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Experimental Optimization of the Ejector Design Developed for a Driver's Airbag

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Abstract. *Design modifications are tested experimentally of the compact supersonic ejector developed for the novel airbag inflation system. The base design resulting from combined numerical and experimental investigations showed itself potentially capable of inflating the 50 L airbag with three parts of entrained air volume together with one part produced by a gas generator. The base design work continues to study its technological flexibility and operational reliability by analyzing a complex flow structure within the inflator. For that, minor changes and supplements to the design were evaluated experimentally to avoid complicated numerical simulations. In particular, it was supposed that a vortex formed at the inflator inlet could significantly reduce its operational cross-section. The impact of this vortex on the airbag filling was investigated in the Laboratory for Advanced Aerodynamics using the developed pneumatic facility. The applied design improvement was found to affect the pressure distribution favorably in the inflator that increased the airbag filling by ~5%.*

Keywords: *pulse ejector, airbag inflation, air entrainment (ejection, aspiration), pressure field measurements.*

Introduction

Modern transportation trends augment the risks for arbitrarily located occupants in fully autonomous vehicles and severe accidents where big airbags can be deployed simultaneously. The latter is illustrated in Fig. 1. In conventional inflation systems, propellant pellets activated by impact sensors generate combustion gases filling the cushion. A sudden pressure surge within the cabin often causes injuries to the eyes and ears of passengers as well as burns from the pyrotechnically produced gas [1]. Airbags, together with seat belts, staying the primary safety system in a car, require advanced engineering solutions to reduce the traumatic impact on passengers.

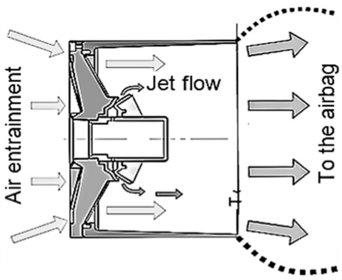

Fig. 1. Ejector base design #5.1 and its operation sketch

Air entrainment into an airbag from the car compartment can significantly contribute to safety compared to the typical inflation with combustion gases. It will also be essential in severe crashes with simultaneous inflation of several airbags [2].

Combined numerical and experimental studies based on the Prandtl-Meier effect [3, 4] showed the validity of this specific approach to developing a supersonic ejector applicable to an airbag module. As a result, the base design of the aspirated inflator (Fig. 2) was developed to inflate the 50-liter airbag within 30 ms [2, 3]. It is axisymmetric and compact, having been considered a proof of concept for testing with the driver's airbag.

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Fig. 2. Traumatic situation of multiple airbags inflated

Experimentally, the concept was verified using the pneumatic facility [5–8] equipped with a high-speed valve [5] that enabled to simulate the airbag inflation using a conventional pyro-cartridge. In the aspirated inflator, the controlled supersonic jet is generated with a smaller cartridge to launch the ambient air entrainment in a one-to-four proportion. Thus the cartridge itself provides about ¼ of the required airbag volume while the rest ¾ of the volume is the air entrained from a cabin. Such features of design and operation as a smaller gas-generator, reduced amount of propellant, stopped airbag deployment on contact with an occupant guarantee both a greater safety of passengers and lower production expenses because of eliminated occupant weight, position, and out-of-position sensors as well as staged airbag deployments.

Investigation aim and strategy

Here, the base inflator model #5.1 is considered with an internally located circumferential slit/nozzle. The nozzle width is the main parameter coupled with the high motive pressure, which determines the best operation of the inflator in terms of aspiration ratio, the volume of entrained air, and the time to inflate the cushion. Parametric studies of this sort revealed ranges of acceptable slit width coupled with high pressure values for the tested models. The experiments were held for the ejecting slit width of 0.25, 0.35, 0.40, 0.45, 0.50 mm within a pressure range of 18–60 bar with 3–6 bar step. [6, 8]. Growing slit width was found to have a stabilizing impact on the ejected jet behavior. However, raised pressure destabilized the flow in the inflator especially in the very beginning of the inflation process. Fig. 3 shows pressure instability in axial and radial directions of the mixing chamber for high motive pressure P = 50 bar; the patterns are obtained at consecutive inflation moments: the process becomes more stable starting from 13.8 ms and rapidly decays after 30 ms.

