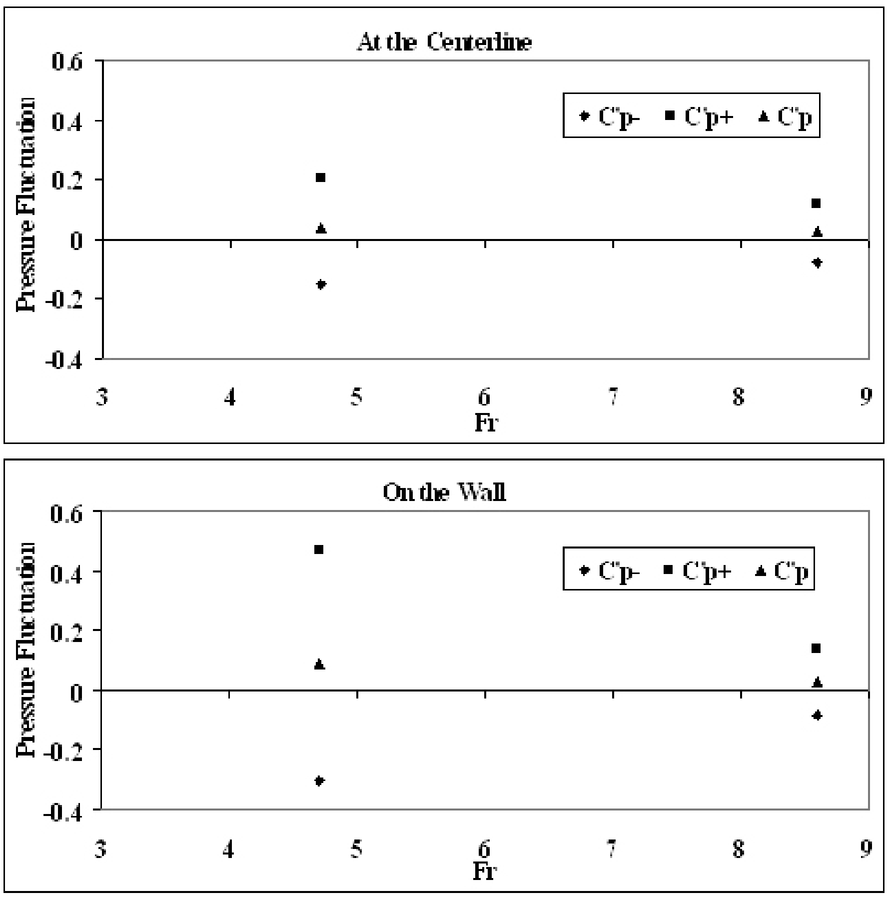

Figure 6- Variations of maximum pressure fluctuations downstream of ramps with respect to Froude No.

Figure 7 shows the overall results for various heights of the ramps with two Froude numbers. In this figure, the variation of relative maximum positive ($C'p^{+}$) and minimum negative ($C'p^{-}$) values of pressure fluctuations with respect to their maximum root mean square values ($C'p$) are shown in the forms of $\frac{C'p^{+}}{C'p}$ and $\frac{C'p^{-}}{C'p}$. The results show that $2<\frac{C'p^{+}}{C'p}<6$ while $-2.5<\frac{C'p^{-}}{C'p}<-3.5$, which confirms that downstream of aerators in outlet tunnels, the intensity of maximum positive values of pressure fluctuations is about two times of the minimum negative values It has been shown that within the recirculation zones downstream of bluff bodies, the intensity of pressure fluctuations arrange the condition of cavitation so that $C'p^{-}>C'p^{+}$ can be recognized (Kavianpour, 1997). However, with flow aeration, the intensity of pressure fluctuations reduces so that $C'p^{+}>C'p^{-}$ will change the situation against cavitation tendency.

As the pressure fluctuations are random in nature, determination of their dominant frequency will help the designers to check the behavior of such structures under dynamic pressures. In order to determine the dominant frequency of hydrodynamic pressures, a computer program was run to analyze the data. The data acquisition system was also set to collect 8192 data at every pressure taps. Two sets of data for the angle of ramps; θ=10º (B=2cm, L=4cm) and θ=10º (B=2cm, L=10cm), were analyzed for this investigation. B and L are respectively the height and the length of the ramp. The position of the severe pressure fluctuations were selected to check the results.

Figures 8 and 9 show typical results of the energy spectral and their dominant frequencies. It can be observed from the figures that the energy around the frequency of 10Hz is about 40 to 50 times of that for the frequency of 20Hz. Therefore, it can be concluded that the frequency dominant of hydrodynamic pressures downstream of aerators in outlet tunnel is about 10Hz. Experimental investigations of pressure fluctuations downstream of gates (without aeration) showed a dominant frequency of about 25Hz to 50Hz (Kavianpour, 1997; Kavianpour, 2000), which means the flow aeration reduces the dominant frequency of pressure fluctuations. Also, according to the previous investigations of Kavianpour (1997), injection of air into the flow reduces the intensity of pressure fluctuations. It can be concluded from the present investigations that the process of aeration not only reduces the intensity of pressure fluctuations, but also changes the dominant frequency of hydrodynamic pressures.

