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COMMONALITY OPPORTUNITES OF ALUMINUM EXTRUDED PANELS ACROSS DIFFERENT VEHICLES

Jakub Kwapisz [11], Manuel M. Freitas, Virginia Infante

UDC: 629.1.07;519.672

ABSTRACT: There are few manufacturers that produce busses and light rail vehicles. Those manufacturers include Bombarider, Siemems, and Solaris among the others. During the case study conducted in one of the manufacturers and presented in this paper, it turned out that potential benefits coming from sharing components between different products are not realized. A great problem for any manufacturer is the engineering effort necessary to produce every set of products for a particular client. One of the solutions for a manufacturer is to use common components in locations not visible for customers and customized elements for product differentiation. Commonality increases quality, prevents resource waste, decreases costs and, most importantly, decreases total development time of the product by eliminating unnecessary development steps of individual components. After a detailed analysis of the car body shell (CBS) components in the light railways and trams, it turned out that there are parts that can be potentially common. The most interesting elements for further study were floor and roof panels. Our hypothesis is that number of profile solutions solution may be reduced and common not only across different rail vehicles, but as well busses. The key problem this research paper investigate is commonality opportunity of reusing the same design for aluminum panels in different light rail and bus applications. Long extrusion is a specific process that takes a long time to set up for final production. The commonality of the aluminum panel concept across different product could lead to decreased development and manufacturing time, and reduce cost. The finite element method (FEM) numerical simulations were performed using the nonlinear commercial finite element software HyperWorks v12 in order to determine properties of different panels already produced by the company and additional optimised panels created during this study. Additional information about panels was gathered from different company division such as industrialization, manufacturing and procurement in order to make final decision which aluminum panel should be shared across different products.

The paper is constructed from five chapters. First is an introduction to the problem and conducted research. The second chapter is an industrial case study which was performed in one of the leading manufacturers or railway and road vehicles. The third chapter describes results coming from this case and especially results of the final element analysis. The fourth chapter is a further discussion about commonality possibilities and description of additional information that had to be considered before making a final decision. In the last chapter, there are conclusions coming from this research that can be generalized to other applications.

This research paper is very valuable for both academia and practitioners. It present a study area that can be further investigated by different researchers and applied to different companies by practitioners. It turned out that commonality is very beneficial and every company should implement it to some extent. A researcher could collaborate with industry as it was done in our case in order to implement state of art methodologies and solutions together.

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KEY WORDS: commonality, finite element analysis, lightweight design, aluminium panels

ZAJEDNIČKE MOGUĆNOSTI ALUMINIJUMSKIH EKSTRUDIRANIH PANELA KROZ RAZLIČITA VOZILA

REZIME: Postoji nekoliko proizvođača koji proizvode autobuse i laka šinska vozila. U ove proizvođače spadaju Bombarider, Siemems, i Solaris između ostalog. Tokom predmeta istraživanja sprovedenog u jednom od proizvođača i predstavljenog u ovom radu, ispostavilo se da potencijalne koristi koje dolaze od deljenja delova izmedju različitih proizvoda nisu realizovane. Veliki problem za bilo kog proizvođača je inženjerski napor koji je potreban da bi se proizveo svaki proizvod za određenog klijenta. Jedno od rešenja za proizvođače je da koriste zajedničke komponente na mestima koja nisu vidljiva za klijente i time prilagode elemente za različite proizvoda. Zajedništvo povećava kvalitet, sprečava slabljenje resursa, smanjuje troškove i što je najvažnije, smanjuje ukupno vreme razvoja proizvoda eliminacijom nepotrebnih razvojnih koraka pojedinih elemenata. Nakon detaljne analize komponenata karoserije automobila, lake železnice i tramvaja, ispostavilo se da postoje delovi koji mogu biti eventualno zajednički. Najinteresantniji elementi za dalja istraživanja bili su podni i krovni paneli. Naša hipoteza je da se broj profilnih rešenja zajednički smanji, ne samo kod šinskih vozila već i kod autobusa. Ključni problem ovog istraživanja je mogućnost zajedništva ponovne upotrebe istog dizajna za aluminijumske panele u različitim autobuskim i železničkim primenama. Dugo istiskivanje je specifičan proces koji traje duži vremenski period za podešavanje završne izrade. Zajedništvo koncepta aluminijumskih panela kroz različite proizvode može dovesti do smanjenja vremenskog razvoja proizvoda i smanjenja troškova. Metodom konačnih elemenata (FEM) izvršene su simulacije pomoću nelinearnog komercijalnog softvera konačnim elemenatima HyperWorks v12 kako bi se utvrdila svojstva različitih panela već proizvedenih od strane kompanije i dodatnih optimizovanih panela nastalih tokom ovog istraživanja. Dodatne informacije o panelima su dobijene iz različitih delova preduzeća, kao što su industrijalizacija, proizvodnja i nabavka, kako bi se donela konačna odluka koji aluminijuski panel treba koristiti za zajedničke proizvode.

Rad čini pet poglavlja. Prvo poglavlje je uvod u problem i sprovedeno istraživanje. Drugo poglavlje je industrijski slučaj istraživanja koje je izvedeno u jednom od vodećih proizvođača železničkih i drumskih vozila. Treće poglavlje opisuje rezultate koji dolaze iz ovog slučaja i posebno rezultate analize konačnim elemenatima. Četvrto poglavlje je dalja diskusija o mogućnostima zajedništva i opis dodatne informacije koja mora da se razmotri pre donošenja konačne odluke. U poslednjem poglavlju, postoje zaključci koji proizilaze iz ovog istraživanja i koji se mogu generalizovati i na druge aplikacije.

Ovaj istraživački rad je veoma dragocen i za akademce i praktičare. Daje prostor istraživanju koje se može dodatno istražiti od strane drugih istraživača i biti primenjeno u različitim kompanijama. Ispostavilo se da je zajedništvo veoma korisno i da svaka kompanija treba da ga sprovede u izvesnoj meri. Istraživač može da sarađuje sa industrijom, kao što je učinjeno u našem slučaju, u cilju primene najsavremenije metodologije i rešenja zajedno.

KLJUČNE REČI: zajedništvo, analiza konačnim elemenatima, lagan dizajn, aluminijumski paneli.

COMMONALITY OPPORTUNITES OF ALUMINUM EXTRUDED PANELS ACROSS DIFFERENT VEHICLES

Jakub Kwapisz[1]*, Virginia Infante*[2]*, Manuel M. Freitas*[3]

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1. INTRODUCTION

Currently, there is an increased amount of electric buses, buses driving on dedicated lanes and there are metro cars which ride on tires [1]. Differences between traditional rail vehicles and road vehicles are not as distinguish as it used to be. Bus electrification is visible because it allows reducing fuel consumption and decreases the environmental footprint [2], [3]. Such situation is caused not only by good intentions of manufacturers and users, but as well by strict regulations. The emission limits for vehicles are very low, Euro VI standards reduced emission limits for NOx several times and particulate matters PM emission for more than double compared with Euro IV standards [4].