This unstable flow behavior is deduced from readings of 15 pressure probes distributed in the mixing chamber, which indicate the jet moving up and down from the inflator axis (Fig. 4). It results in reduced aspiration and, consequently, the reduced operational potential of the system. Thus other possibilities should be sought to improve the ejector design, which stayed beyond the combined numerical and experimental efforts. Among them, there are engineering solutions that would require complicated formulation and implementation of numerical tasks.

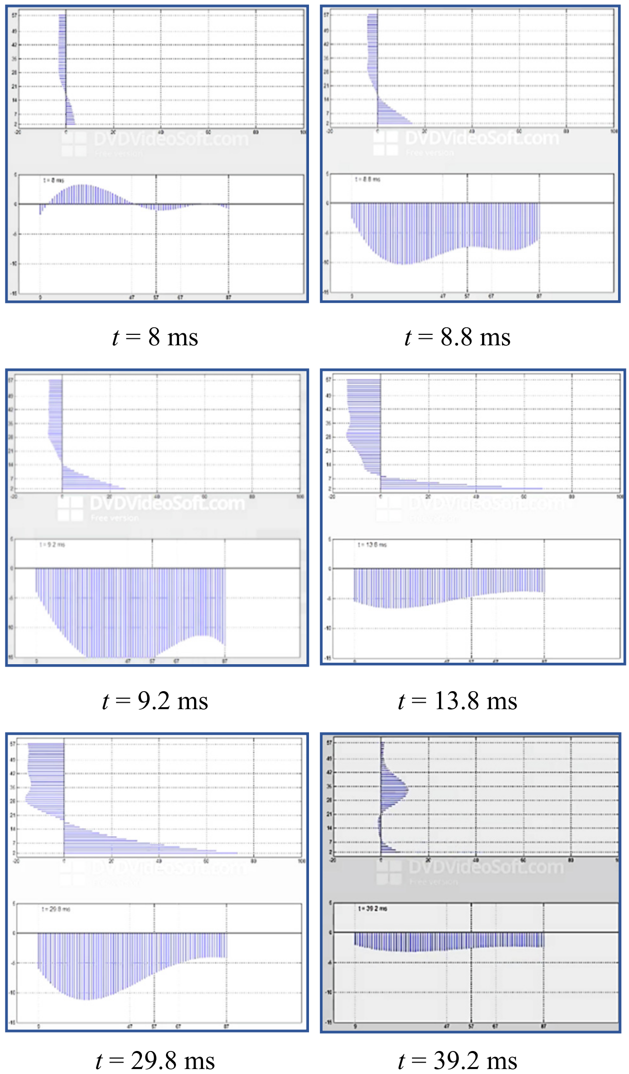


Fig. 3. Measured pressure distributions along the radial (top graph in each pair) and longitudinal (bottom of each pair) axes of the inflator depending on the inflation time at six consecutive moments

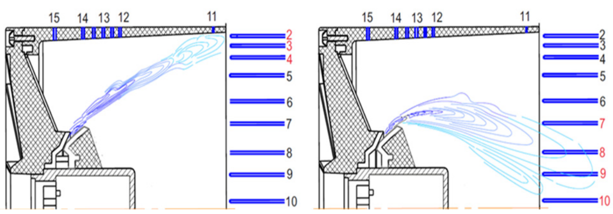
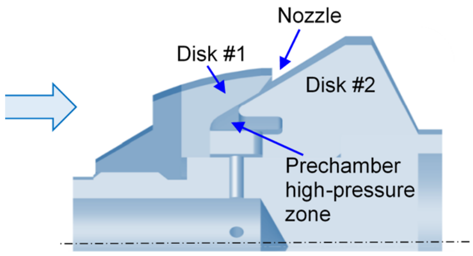
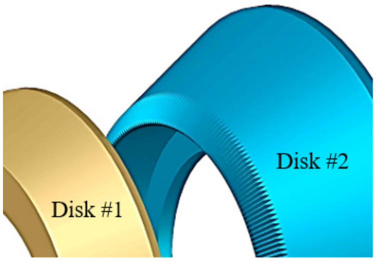


Fig. 4. Supersonic jet location determined from pressure probe readings: red probe numbers correspond to greater values of dynamic pressure

They are, for instance, modifications of the nozzle surface like the streamwise ribbing of one of the nozzle surfaces (Fig. 5, *b*); the idea was conceived due to the development of smart flow control techniques [9, 10]. Also, it includes smoothing of the inflator flow paths, the pre-chamber and mixing chamber shaping, rounding edges of the aspirator inlet as well as attempts to miniaturize the whole device using the folded mixing chamber.



