Agronomy Research **14**(5), 1609–1618, 2016

The possibilities of pneumatic reactive stabilization of vehicles

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Abstract. This paper describes a new and original way of car stabilization as an alternative or support for the common ESP stabilization method. It summarizes the properties of present car stabilization systems and their advantages and disadvantages. Then the pneumatic stabilization method is described, which uses compressed air to trigger the necessary reacting forces that are applied to a vehicle in case of the loss of adherence. To prove the new stabilization method, there are stated some basic calculations of the jets and the obtained reacting forces are identified. Finally, the results are discussed and evaluated.

Key words: ABS, ESP, anti-skid systems, pneumatic stabilization, jets, compressed-air reservoir.

INTRODUCTION

Among the basic active and passive safety components, which are included in modern cars, trucks, motorbikes, is the ABS – Anti-Lock Braking System (Zhao et al., 2013; Zhao et al., 2014). This anti-lock system was first introduced in 1978 by firms Bosch and Mercedes-Benz as extra equipment for additional charge at model S and since then it has been widely spread in all models of all car types (Kovanda et al., 2009). Anti-lock braking system is today an obligation without which the car couldn't successfully obtain a homologation.

This article represents the results of our work which is deal with new idea. This was not published till this time. The scope of our work is to explore the possibility of pneumatic stabilization of vehicles entirely by theoretical calculations. The next step of this work was to design the suitable Laval jet and analyze the correction power of pneumatic system according to power of centrifugal force during the car's thoroughfare of curve.

Present state of car stabilization

Together with ABS there are other systems to make comfort better and increase safety such as:

- BAS (brake assistant) – recognizes critical situations and by increasing the pressure it enables the full braking effect.
- ASR – (anti-slip regulation) – prevents slip-spinning at acceleration and moving off by reducing the torque of the engine.
- EMS – reduces the rotary inertia until the powered wheels are at the full adhesion.
- MSR (Motor-Schleppmoment-Regelung) – prevents slip-spinning when braking using the engine.

– ESP (Electronic Stability Program) – prevents the car slipping by braking a selected wheel and thus eliminating the understeering and oversteering.

These systems keep the vehicle in required direction but they have a common disadvantage: there is a limitation of the friction force that can be transferred between the tyres and the surface. This friction force depends for example on the coefficient of friction μ [-], which can sink to the value of 0.1 on ice, compared to values 0.8–0.9 on a dry road. As a result, the transferred force can sink up to 0.1 of the maximal possible value. The corrective forces would be insufficient in such cases to maintain the vehicle on the desired track or even to prevent the vehicle to leave the road.

The weather phenomena plays an important role because there are some unpredictable situations, e.g. when on a very clean road without snow or ice after a machinery clearing, there are some rest icy places – for example on bridges. In these situations the new method of car stabilization could be useful and it could help the driver to solve a problematic situation using additional reactive forces.

A similar solution is using by landing aircrafts, the braking force of the tyres, which is limited due the friction, could be in some situations insufficient to stop the aircrafts within the runway. So another force – the reverse thrust – is applied in such situations that increases the sum of the breaking forces and enables the deceleration more quickly.

Currently used stabilization systems work in connection with the ABS. From the pressure sensor of brake fluid the control unit is informed about the pressure in braking system. The sensors measure the pressure that is created by pressing the brake pedal. Then the ABS control unit compares these signals in both ways. The control unit is informed about the actual pressure in brake system by the pressure sensor of the brake fluid. If interference is necessary, the control unit uses then the actual value of the brake pressure to the calculation of side forces.

The sensor of the longitudinal vehicle acceleration that is the next part of the system is assembled to a car with drive on all wheels. On cars with drive of only one axletree the system calculates the longitudinal vehicle acceleration from the brake pressure sensor signals, from the wheels revolutions sensors and from the information of the engine control unit.

The sensor of the side acceleration of the vehicle informs about side forces applied on the car. This information is important for calculations of the forces that have to be overcome for staying up the car in the intended way. The sensor read stay if the car doesn’t revolve around the vertical axis. The micro mechanic system with the double tuning fork from silicon monocrystal placed on the sensor desk is the basic part of the sensor of the rotary speed. The double tuning fork is created by exciting tuning fork and specific tuning fork.