There are few manufacturers that produce both types of vehicles, buses and light rail vehicles. Those manufacturers include Bombarider, Siemems, and Solaris among the others [5]. During the case study conducted in one of the manufacturers and presented in this paper, it turned out that potential benefits coming from sharing components between different products are not realized. Other manufacturers most likely also don't maximize benefits because different company divisions are responsible for development and manufacturing of parts designed for different products. A great problem for any manufacturer is the engineering effort necessary to produce every set of products for a particular client. Depending on the area of the world in which buses or railway vehicles will be used, design requirements for the same type of vehicle change. Moreover, specific climate may require additional equipment such as heating or air-conditioning. One of the solutions for a manufacturer is to use common components in locations not visible for customers and customized elements for product differentiation. Commonality is an approach of calculated reuse of parts in different products [6]. Such approach provides a mechanism for bringing products to market faster: by a development of robust product platform architecture with common components [7]. Commonality increases quality, prevents resource waste, decreases costs and, most importantly, decreases total development time of the product by eliminating unnecessary development steps of individual components [8]. A major commonality step is to look for parts with different designs, but the same function. This may provide an idea of possible optimization opportunities and selection of the most suitable design that can be common across a few products. After a detailed analysis of the car body shell (CBS) components in the light railways and trams, it turned out that there are parts that can be potentially common. The most interesting elements for further study were floor and roof panels. There is some literature proposing different solutions for lightweight

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floor and roof panels such as honeycomb, and sandwich composite solutions [9], [10]. In the case of aluminium CBS, extruded profiles are the most common solution. Our hypothesis is that number of profile solutions solution may be reduced and common not only across different rail vehicles, but as well buses. The majority of buses are made from steel bars welded together [11], [12]. Light rail is more shifting towards aluminum usage for structural parts. Aluminium has been used in customers vehicle construction more than twenty years, however, its use in buses has been limited. Aluminium, is expensive, joining and forming technologies make the application more difficult than steel [13]. Aluminium apart from lightweight is also non-flammable and doesn’t generate hazardous gases which make it a preferable material for applications in flammable or explosive situations in comparison to lightweight honeycomb solutions [14].

Since extruded profiles with C-rails occur in most of the aluminum platforms, when we optimize their weight and strength and make it common, we will be able to make improvements in many locations at the same time. Selected panels and interfaces were analysed by numerical simulation in order to evaluate their mechanical behaviour.

Many railway car manufacturers make their floors and roofs from a few long aluminium extruded panels that are later welded together. Such a structural assembly supports multiple equipment attached to it in a variety of ways. During CBS analysis, it turned out that those critical elements often have different designs depending on the train type within they are used. Even on one coupled vehicle, many different panels were used because of the variety of equipment. Final assembly of those panels is relatively heavy, that allows for potential weight reduction after optimization.

The key problem this research paper investigates is commonality opportunity of reusing the same design for aluminum panels in different light rail and bus applications. Long extrusion is a specific process that takes a long time to set up for final production. Commonality of the aluminum panel concept across different product could lead to decreased development and manufacturing time, and reduce cost. If a panel concept could be used across a variety of platforms, many weeks would be saved during the development phase. The same tooling could be used during manufacturing and production would be made in larger batches. That’s why tis paper present efforts that need to be undertaken in order to make parts common across different products.

2. SELECTION OF COMMON PARTS

Increasing the number of common parts not always bring desired benefits, that is why it is important to focus on execution and selection of correct parts for commonality [15]. There should be some method, rule, or criteria in order to decide which components to make common. From a commonality perspective, the components that have high design costs and require a high amount of redesign effort should be focused on first. Moreover [16] also emphasizes that commonality is not only used by mass production, but also by mass customization companies. Companies producing mass customized products fix the base product design and later on a family of variants is made. Companies that have multiple products in their product portfolio, in theory, should look for ways to reuse design information from one order to the next, but many times such opportunity is lost [17].

3. CASE STUDY

In this research a commonality methodology that allows manual search for commonality opportunities was used. This case study was conducted on the European manufacturer, which produce railway and bus products. The first step was to list all existing interfaces and CBS elements. By doing so, it was possible to select the most frequent solution. Such an approach allows for affecting the largest amount of solutions at the same time. It can be predicted that, by doing so, development time could be reduced. Extruded profiles with C-rail are widely used across all of the train platforms, including tram and light railways, as floor or roof profiles. In buses such a solution did not exist, but there is an on-going research and development of a lightweight bus, which potentially could use the same concept. Extruded profiles with C-rail have the same function, but different designs. All panels are used to support different types of equipment or passengers. C-rail solution provides a flexibility which type and size of equipment can be mounted. There are big differences profile designs in the manner of dimensioning, shapes, C-rail type's locations in relevance to a whole floor (or roof), and in relevance to the profiles inside webs. If it would be possible to select a concept that could be common, then significant reductions in development time would be achieved, as well as the reduction in manufacturing cost. Final extruded elements can take up to 40 weeks to be ready for manufacturing. Savings in a development time could give big competitive advantages.

In order to have comparable results, all of the panels were adapted to have the same height and length. The main difference between analyzed panels was the location and shape of inside webs. The first step was to create a base model of interface connections that later would be the same in all panels. This allows for the understanding of the behavior of the interface system and, further, its influence on whole panel structure. Also, it will allow using different length op panels to be used in buses and railway products. Next, panel cross-section cuts were adapted to be comparable and meshed. This step allows comparing local characteristics of different design variants. The last step was to model entire floor panels that allowed having a global perspective of panel behavior under multiple loads. When critical issues are addressed during the initial phase, then further costs of expensive testing and design changes can be reduced [18].

3.1 Initial model of panel sections with C-rail interface

The model was simplified drawing of three panels used by company and one additional panel developed in CATIA v5. The finite element method (FEM) numerical simulations were performed using the nonlinear commercial finite element software Hyper Works v12 [19]. Three dimensional mesh elements were used for this model in order to be able to observe results in all directions. All of the components were meshed with quad element walls, with no tetra mesh being used. Mesh element size was the smallest utilized in C-rail because this was the component in which failure was predicted (high stresses in C-rail corners). All materials in the model are MATS1 (defined in Hyper Works as Stress-dependent Material Definition); C-rail and Profile are aluminium while the bolt was from stainless steel. Material properties were imported from a table of aluminum 6xxx series, in order to include the stress-strain curve, and were assigned to components.