a



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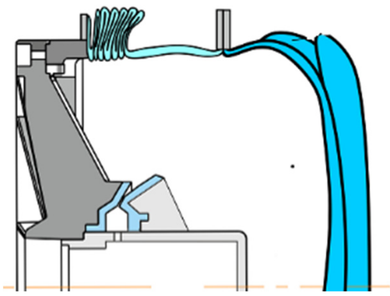

c

Fig. 5. Inflator design modifications tested experimentally: (*a*) base model with smooth surfaces of the nozzle formed by 2 disks; (*b*) ribbed jet-forming surface of disk #2; (*c*) folded mixing chamber

Here, the inflator inlet shape investigated in a series of experimental tests showed the generation of a circumferential vortex on the internal wall of the mixing chamber that could reduce the operational cross-section. The comparative analysis of the inlet vortex behavior and its influence on the airbag filling was made for the base model (Fig. 2) and for the model equipped with a flow smoothing detail to eliminate this vortex (Fig. 6). The geometry of the jet-forming ring-type slit, its coupling with a high-pressure zone, and overall dimensions of the inflator model stay almost the same, length l = 110 mm, diameter d = 120 mm, according to engineering requirements.

Fig. 6. Flow smoothing detail in a form of a rounded leading edge mounted at the inflator inlet

Experiment arrangement

To study processes taking place inside the inflator, a block of full pressure probes (BPPT) for the inflator inlet was developed and embedded in the inflator. Fig. 7 shows a 3D computer model of the unit. It is a duralumin parallelepiped where six tubes with a diameter of 2 mm are fixed (glued) and bent according to the drawing. Fig. 8 shows the manufactured inflator with the mounted BPPT unit and locations of 15 pressure probes. The №1 sensor measures the pressure inside the pre-chamber just before the nozzle; probes #2 to #7 measure the total pressure inside the inflator along its radius; probes #11–15 measure static pressure along the inner wall of the inflator mixing chamber (housing). The high-pressure air inlet is on the left, exit through the nozzle slit is on the right.

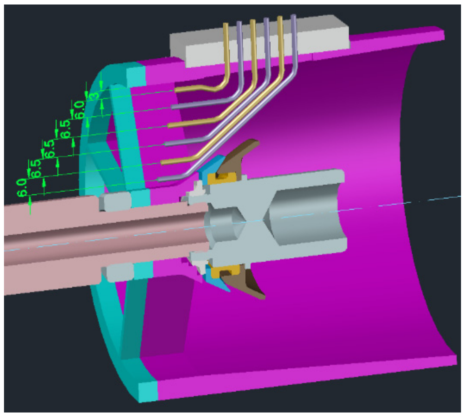

Fig. 7. Three-dimensional BPPT model

As expected, after opening the reverse-flow valve and the 5 ms transition time, the total pressure on the probes #3 to #7 is almost equal to the atmospheric one because hydraulic losses are negligible in a short channel from the inflator inlet to the BPPT. Probe #2 shows significant underpressure (vacuum). By the connection nature, full pressure probes are dynamic pressure sensors measuring the difference between the total pressure in the flow and the static pressure at the sensor location.

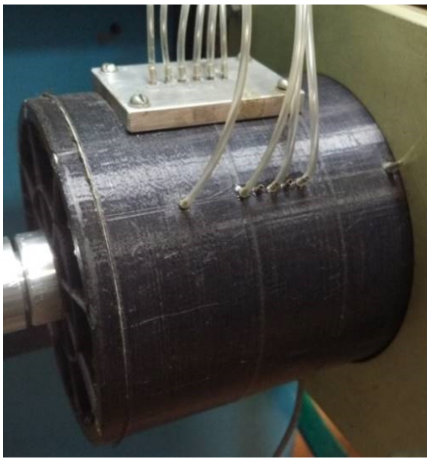

Fig. 8. BPPT installation on the inflator

The tested inflator is equipped with five static pressure probes (PST) ##11–15 located along the inflator generatrix, see Figs. 7 and 8. The PST closest to the inlet is located at a distance of 23 mm from the inlet nearby the BPPT location. Since the jet is absent in this area and the distance from the inlet is short, one can assume that the static pressure is constant throughout the whole inflator cross-section and about the pressure measured by probe #15. Therefore, the difference between the static pressure measured by the #№15 probe and the total pressure measured by the BPPT with connected probes #2 to #7 represents the dynamic pressure inside the inflator.