The next part of the car stabilization is the sensor of the steer angle. This sensor sends a partly signal about the steer angle and a partly signal about the speed of the steering-wheel turn. Both signals are at first evaluated in the control unit and they are sent to the control unit of electromechanical servo control (Cerha, 2010). Two absolute magnetic angle sensors are to disposition for the control unit Bosh. These ones (in contrast to incremental sensors) give the information about the steer angle in the full angles range in every time (Kovanda, 2010).

The considerable information part about the car behavior is given by accelerometers. The accelerometers are sensors for measurement of static and dynamic acceleration. They are used not only for measurement of eccentric or inertial forces, but also for determination of the subject position, it's declination or vibrations, too.

All these car stabilization types use information about the car behavior and about the upon a car acting forces to keeping the car in the intended trajectory by separate wheels braking, by the engine torque changing, or by its redistribution to the separate axletree, respectively on the separate wheel. The common disadvantage of these systems, i.e. the limitation due do friction, has been described above.

MATERIALS AND METHODS

The main scopes of this work are:

1. Make a review and analysis of current posibility of cars stabilization.
2. In theoretical way make a proposal of pneumatic reactive stabilization of vehicles collaborating with ESP.
3. In theoretical way enumerate the parameters of jet and corrections energy at each differencial steps of pneumatic stabilization.
4. Evaulate the possibility of this new reactive stabilization of vehicles.

The new trend during development of adhesive safety system could by the reactive pneumatic stabilization of cars.

This is new original idea using Newton law of action and reaction by the medium of compress air and jets located near the wheels. In critic situations, when the current safety systems are not sufficient, the system blow out air for a short time and according Newton law can help to hold the vehicle in its original direction.

All calculations in this work were made using program Octave – open source alternative to Matlab.

Pneumatic stabilization of car

The new trend in development and system upgrade could be cohesive security system of pneumatic car stabilization based on the Newton's Law of Action and Reaction. Very pressurized air volume will grab in the critical moment form jets placed in car's body corners near from wheels (Direct Industry, 2013; Humidifiers, 2013).

The necessary components are:

- ✓ quick vents at the jets,
- ✓ connection to the ESP control unit,
- ✓ compressed air reservoir,
- ✓ compressed air tubes to the jets,
- ✓ independent jets at wheels.

The compressor will preferentially use electrical energy obtained by car braking or by riding from a hill, or the right moment of the compressor run may be defined by means of GPS navigation data of the car. In this case the energy recuperation can be also used. By this way the ESP control unit can by better prepared to the relevant action and the driver can be informed by a shining pilot light about the impending danger relatively on time. Figs 1 and 2 describe the components´ layout in a car equipped in this way.

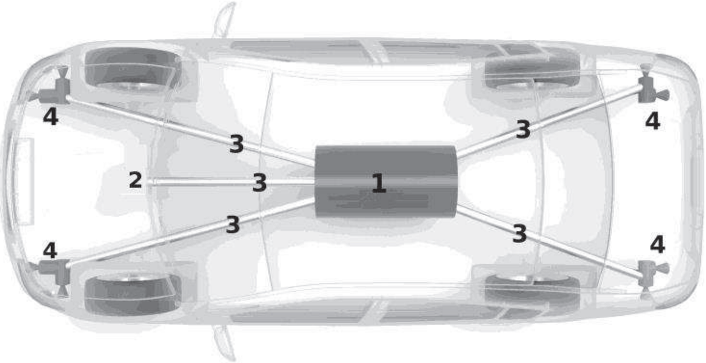

Figure 1. The top view on a car quipped with the pneumatic stabilization system.