The first model created was a squared panel with vertical webs and the initial model of a C-rail interface. The second design was a panel widely used among different railway platforms based on triangulations of webs (inside part of extruded profile). The third design was a variation of triangulation in which webs are speeded apart in order to join with the flange (horizontal parts of panels) in the location where the C-rail begins. The fourth design used a three web panel with an inside C-rail. All of the design variants and previously meshed models of the four profile sections used for the study can be seen in Figure 1.

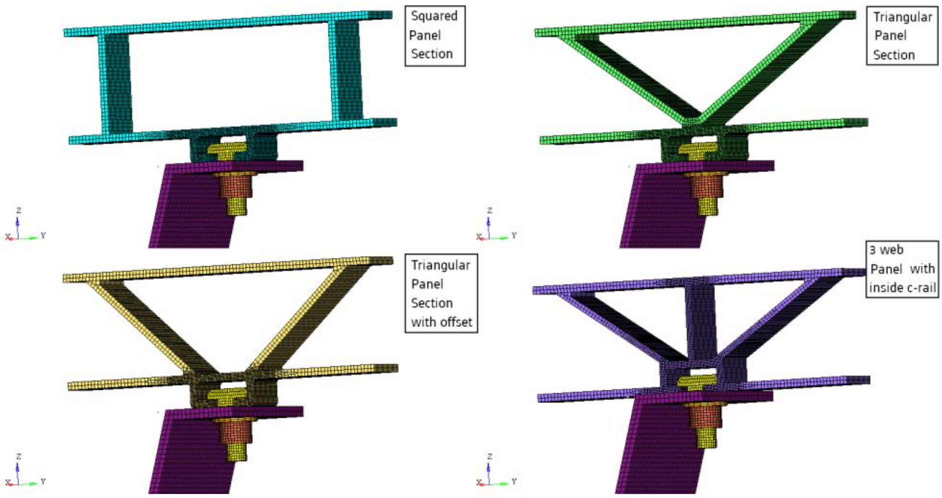

Figure 1 Meshed models of four profile sections used for study

In order to get comparable results from the panels, global dimensions were adapted so that all models had the same height, (along the z-axis), width (along the x-axis) and length (along the y-axis), without taking into consideration the C-rail. Boundary condition BC1 was shifted to the end of the panels along the x-axis. The solution with the inside C-rail was a potentially interesting solution in terms of small dimensions, the possibility to increase cabin volume. Moreover inside C-rail leaves the flat surface, which increases the flexibility of use.

3.2 Simulation of floor panels made from profiles with C-rails

As a last step in the panel analysis, a simulation of assemblies made from panels with an inside C-rail was conducted. Four panel assembly models based on the panels presented in figure 2 were made, but with extended width and length now close to the dimension of the average panels used in vehicles. Those panels were used not only for further simulation, but also for weight comparisons. Figure 2 presents an example of a triangular panel with offset, which is one of five simulated panels.

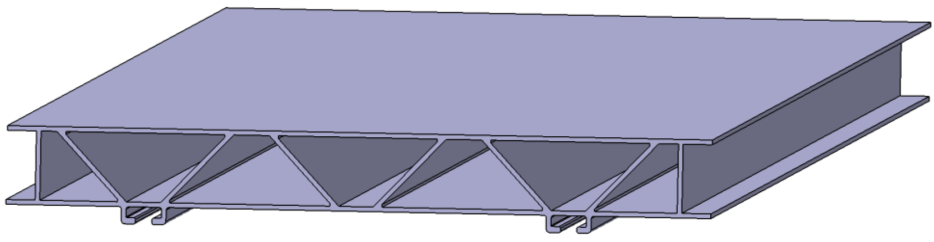

Figure 2 CAD model of floor panel used for weight calculation, and after meshing for floor simulation

Usually, a train floor is made from 5 panels. The overall dimensions of the train floor depends on the model but, for the simulation, 9 meters (length) x 2 meters (width) x 50 mm (height), subject to the boundary conditions and the distributed pressure load with 6 persons (each 70 kg) / m^2. Such dimensions are actually in use in railway application and potentially allow usage of the same panels in bus application. To maintain symmetry conditions, only half of the width was modeled, using two and a half panels. In order to decrease calculation time, 2-dimensional mesh and shell elements, in order to assign thickness to the web and flange, were used.

3.3 Results

A file generated by HyperMesh and later modified was uploaded to Optistruct, which is a solver program. Among many possible outputs, displacement, contact pressure, and stresses were further analysed. The first analysis was concerned in order to check under which load would the interface start to lose tightness, which will lead to a loose connection. The gap opening between C-rail and profile represents the loosening of the interface connection. The load applied on the interface was gradually increased until it reached the point in which gap opening occurred. Gap opening was measured in micrometres, a very small unit of measure, but it represents the initial phase of opening, or loss of contact pressure, which is proof that the connection will start losing tightness at that particular point. Figure 3 presents the area in which gap opening was measured between the C-rail and profile. The locations of the measuring points were on the side of the applied load below the T-bolt head.

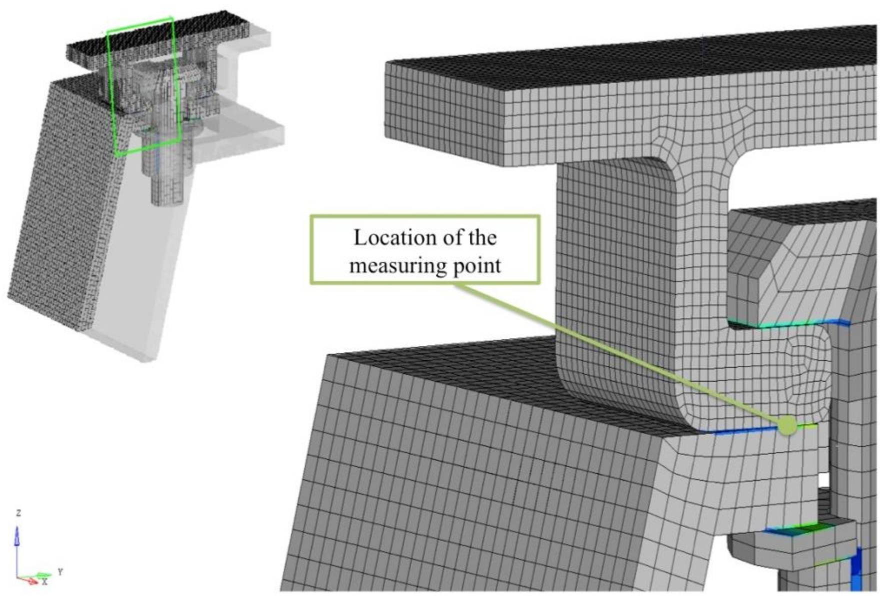

Figure 3 Global and a detail view on the area in which gap opening was measured. The square adjacent to the global view indicates the area selected for the detail view.