Varying flow parameters are shown in Fig. 9 for the base inflator: dynamic pressure at the inflator inlet from the probes ##2–7 and static pressure along the inflator wall from the probes ##11–15 (probes ##8–10 were not used). Probe #2 typically shows the negative dynamic pressure that evidences the available reverse flow in the near-wall region. The inlet smoothed with a rounded ring of Fig. 6 changes the pressure to positive at the #2 location (Fig. 10), i.e. eliminates the reverse flow area. At the same time, Fig. 10 patterns show dropped underpressure (static probes ##11–15) compared to the initial base case, i.e. higher flow velocities. That is, the increased operational cross-section area without the wall vortex results in the decreased dynamic pressure at the inlet to the inflator.

For evaluation of the smoothed inlet on the airbag filling, a special measuring bag of 120 liters (Fig. 11) was inflated using the base inflator and the one with the modified inlet. In both cases, the inflated air was sucked off the bag after the inflation with an air pump connected to a gas meter.

For both cases, four measurements were made in a pressure range of 30 to 50 bars. The measurement results were processed and depicted in Fig. 12. It shows a favorable result obtained due to the increased operational cross-section that prevailed the effect of slightly lower flow velocities inside the inflator mixing chamber. The modified design with the applied smoothing inlet attachment increased the volume of inflated air by 2.0–2.5 liters compared to the base model.

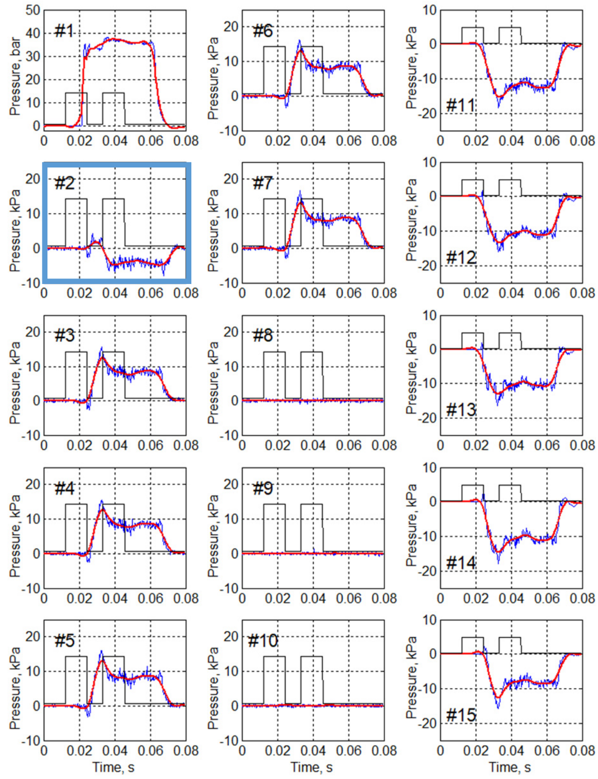

Fig. 9. Pressure patterns in the base inflator model #5.1: slit nozzle width, c = 0.35 mm, motive high pressure, P_m = 37.25 bar

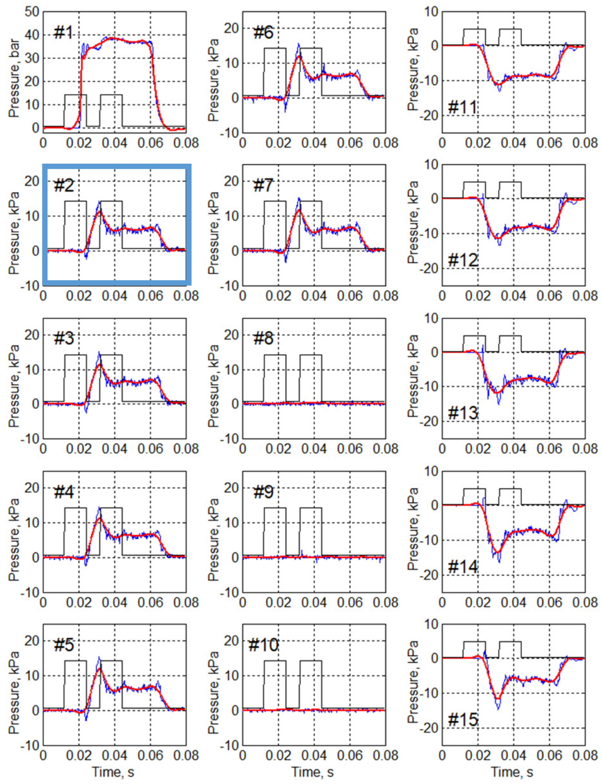

Fig. 10. Pressure patterns in the #5.1inflator model *with the modified inlet*: slit nozzle width, c = 0.35 mm, motive high pressure, P_m = 38.29 bar