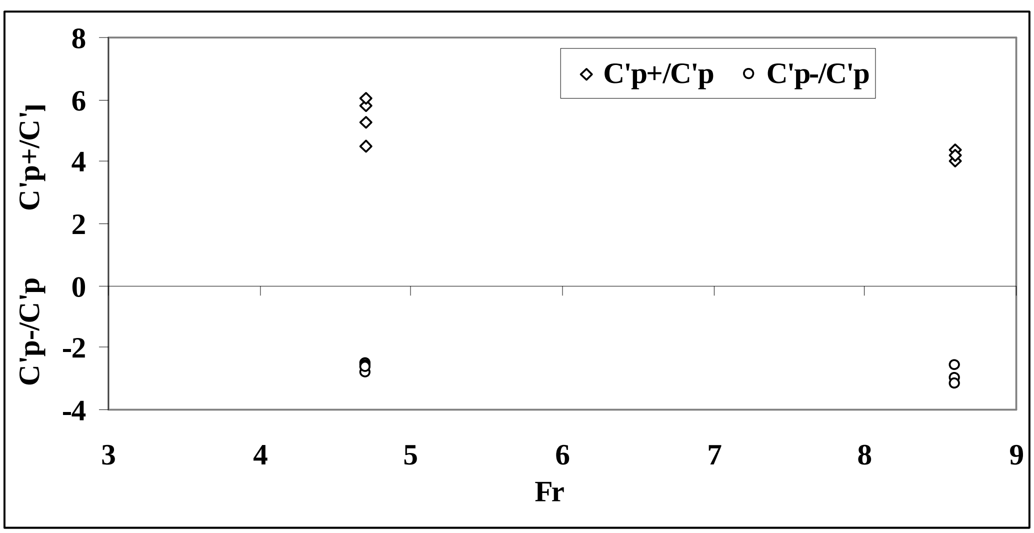

Figure 7- Variation of *C'p+*, *C'p-* and *C'p* downstream of ramps with respect to Froude No.

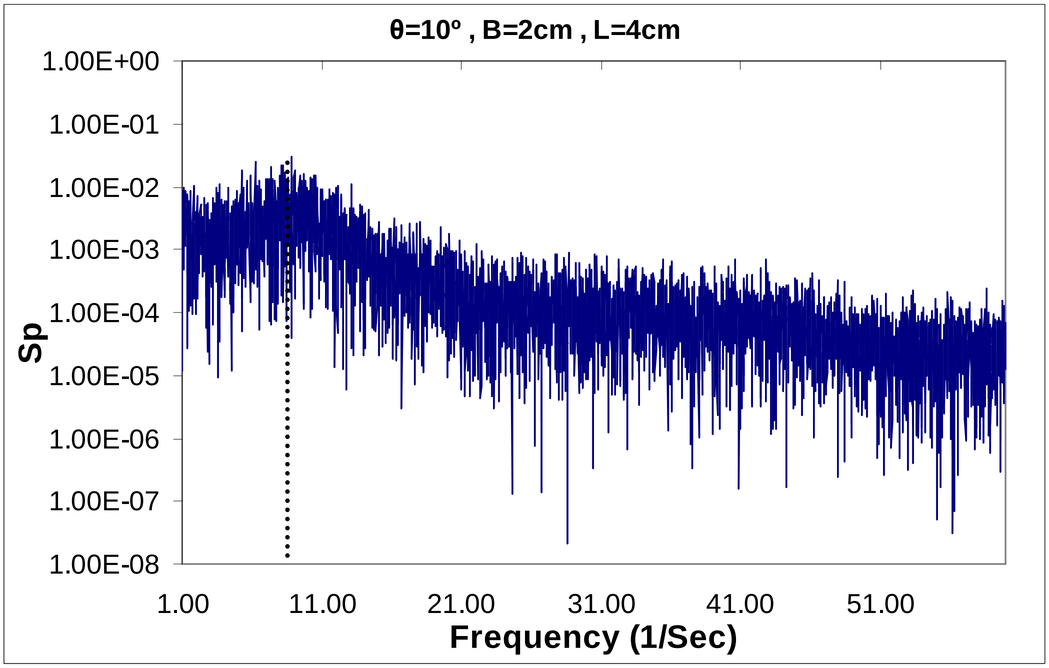

Figure 8- Frequency spectra of pressure fluctuations downstream of ramps.