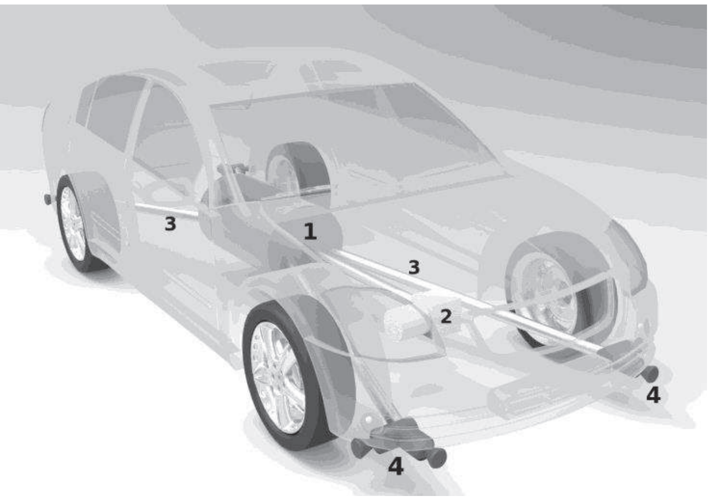

Figure 2. The front view on a car quipped with the pneumatic stabilization system.

In the figures, number **1** marks the compressed-air reservoir, placed in car's center of gravity; number **2** the high-pressure compressor; number **3** labels the compressed-air piping and number **4** the jets in the car's body corners.

A draft calculation of jets

Initial state of the air pressure container:

$$V_{0c},\ p_{0c},\ T_{0c},\ \varrho_{0c}$$

True that:

$$m_0 = V_0 \cdot \frac{p_0}{T_0}\ ; \quad \varrho_0 = \frac{p_0}{r \cdot T_0}$$

where: m_0 [m^3] – the total amount of the compressed air in the pressure container and in the piping (given by the product of the air volume and the air density); V_0 – Initial volume of air at pressure tank; p_0 – Initial air pressure at pressure tank; T_0 – Initial air temperature at pressure tank; ϱ_0 – Initial air density at pressure tank; r – Gas constant (for air 287.04 Jkg^{-1}K^{-1})

$$w_{krit} = \sqrt{2 \cdot c_p \cdot (T_0 - T_{krit})} = \sqrt{\kappa \cdot r \cdot T_{krit}} \tag{1}$$

where: a [m s^{-1}] – Air speed (in this case = $\boldsymbol{w_{krit}}$); w_{krit} – Air speed at critical place of nozzle (narrowest place); T_{krit} – Air temperature at critical place of nozzle (narrowest place); κ – Poisson constant; c_p – 1,004 Jkg^{-1}K^{-1}

$$\dot{m} = m_{krit} = A_{krit} \cdot w_{krit} \cdot \varrho_{krit} \tag{2}$$

Then:

$$a_{krit} = w_{krit} = \sqrt{\kappa \cdot r \cdot T_{krit}} = \sqrt{2 \cdot c_p (T_{0c} - T_{krit})}$$

$$\kappa \cdot r \cdot T_{krit} = 2 \cdot c_p \cdot (T_{0c} - T_{krit})$$

$$\kappa \cdot r = 2 \cdot c_p \left(\frac{T_{0c}}{T_{krit}} - 1\right)$$

$$\frac{T_{0c}}{T_{krit}} = \frac{\kappa \cdot r}{2 \cdot c_p} + 1 = \frac{\kappa \cdot (c_p - c_v) + 2 \cdot \kappa}{2 \cdot c_p} = \frac{\kappa \cdot (\kappa - 1) + 2 \cdot \kappa}{2 \cdot \kappa} = \frac{\kappa - 1 + 2}{2} = \frac{\kappa + 1}{2} = 1.2$$

Further:

$$\varrho_{krit} = \frac{p_{krit}}{r \cdot T_{krit}} \tag{3}$$

$$\frac{T_{0c}}{T_2} = \left(\frac{p_{0c}}{p_2}\right)^{\frac{\kappa-1}{\kappa}} => T_2 = T_{0c} \left(\frac{p_2}{p_{0c}}\right)^{\frac{\kappa-1}{\kappa}}$$

$$\frac{w_2^2}{2} = c_p \cdot (T_{0c} - T_2) = c_p \cdot T_{0c} \left(1 - \frac{T_2}{T_{0c}}\right) \tag{4}$$