Fig. 11. "Big bag" experiments to determine the inflated air volume and aspiration ratio values: measuring 120–160 L bag connected to the aspirated inflator and gas meter

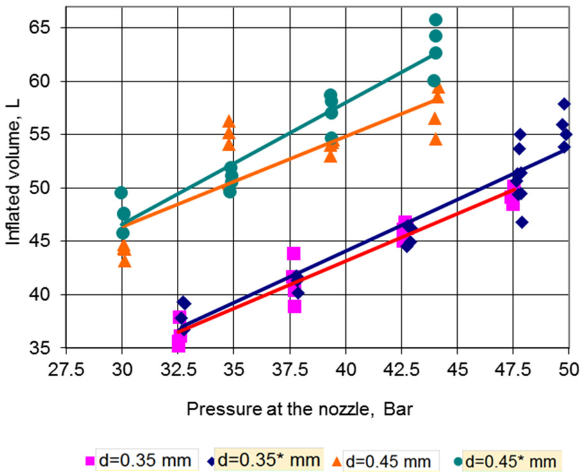

Fig. 12. Inflated air volume depending on pressure at the nozzle 0.35 mm and 0.45 mm wide for cases of the base and optimized (marked yellow) design

Conclusions

The developed base model of the compact supersonic ejector was thoroughly tested in experiments to ensure the device's applicability to the airbag aspirated inflation system. Instability of its operation in the form of measured "breathing" pressure fields was found under certain conditions. It was analyzed to determine possible ways of design improvement. A number of engineering solutions was offered and tested experimentally to avoid time and resource-consuming numerical simulations. First of all, these improvements were related to smoothing flow passways in the inflator to prevent stagnation areas as well as proper shaping the nozzle surface and separate inflator details.

One of such design improvements considered here was the rounded inlet edge of the inflator to prevent the vortex formation around the inner wall of the mixing chamber. The latter could cause the reduction of the effective cross-section of the inflator and its operation different from that calculated. In experiments, additional design-smoothing detail was fabricated and mounted in the inflator inlet. A series of distributed static and dynamic pressure measurements showed a favorable stabilizing impact of this superstructure on the jet behavior and the whole inflator operation. The airbag filling increased by about 5% that confirms the correctness of this kind of approach.

The built experimental complex together with the integrated measurement system for jet flow investigations and, in particular, for testing novel airbag inflators, showed itself perfectly satisfactory. Thus further design improvements are expected to be appropriate for studies, e.g., a new surface profile of the nozzle in the form of longitudinal ribs, which were found to be efficient for flow control; also, it would be scientifically correct and practically important to take into account the steering wheel column design where the aspirated inflator is to be mounted and thus influences by surrounding structures.

Acknowledgments

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Експериментальна оптимізація конструкції ежектора розробленого для наповнення водійських подушок безпеки

Н.Ф. Юрченко, П.М. Виноградський

Анотація. *Експериментально перевірено конструкційні модифікації компактного надзвукового ежектора, розробленого для нової системи надування подушок безпеки. Базовий дизайн, створений в результаті комбінованих чисельних та експериментальних досліджень, показав себе потенційно здатним надути подушку безпеки ємністю 50 л за допомогою 3 частин об'єму захопленого повітря разом з однією частиною, виробленою газогенератором. Продовжується робота над базовою конструкцією для вивчення її технологічної гнучкості та експлуатаційної надійності на основі аналізу складної структури потоку всередині інфлятора. Для цього незначні зміни та доповнення до конструкції були оцінені експериментально, уникаючи складного чисельного моделювання. Зокрема, передбачалося, що вихор, що утворився на вході інфлятора, може значно зменшити його робочий переріз. Вплив цього вихору на наповнення подушки безпеки досліджували в Лабораторії передової аеродинаміки за допомогою розробленої пневматичної установки. Було виявлено, що застосоване вдосконалення конструкції сприятливо впливає на розподіл тиску в камері змішування, що збільшує наповнення подушки безпеки на ~5%.*

Ключові слова: *імпульсний ежектор, нагнітання подушок безпеки, забір повітря (ежекція, аспірація), вимірювання поля тиску.*