Such an interface can withstand loads up to 1288 [N] load, which comes from a multiplication of 3g by 175kg and dividing it among 4 supports. The maximum value of stresses does not change significantly after applying only pretension and adding load, but the locations of stress concentrations change. It is possible to observe that compressive stresses are higher in C-rail, and tension stresses are greater in T-bolt.

Results show that under the same load, all panels with an outside C-rail have the same gap opening of 0.001 [mm]. Most interesting is the fact that the panel with an inside

C-rail produced a greater gap opening of 0.003 [mm]. Panels with an inside C-rail have the least tight connection, and it is possible that the load interface will become loose.

The second result analyzed was displacement under the same load. Squared panels have the greatest displacement in the Z-direction among the simulated panels. The original triangular panel and the triangular panel with offside exhibit a very similar behavior. The profile with an inside C-rail has the smallest displacement and the best flatness of the top flange surface. This panel is the stiffest solution, which explains why the gap opening is greater under the same load than in panels with an outside C-rail. In panels with an inside C-rail, the mounting profile shows deformation because the panel is not "working." In other words, the panel elements are not deforming. For panels with outside C-rail flanges and webs, all components absorb part of the load by their deformation. This allows the outside C-rail to be in longer contact with the profile.

Comparison of ZZ stresses in four analyzed panels is presented in Figure 4. A T-bolt was used in all calculations, but it is removed from the visualizations in order to present the stresses in the C-rails. In all four cases, the highest stress concentration is in the C-rail, but the magnitude and exact locations vary depending on the panel type. In the case of the squared profile, there are also high stresses in the panel web. This is why, in Figure , we can see a larger view on the squared profile and a more detail view on the C-rail in the other simulations. In the case of the triangular profile, there are also stresses in the bottom joint between the web and flange, which can be seen in Figure 4.

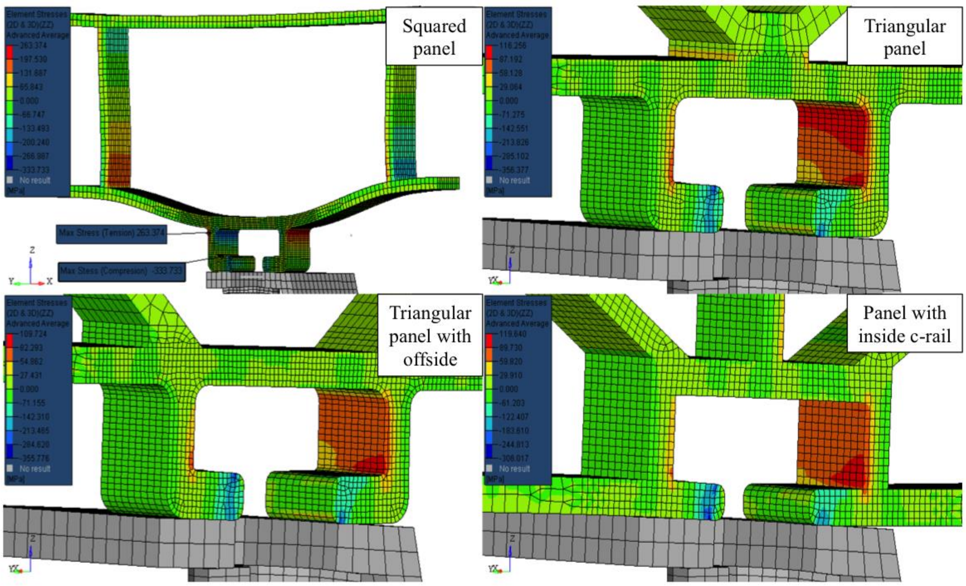

Figure 4 Comparison of ZZ stresses in four analysed panels. T-bolt used in simulation, but removed for clarity of view

Highest negative stresses (compressive) can be found in the triangular panel and in the triangular panel with offside in the place where the T-bolt is located. In all cases, the value of compressive stress exceeded the plastic limit as was seen in the primary model. Highest positive stresses (tension) can be found in the squared panel, and it is the only model in which tension stress exceeds the plastic limit, thus causing permanent deformation.

The last part of the results involves whole panel simulations. Figure 5 presents results of the displacement of half of the floor made from panels: the top floor is made from a panel with an inside C-rail with 3 webs and the bottom floor is made from a panel with a triangular web with offset. The profile with inside C-rails has displacement which is not acceptable according to initial study requirements. Because of its properties, panels with an inside C-rail are not advised to be used in an underframe. This solution is only advised for roof interfaces with lightweight equipment. On the roof, the requirement is to withstand equipment weight and support the weight of one person with a toolbox. Floors made from panels with an outside C-rail or triangular webs with offside passed deflection constraints which show that both panels can be used as underframes and roofs.

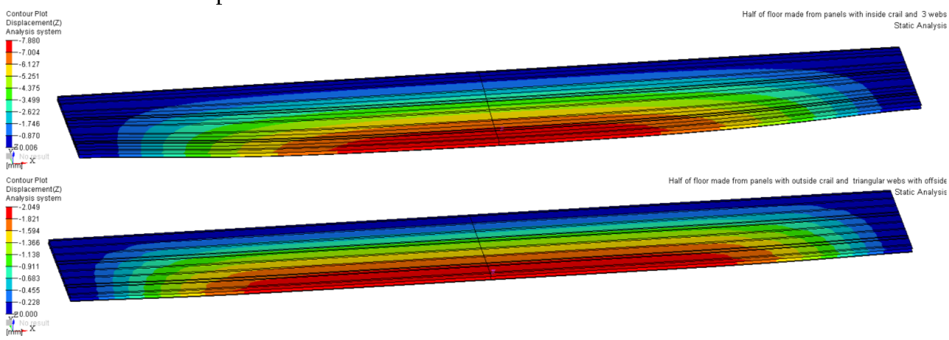

Figure 5 Half of floor made from panels: top) inside C-rail with 3 webs, bottom) triangular web with offset

Summarized in Table 1 are the most important results which determine the technical parameters of the floors made from different type of panels.