$$\frac{w_2^2}{2} = c_p \cdot T_{0c} \left[1 - {\frac{p_2}{p_{0c}}}^{\frac{\kappa-1}{\kappa}}\right]$$

$$w_2 = \sqrt{2 \cdot c_p \cdot T_{0c} \cdot \left[1 - \left(\frac{p_2}{p_{0c}}\right)^{\frac{\kappa-1}{\kappa}}\right]} = \sqrt{2 \cdot \frac{c_p}{r} \cdot \frac{p_{0c}}{\varrho_{0c}} \cdot \left[1 - \left(\frac{p_2}{p_{0c}}\right)^{\frac{\kappa-1}{\kappa}}\right]} =$$

$$= \sqrt{\frac{2\,.\,\kappa}{\kappa - 1} \cdot \frac{p_{0c}}{\varrho_{0c}} \cdot \left[1 - \left(\frac{p_2}{p_{0c}}\right)^{\frac{\kappa-1}{\kappa}}\right]} \tag{5}$$

Speed of sound:

$$a = \sqrt{\kappa \cdot r \cdot T}$$

$$a_{krit} = \sqrt{\kappa \cdot r \cdot T_{krit}} \tag{6}$$

The speed of the ejecting air:

$$w_2 = \sqrt{2 \cdot C_p \cdot (T_0 - T_2)} \tag{7}$$

The pressure in the critical place p_{krit} is:

$$p \cdot v^k = const.$$

where: v [m^3 kg^{-1}] – Means specific volume of the air; m_{krit} – Air mass at critical place of nozzle (narrowest place); a_{krit} – Sound speed at critical place of nozzle (narrowest place).

Further considering the Equation of state of ideal gas $p \cdot v = r \cdot T$ we obtain:

$$\frac{p_0}{p_{krit}} = \left(\frac{T_0}{T_{krit}}\right)^{\frac{\kappa}{\kappa-1}} \tag{8}$$

The state in the critical cross-section is given by:

$$T_{krit} = T_{0c} \cdot \frac{2}{\kappa + 1} \tag{9}$$

$$p_{krit} = p_{0c} \cdot \left(\frac{2}{\kappa + 1}\right)^{\frac{\kappa}{\kappa-1}} \tag{10}$$

$$\varrho_{krit} = \frac{1}{V_{krit}} = \frac{p_{krit}}{r \cdot T_{krit}} = \frac{p_{0c}}{r \cdot T_{0c}} \cdot \left(\frac{2}{\kappa + 1}\right)^{\frac{1}{\kappa-1}} \tag{11}$$

The amount of air flown through the jet:

$$\dot{m} = A_{krit} \cdot \sqrt{\kappa \cdot r \cdot T_{krit}} \cdot \varrho_{krit} = A_{krit} \cdot \sqrt{\kappa \cdot r \cdot \frac{\kappa}{\kappa - 1} \cdot T_{0c}} \cdot \varrho_{krit} \tag{12}$$

where: $\dot{m}$ [kg s^{-1}] – Mass flow rate; A [m^2] = Cross-section area of the jet, A_{krit} = Nozzle aperture at critical place of nozzle (narrowest place); ϱ_{krit} = Air density at critical place of nozzle (narrowest place).
For further calculations for a given time we consider: $t = t_0 + \Delta t$

After application of the adiabatic equation we obtain:

$$p_0 \cdot {V_{0c}}^{\kappa} = (p_{0c} - \Delta p) \cdot (V_{0c} + \Delta V)^{\kappa} \tag{13}$$

For further calculations we choose:

$\Delta V = 0.01\, m^3$

1. Step $t = t_{0,}$ $V = V_0$, $p = p_0$
2. Step $t + \Delta t,$ $V = V_0 + \Delta V,$ $p = p_0 - \Delta p$

Given by the equation of state: $\Delta m = \Delta V \cdot \varrho_0 = \Delta t \cdot \dot{m}_{krit} \;=>\; \Delta t \frac{\Delta m}{\dot{m}_{krit}}$.