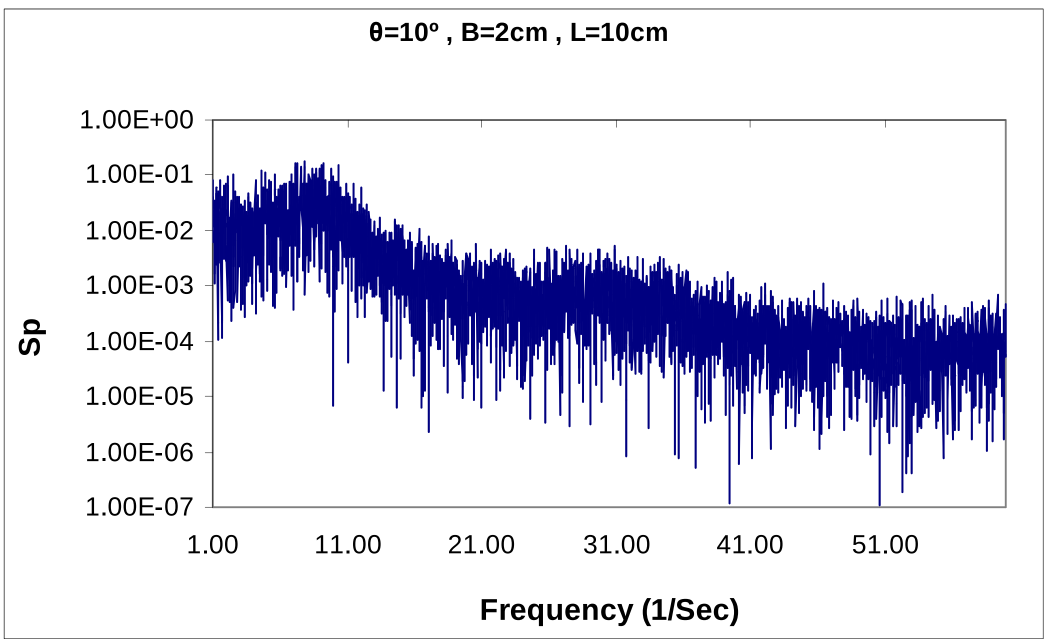

Figure 9- Frequency spectra of pressure fluctuations downstream of ramps.

Conclusion

In this paper a set of experiments was performed to determine the intensity of pressure fluctuations downstream of aerators in a circular tunnel. The study includes the effects of the flow characteristics and the geometry of aerators on pressure fluctuations. These parameters are arranged in the form of Froude number. The results showed that:

- the maximum intensity of pressure fluctuations occurs on the wall of the conduit
- the relative maximum positive and negative values of pressure fluctuations are respectively about $2<\frac{C'p^{+}}{C'p}<6$ and $-2.5<\frac{C'p^{-}}{C'p}<-3.5$.
- the dimensionless root mean square value of pressure fluctuations (*C'p*) reduces as the Froude number of flow increases
- the dominant frequency of pressure fluctuations of about 10 Hz, independent of the inflow characteristics and aerator geometry, was observed downstream of aerators
- the process of aeration reduces the dominant frequency of hydrodynamic pressure fluctuations

References

Falvey, H. T. (1990), *Cavitation in chute and spillway,* USBR Monograph No. 42, USA.

Kavianpour, M. R. (1997), "Wall pressure field in the reattaching flow past deflectors-with and without aeration," Ph. D. Dissertation University of Manchester, Institute of Science and Technology UMIST, Manchester, UK.

Kavianpour, M. R. (2000), "Effect of Air on the Structure of Flow Downstream of Ramps," *4th International Conference on Hydroscience Engineering*, Seoul, Korea.

Kavianpour, M. R. (2003), "Aerators in Bottom Outlet Conduits," *Amirkabir Journal of Science and Technology*, Autumn, Tehran, Iran.

Khosrojerdi, A. and Kavianpour, M. R. (2003), "Experimental Investigation of Pressure Distribution in Bottom Outlet Leaf Gates," *Proceeding of 13th Waterpower Conference*, July, Buffalo, New York, USA.

Lopardo, R. A., Lio, J. C. and Henning, R. E. (1987), "Modeling techniques for preventing cavitation in structures submerged in hydraulic jumps," *22nd Congress IAHR*, Lausanne, Switzerland, pp. 177-182.

McGee, R. G. (1988), "Prototype evaluation of Libby dam sluiceway aeration system," *Proceedings of the International Symposium on Model-Prototype Correlation of Hydraulic Structures*, ASCE/IAHR, Colorado Springs Co., pp. 138-147.

Nakhaei, M. and Kavianpour, M. R. (1999), "Pressure fluctuations downstream of a normal plate," *Proceedings of the 2nd Iranian Conference on Hydraulics*, University of Science and Technology, Tehran, Iran.

Narayanan, N. and Kavianpour, M. R. (2000), "Wall Pressure Field in the Reattaching Flow Past Deflectors-Without Aeration," *Proceedings of Institutions of Civil Engineers*, Water and Maritime Engineering, London, Vol. 142, pp. 79-86.

Peterka, A. J. (1953), "The effect of air on cavitation pitting," *Proceedings of Minnesota International Hydraulic Convention*, USA.

Submitted: October 23, 2004
Accepted: January 31, 2006