Table 1 Summary of most important technical parameters

Panel type	Stress (ZZ) in C-rail and Bolt [MPa]	C-rail Displacement [mm]	Floor Deflection [mm]	Max. weight applied on C-rail (4 bolts) under 3g [kg]	Mass of one floor panel [kg]
Squared profile	263,37 -333,73	0 -1,81	2.20	175	89,18
Triangular profile	116,26 -356,38	0,16 -0,20	2.04	175	113,26
Triangular profile with offset	109,72 -355,78	0,18 -0,23	2.05	175	106,87
Inside C-rail with 3 webs	119,64 -306,02	0,02 -0,17	7.88	65	105,55
Inside C-rail with 2 webs	115,05 -306,51	0,03 -0,24	7.99	65	101,32

3.4 Additional inputs for commonality decision

Technical inputs are critical when selecting the best solution, but the final cost is also highly weighted. Cost information was difficult to obtain since it is very due to the sensitive nature of competitive data. Generally the cost of aluminium extruded panels is determined by raw material cost, extrusion cost, and the necessity of further processing (machining, welding). The least expensive solution turned out to be the squared profile, and the most expensive was the triangular profile. The optimised solution was approximately 10 present cheaper than the widely used triangular solution. Another factor, which highly influences panel selection, is industrialization. In this study, the most influential elements included lead time, the number of parts eliminated, customization feasibility, failure inspection and rework rates, how often the solution is currently utilized, and material waste.

Many times it happens that in different vehicles there is different equipment and thus different panel designs. Such a situation results in long development and manufacturing time for panels. This scenario will be avoided by introducing common panels. This solution could in theory decrease development time to 37 weeks from 120 needed for different panels currently used (extrusion + welding) and manufacturing would be faster because of usage of the same tooling.

The possibility of customization is also an important factor in determining which panel is the preferred commonality option. Customization represents the possibility of adding other equipment in a different location than C-rail. In cases when other equipment added, a squared profile may not withstand the new load. This can be caused not only by heavier equipment but also by the more critical load location between two webs. In the case of triangulation, the location of new added C-rails will possibly also decrease the panel strength, but in a smaller magnitude.

When a particular panel has already been in use, there is a potential return of experience about it in all lifecycle steps. This means it will be easier to do all the steps again even with small modifications. In the case of a new profile, even if it is theoretically better, there is a risk that in one of the project steps unexpected problems will be found. Different types of insulation are frequently applied on floor and roof panels. In company products, the thickness of insulation is similar to the height of the outside C-rail which allows ease of assembly, assures lack of interference, and requires no additional modifications in insulation. In the case of an inside C-rail, there may need to be an adjustment of the insulation, and there is the possibility of interference with assembly components.

4. DISCUSSION

Based on the analysis of displacement and stress concentration, it can be concluded that squared profile is the least preferable solution. The triangular profile also has a stress concentration in the area of the joint between the web and flange, but its magnitude is relatively low. Gap opening analysis shows that panels with an inside C-rail can potentially have problems with loosening of the interface. For floor creation, “Triangular profile with offset” is the preferred option for equipment which weighs between 65 and 175kg (divided among 4 screws), mostly due to a good weight to performance ratio. Under this load condition, squared profile has high stresses and C-rail displacement. The original triangular profile is too heavy, and it has stress concentration in more critical areas than the triangular panel with offside. Panels with an inside C-rails are not allowed to be used under heavy load because of tightness problems. That is why in above table, the maximum weight applied on the C-rail is only 65kg. In addition, even for lighter equipment, this solution is prohibited to be used in an underframe because of the large floor deflection. For smaller weight equipment (less than 65kg mounted on four bolts), inside C-rail or squared profile could be an option on the roof. An inside C-rail with 3 webs has the additional benefit that the top flange is less deformed under the load than in other solutions, which in some cases could be beneficial. Depending on the actual location of the implementation of the panel, additional constraints and restrictions of different panels will determine the preferable option.

Taking into considerations all the technical inputs, additional inside company inputs as well as general market trends it was decided to make the triangular panel with offset common across different products. Since the exact requirements are only known for the rail vehicle and not for buses further work is necessary, but general design concept, and manufacturing type may be common. Lightweight design was preferable option, but as well it need to withstand loads coming from potential equipment such as batteries or other heavy components.

5. CONCLUSIONS

Finite element analysis turned out to be a suitable method of initial selection of commonality opportunities in which strength to weight ratio is critical. Based on the analysis, panels with an inside C-rail, although having many theoretical benefits, was ruled out as an under frame component. It is still possible to use it, as a roof component since equipment there in many cases is lighter and interface failure is less critical. Best technical performances, as well as additional external and internal benefits, were achieved with the triangular panel with offset. This panel was created during the study as a variation of the most frequently used triangular solution. The newly developed panel weighs less than the original that is used by a variety of manufacturers. Moreover, results show that stresses are smaller and in less critical locations than in the original design. This article provides proof that finite element analysis is a good initial step for commonality affords, which at the same time can lead to optimization of existing components. Moreover it presents an opportunity for companies producing railway and road vehicles to look for other commonality opportunities. Currently, there is a small number of shared components, but if future work will focus on part reuse it is possible to achieve higher commonality level. This approach can potentially save resources and improve efforts for developing new concepts or modifications are made. As well as improve manufacturing, purchasing and decrease price of parts. All of those benefits together may allow companies to introduce lightweight products at reasonable cost for end used causing a wide spread of new environmentally friendly solutions.

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INVESTIGATION OF THE DRIVER - VEHICLE DYNAMICS

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UDC:629.1;519.6

ABSTRACT: This paper reviews the current problems in the development of vehicle design and its optimal adaptation to drivers in terms of safety driving. Summarizes the characteristic mathematical model to describe the driver control. On suitable models discussed the dynamics and own vehicle instability in an open loop. As well as the interaction of vehicle dynamics and parameters of sight field of the driver are considered. Control system driver-vehicle-environment is modeled. It is designed optimal LQG regulator in parallel and in series-parallel contours with contour effects drivers. The results of research indicate instability of the vehicle in open loop, the effects of the stabilization system achieved by driver. In addition, the application of the optimal controller in this study served as the basis of forming criteria for evaluating vehicle dynamics with respect to driver control.

KEY WORDS: vehicle, driver, model, Kalman, estimator

ISTRAŽIVANJE DINAMIKE VOZAČ-VOZILO

REZIME: Ovaj rad razmatra aktuelne probleme u razvoju dizajna vozila i njegovo optimalno prilagođavanje vozaču u pogledu sigurnosti vožnje. Sumira karakterističan matematički model kako bi opisao kontrolu vozača. Na pogodnim modelima diskutovana je dinamika i nestabilnost vozila u otvorenoj petlji. Uzete su u obzir i interakcija dinamike vozila i parametara vidnog polja vozača. Sistem kontrole vozač-vozilo-okruženje je modelirano. Dizajniran je optimalan LQG regulator u paralelnim i serijsko-paralelnim konturama sa konturom efekta vozača. Rezultati istraživanja ukazuju na nestabilnost vozila u otvorenoj petlji, i efekte sistema stabilizacije koji se postižu od strane vozača. Onda se efekat optimalnog kontrolera kada je u pitanju poboljšanje ponašanja celokupnog sistema. Pored toga, primena optimalnog kontrolera u ovoj studiji poslužila je kao osnova za formiranje kriterijuma vrednovanja dinamike vozila u pogledu kontrole vozača.