In the following step, we repeat the calculations with new values:

$$t_{i+1} = t_i + \Delta t_{i+1}$$
$$T_{i+1} = T_i - \Delta T_{i+1}$$
$$t_{i+2} = t_{i+1} + \Delta t_{i+2}$$
$$p_{i+2} = p_{i+1} - \Delta p_{i+2}$$
$$T_{i+2} = T_{i+1} - \Delta T_{i+2}$$

The outflow speed from the jet w_2 is a speed, by which during the expansion of the air in the cross-section A_2 the pressure decreases to the atmospheric pressure $p_2 = p_e$. From the Continuity equation: $\dot{m} = \dot{m}_{krit} = A \cdot w \cdot \varrho = A_2 \cdot w_2 \cdot \varrho_2$

Using: $T_2 = T_0 \cdot \left(\frac{p_e}{p_{0c}}\right)^{\frac{\kappa-1}{\kappa}}$ $\quad \varrho_2 = \frac{p_2}{r \cdot T_2}$ $\quad w_2 = \sqrt{2 \cdot c_p \cdot (T_0 - T_2)}$

The output cross-section of the jet will be: A_2

$$\dot{m}_{krit} = A_2 \cdot \varrho_2 \cdot w_2 \;=>\; A_2 = \frac{\dot{m}_{krit}}{\varrho_2 \cdot w_2} \tag{14}$$

The resulting corrective force of the ejecting compressed air in the first stage of expansion (an under-expanded jet):

$$F = \dot{m}\, w_2 + A_2\, (p_2 - p_e) \tag{15}$$

where: F [N] – The obtained corrective force.

In case of an ideal expansion is true:

$$F = \dot{m} \cdot w_2 \tag{16}$$

In case of an over-expanded jet is true:

$$F = \dot{m} \cdot w'_2 \tag{17}$$

where: w'_2 [m s^{-1}] – The imaginary speed during the ideal expansion to the pressure p_e.

The control calculations were implemented for the jet with the output diameter 35 mm, in the narrowest diameter 15 mm, pressure values in the air reservoir of 10 MPa, 15.5 MPa and 20 MPa, volume of the reservoir 0.05 m^3, car mass 1,000 kg, car speed 80 km h^{-1} (22.2 m s^{-1}) and the radius of turn 50 m. Fig. 2 shows the results of the calculations for the given initial pressure values.

The final air pressure in the reservoir decreased to the value of 3.5 MPa within 3.2 s. Considering the initial temperature 323 K, the sum of acting forces reaches the value 3.8 kN for the initial air pressure value of 10 MPa, 6.3 kN for 15.5 MPa and 8.3 kN for 20 MPa. The centrifugal force in the curve reaches the value of approximately 10 kN for the defined car and conditions. The results for selected initial pressure and temperature values are represented graphically in Figs 3, 4, 5.

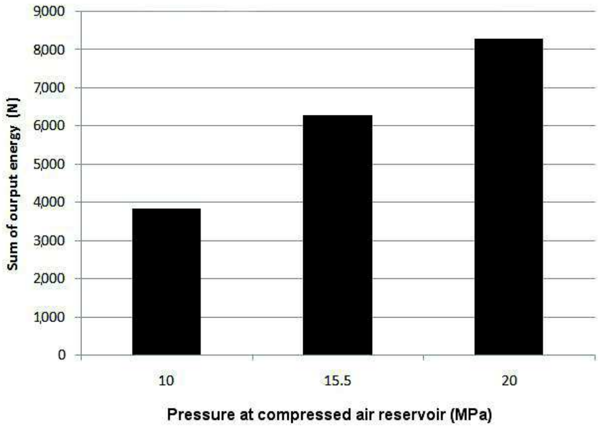

Figure 3. Dependence of the sum of the reacting forces on the initial air pressure for 323 K.

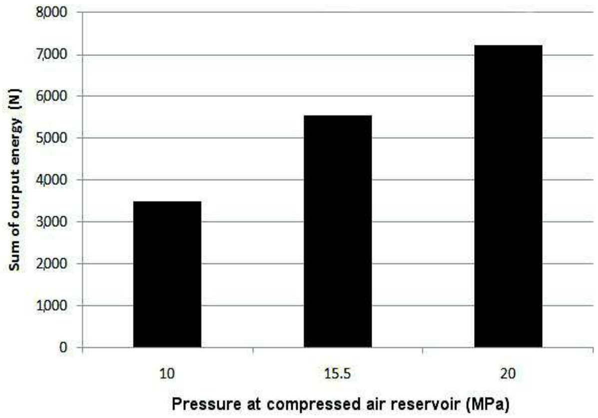

Figure 4. Dependence of the sum of the reacting forces on the initial air pressure for 423 K.