KLJUČNE REČI: vozilo, vozač, model, Kalman, procenitelj

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INTRODUCTION

Development and construction of modern motor vehicles follow strict requirements to adapt their properties to regulatory - technical and psycho-physiological abilities of drivers. In this regard, it should be pointed out is always current problems of comfort, handling, movement stability, which is reflected in the safety movement. So far, published a number of papers from this issue and made significant efforts to better understand the behavior of drivers in different modes and conditions of movement. In doing so, they used different approaches and methods of research. One of the most commonly used approach to observe the vehicle as an object of control, as part of the control system, the driver-vehicle-environment in which the driver acts as a regulator, [1], [2], [3], [4], [5]. To this end have been developed appropriate mathematical models to describe of the driver control effects. Depending on the control tasks, the structures of these models are single loop or multi loop. Viewing the typical driver models, their relations to the vehicle and the environment, as well as one's own approach to research control system, driver-vehicle-environment, in terms of evaluation and improvement of its performance are presented in the following sections of this paper.

DRIVER MODELS

Conduct research pilot spacecraft started 1940 - these, in terms of modeling their effects, were transferred during 1960 - the study of the behavior of drivers of motor vehicles. During such periods, and later, an important role was played by the concept of quasi - linear model, shown expression (1)

Quasi-linear compensatory model of the driver [4], consists of a describing function component with parameters which depend on the system and driving situation, a set of adjusting elements and an additive remnant,

$$F_D = K\frac{1+T_L s}{1+T_I s}e^{-s(\tau+T_N)} \cong K\frac{e^{-\tau s}}{1+T_N s}\frac{1+T_L s}{1+T_I s} \qquad (1)$$

where: τ - time delay, T_N – the neuromuscular system time lag, $(T_L j\omega+1)$ / $(T_I j\omega+1)$ – equalization characteristic, K – gain factor. The last two characteristics are the major adaptive elements of the driver which allow him to control many different vehicle dynamics. Particularly rational and efficient variant of this model is the so-called, “crossover” model for driver – vehicle open – loop system in region of the crossover frequency.

Generally, drivers use multiple information as input for controlling the vehicle. Good multi-loop system structures are those which no require the driver equalization, for

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example, only gain plus time delay in each of the loops. But driver dynamics as a multi-input system is often approximated by equivalent a single loop system. In the study [9],[11] driver dynamics is described by equivalent closed – loop system which comprising vehicle lateral position and yaw angle feedback loops from corresponding multiple loop. This model is useful to examine the vehicle with 2WS steering system which shows a close correlation between its yaw angle and lateral position response,

The driver block, $F_{D\varepsilon}$, in inner control loop includes, according to (1):

$$F_{D\varepsilon} = K_{\varepsilon}\,(T_L\, j\omega + 1)e^{-j\omega\tau} \qquad (2)$$

where is, K_{ε} – gain, $T_L j\omega + 1$ – anticipation term for outer loop compensation time lag in vehicle lateral response, τ –time delay. The driver block F_{Dy} is a pure gain feedback for the lateral vehicle deviation. This driver model structure can be suitable base to study changes in driver steering control with learning [9].

Typical transformation multi-loops to single control loop system with the driver in-the-loop can be realized by means driver model concept based on the ″ vehicle inertial lateral deviation advanced in time ″. The model structure in this case assumes that the driver operates on an estimated or projected lateral deviation error. The perceptual preview time, as relation of preview distance, L (look-ahead distance) and vehicle forward speed, results in a pure lead equalization term in the effective vehicle dynamics. Equivalent to ″ lateral deviation advanced in time ″, as distance between sight point S_i, and aim point A_i, is angular deviation, γ as sum of heading angle deviation Δy_{ε} and weighted lateral deviation, Δy, in figure 1:

$$\gamma = K_y \Delta y + \Delta y_{\varepsilon} \qquad (3)$$

This driver model concept represents high degree driver perceptual efficiency during driving in the sight field. Instead of perceiving separately the lane position and heading errors in multi-loop control system, perceives only the composite angular error or advanced (projected) lateral deviation in single-loop control system [2], figure 1.

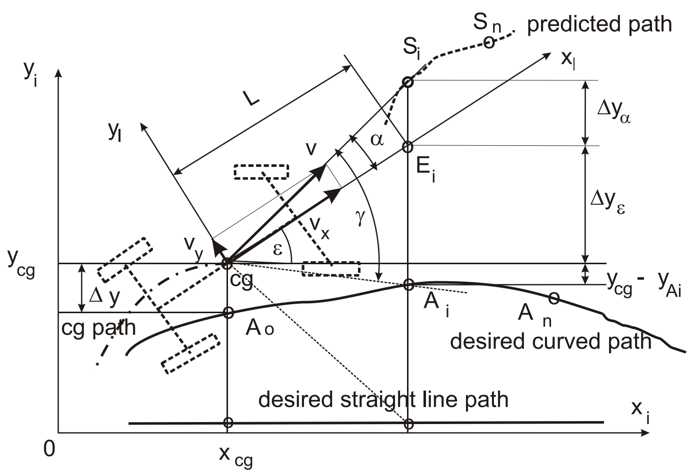


Figure 1 Vehicle position and driver sight field.

Driver can improve the system control performance by using derived path command information in visual field and operating in anticipatory mode. That is, driver can perform the steering task hierarchically into two levels, guidance and stabilization, [6], [7], [8]. In the case of driving into a curve, driver perceives desired path curvature and responds to it an anticipatory open – loop control mode with a part of total necessary steering wheel angle. Based on the perceived path error in closed – loop compensatory mode the driver generates a correcting steering wheel angle.

MODEL OF THE DRIVER - VEHICLE – ENVIRONMENT SYSTEM

Geometric diagrams of a vehicle model following a desired straight line path or a desired curved path, to investigation in this paper, are given in figure 1. As examples are given, single and double lane change, obstacle avoidance, straight line driving: against crosswind, with brake pull, on uneven road and so on. The projection of vehicle center gravity deviation on the look – ahead distance of driver, L, with sight point S_i, in direction of vehicle velocity vector v, is given as distance between points S_i and A_i, for curved path driving,

$$\Delta Y = y_{cg} - y_{Ai} + \Delta y_{\varepsilon} + \Delta y_{\alpha} \cong y_{cg} - y_{Ai} + L\varepsilon + L\alpha \tag{4}$$

and for straight line path driving as,

$$\Delta Y = y_{cg} + \Delta y_{\varepsilon} + \Delta y_{\alpha} \cong \Delta y + L\varepsilon + L\alpha, \qquad y_{Ai} = 0, \quad \Delta y = y_{cg}, \tag{5}$$

where is, L – look – ahead distance of driver, y_{cg}, y_{Ai}, Δy, Δy_{ε}, Δy_{α} – the parts of advanced deviation of vehicle ΔY, caused by vehicle center gravity coordinate, aim point A_i coordinate, vehicle center gravity lateral deviation, vehicle heading angle ε, vehicle side – slip angle, α, respectively.

Vehicle dynamics state space model is selected from presentation of vehicle – sight field interaction in figure 1 and given as follows,

$$\dot{x} = Ax + Bu, \qquad z = Cx \tag{6}$$

where, x = [y, y′, ε, ε′], is the vehicle state variables vector , u = [β, M], is the input vector determined by driver. The output vector, z, can be defined in different forms as a linear combination of the state variables depending on the chosen form of matrix C.

For a description of the regulatory activities of the driver and the implementation of its model in the model system, vehicle - field, shown in figure 1, we started from the concept quasi-linear models of the human operator given in [4], and detailed in [5]. Model driver is presented in the time domain in the form of differential equations of second order,

$$\beta(t) + T_1\dot{\beta}(t) + T_2\ddot{\beta}(t) = \sum_{i=1}^{n} A_i x_i(t - T_i) \tag{7}$$

where, β - turning the steering wheel angle, T_1, T_2 - time constant, as the characteristics of the neuromuscular dynamics of the driver, and A_i - coefficients evaluating information from the driver, T_i - delay the receipt of certain information. In accordance with the physical model, the vehicle - sight field, in figure 1, and the corresponding mathematical models presented by expressions (4), (5), (6) can be specified information to the driver, xi (t - T_i), on the basis of state variables contained in the vector, [x] = [y, y′, ε, ε′], then the variables in the vector output, [z], the variables of the input vector, u = [β, M], and combinations thereof. In this regard, the overall display driver model, given by (7) is reduced to concrete form,

$$\beta(t)+T_1\dot{\beta}(t)+T_2\ddot{\beta}(t)=A_y y\left(t-T_y\right)+A_{\dot{y}}\dot{y}\left(t-T_{\dot{y}}\right)+A_\varepsilon \varepsilon\left(t-T_\varepsilon\right)+A_{\dot{\varepsilon}}\dot{\varepsilon}\left(t-T_{\dot{\varepsilon}}\right) \quad (8)$$

Using the relation of the vehicle state variables,

$$\ddot{y}=v_x\left(\dot{\varepsilon}+\dot{\alpha}\right) \quad (9)$$

where, d^2y/dt^2 - lateral acceleration of the vehicle, v_x - longitudinal component of the vehicle velocity, dε/dt - angular velocity of turning the vehicle around its vertical axis, dα/dt - angular velocity of swimming vehicles.

It can be the structure of the base model of the driver (8), as a multi-variable controller, converted on the structure model, based on the concept of "vehicle deviation advanced in time". Taking into account the model of the visual field (4), (5) and reducing the neuromuscular dynamics of the driver on the model of the first order, we get the resulting model driver in the equivalent single - input, single - output system as part of a complex simulation - estimation system, shown in figure 2.

$$F_D(s)=\frac{\beta(s)}{y_{ad}(s)}=K\frac{e^{-T_d s}}{1+T_1 s}\left(1+\frac{L}{v_x}s\right), \qquad T_a=L/v_x \quad (10)$$

In this case, the time constant, $T_a = L/v_x$, is the quantity ratio of physical variables, the distance of driver sight point, L, and longitudinal components of the vehicle velocity, v_x in the zone extended vehicle dynamics in the visual field, rather than the result generated by predictive control of driver . In this way, its regulatory activity is much easier in the visual field with meaningful visual information, YΔ, for the strategy driving the "single point sight" or YiΔ, i = 1, for the strategy driving the "multi sight points."

With this approach, the formation of driver model in its structure included two state variables, according to the expressions (5), (6). The direct and bearing in mind the relation (9), two state variables indirect, therefore, the total vector of state variables for the adopted model vehicles. This system formed a closed contour, as shown in figure 2 and conducted research in this paper, in a sense, 1) checking the stability of the vehicle in an open contour, 2) study driver behavior in terms of stability of the system in a closed contour, 3) establishment of criteria for assessing the dynamics of vehicles in terms of the required performance and ease of control. In order to display theoretical assumptions as a basis for solving the above-defined segment of the third survey, the establishment of criteria for the evaluation of vehicle dynamics, it is presumed that a well-trained, experienced and motivated driver performs its task in an optimal way in terms of required system performance and minimal fatigue at operation of the vehicle. In this sense, the closed control system, the driver - vehicle - environment, has been expanded with two LQGR1, LQGR2, and controller, connected to the system block diagram as shown in figure 2. In addition, the regulator LQGR1 is placed in parallel to driver control feedback, therefore, can completely replace its effect in some cases research, and its structure is further shown in figure 2, as the primary regulator. The secondary regulator, LQGR2, is set parallel to the subsystem of the steering mechanism - the rear steering wheels and can be alternatively coupled in series with the driver.

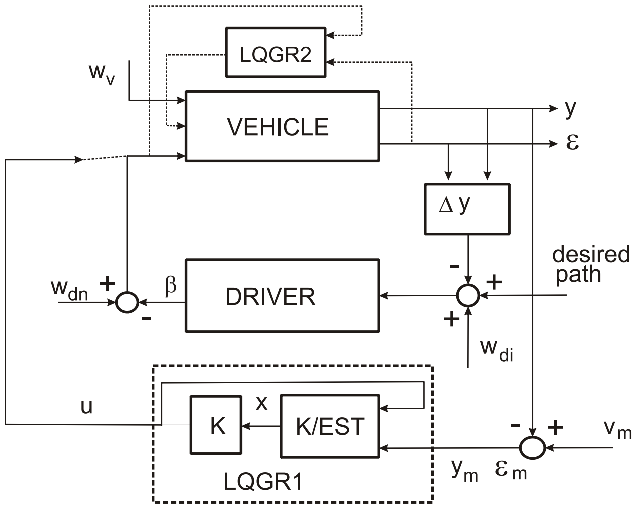


Figure 2 The block diagram of closed loop system, driver – vehicle – sight field - regulators

Design of controllers shown in the block diagram in figure 2, was carried out in two stages. The first phase was chosen concept of optimal control for a given system and set requirements. In the second phase, to define the conditions of implementation of the controller in the system depending on the number of state variables system, their specificity, the difficulty of measurement, measurement errors, the relation between the state variables and inputs, outputs and other impacts in the system and the environment. In this sense, the basis for the effective functioning of the optimal controller K, is the Kalman estimator K / EST, included in this structure, in block LQGR1 on figure 2.