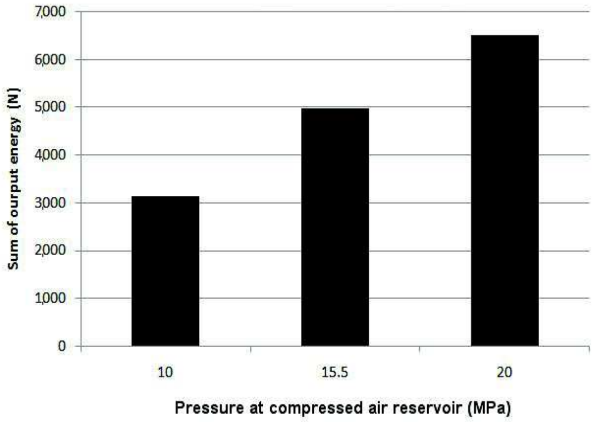

Figure 5. Dependence of the sum of the reacting forces on the initial air pressure for 523 K.

The calculated sum of reacting forces reaches the value up to 8.3 kN, which is about 83% of the centrifugal force acting on the vehicle. The value increases with increasing initial pressure in the container, and decreases with increasing temperature. Thus, cooling of the compressed air is necessary for better efficiency of the system.

However, we must consider, that the total reaction force acting on the vehicle is a sum of the considered pneumatic reaction forces and the forces given by the conventional stabilization system, i.e. the ESP that are nevertheless strongly dependent on the surface conditions of the road. In some cases the adhesive stabilization system may be sufficient, in other cases the pneumatic stabilization system may act as a safety margin to the conventional systems. With the highest initial pressure, we can virtually obtain the required corrective force without any further adhesive forces.

CONCLUSION AND DISSCUSION

We introduced a new and original method, the comparable studies were not published yet. The pressurized air is used to compensate the forces acting on a vehicle. We have proved that the described system may considerably help the present adhesive-based stabilization systems like the ESP. The control calculations demonstrated the possibility to compensate the centrifugal force acting on the given vehicle in the ranges of 38% to 83%, which can considerably help the adhesive forces or even virtually to compensate them to stay the car in the intended trajectory.

The primary goal of the this work was to explore the possibility of using this idea only by help of mathematics calculations (see appendix) an to design the suitable Laval jet. This is only the purely theoretical work with original and promising results. At real this is an upgrade of current ESP system in case of adhesive stabilization is not fully sufficient and there is the risk of emergency situation. We do not suppose to use this at everyday usage.

The next step depends on manufacturers if they decide to use the system as a way to make the car operation better and safer. Add-on systems could make cars more complicated and more expensive. But the massive production can lower the costs. The price of the life is incalculable. As for the space needed for this technical device, it may not be a big problem because the device can be placed at the bottom of the car and it will not occupy more space than for example the gas reservoir that is used in cars equipped with this invention.

The pressure at pressure tank is according today’s material a technology potential. At industries there are using pressures around 30 MPa and more normally. This study is at the begging so the financial costs are higher then usually but this is normal at every development. I’d like to refer the costs of ABS of beginning its development. And today it is the basic of safety cars. Influence to environment is always small since this technology use the clear pressured air. And also in this case we can omit the effect of speed and direction of wind because of the speed of air from jet is multiply bigger. The scope of this study was only to confirm the physical possibilities of my idea and to design the suitable Laval jet. The statistics methods were not used because the calculation using math program gives us relevant results.

The technology of the adhesive solutions is still limited due to the friction between the tire and the surface, but the pneumatic technology may still develop further, producing higher pressures and thus higher compensation forces. Considering this limitation of the adhesive-based systems, this could be a revolutional solution for the future.

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