The optimal control concept for both regulators is formulated as a problem to minimize a functional of general form [10]:

$$J = \frac{1}{2} z^T (t_f) S z(t_f) + \frac{1}{2} \int_{t_o}^{t_f} \left[z^T (t) Q(t) z(t) + u^T (t) R(t) u(t) \right] dt \tag{11}$$

where Q, R, S are symmetric weighting matrices, u(t) input, z(t) output variables. With Hamilton – Jacobi equation:

$$H\left[z(t), u(t), \lambda(t), t\right] = \frac{1}{2} z^T Q z + \frac{1}{2} u^T R u + \lambda^T A z + \lambda^T B u \tag{12}$$

and by used maximum principle:

$$\begin{aligned} \frac{\partial H}{\partial u} &= 0 = R(t) u(t) + B^T (t) \lambda(t) \\ \frac{\partial H}{\partial z} &= -\dot{\lambda} = Q(t) z(t) + A^T (t) \lambda(t) \end{aligned} \tag{13}$$

at constraint condition:

$$\lambda(t_f) = \frac{\partial\theta}{\partial z(t_f)} = Sz(t_f) \quad (14)$$

needed solution of (9) is :

$$u(t) = -R^{-1}(t)B^T(t)\lambda(t) \quad (15)$$

with presumed partial solution:

$$\lambda(t) = P(t)z(t) \quad (16)$$

where P(t) is the solution of Riccati matrix equation:

$$\dot{P} = -P(t)A(t) - A^T(t)P(t) + P(t)B(t)R^{-1}(t)B^T(t)P(t) - Q(t) \quad (17)$$

by constraint condition $P(t_f) = S$.

With P(t) solution from equation (17) can be synthesized optimal controller structure in time domain:

$$u(t) = K(t)z(t) = -R^{-1}(t)B^T(t)P(t)z(t) \quad (18)$$

The end result of this mathematical model of the optimal control law (18) carried out the structure and parameters of the block, K in figure 2. The structure and parameters of Kalman estimator, K / EST, determined based on the equation of state Kalman filter are given in the following form,

$$\frac{d\hat{x}}{dt} = A\hat{x} + Bu + L(\bar{z} - C\hat{x} - Du) \quad (19)$$

With defined of the process noise and the measurement noise covariance data, E (ww^T), E (ww^T) respectively, and the expression (19), was formed in the state space model of Kalman estimator, as follows, as a system with two vector inputs and one output vector,

$$\dot{x} = Ax + Bu + Gu, \qquad \bar{z} = Cx + Du + Hw + v \quad (20)$$

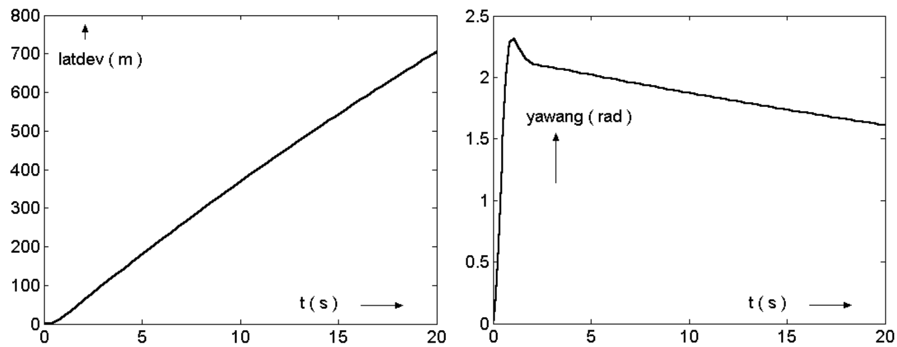
on the basis of determined covariance matrices and estimator gain, obtained as solutions of algebraic Riccati equations, is synthesized the optimal LQG controller, as the coupling of components, K and K / EST, with the state space the equation, 21,

$$\frac{d\hat{x}}{dt} = \left[A - LC - (B - LD)K\right]\hat{x} + L\bar{z}, \quad u = -K\hat{x} \quad (21)$$

In this paper optimization control problem is solved with formed algorithm from equation (6), (10) and from (11) to (18) for defined control task, vehicle and driver. The results of the Riccati matrix equation solutions are used of line in simulation procedure. Real and optimal vehicle control for above in text mentioned research segments are examined on the example a typical passenger car and some results presented in next chapter.

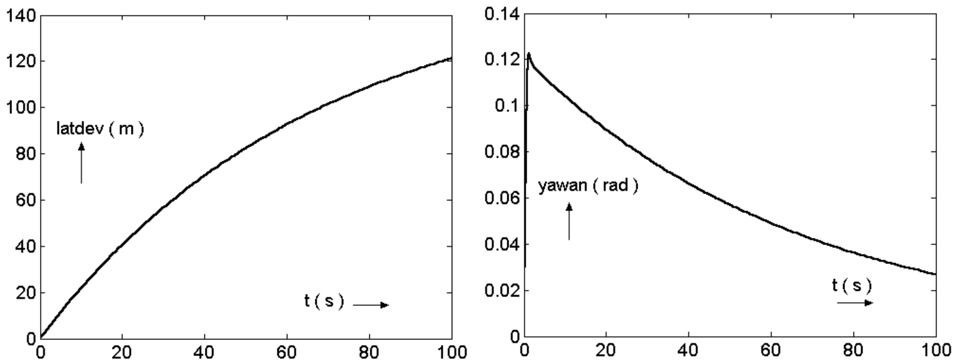
RESEARCH RESULTS

The research results are shown in figures 3 to 10. Figure 3a, b, shows the time history of the vehicle lateral deviation and angular deviation from desired straight line path at constant speed of 70 km/h and by impulse disturbance over front steering wheels. These results illustrate an example of vehicle unstable motion. Namely, after an impulse at zero initial time the vehicle lateral deviation in figure 3a, increases progressively with time. Similar behavior vehicle exhibits by impulse lateral disturbance, in figure 4a, but with different curve slope and settling time of the transient process. Also, the time history of the vehicle state variables, presented in figure 3, 4, can be used as indicators of vehicle instability in time domain. The equivalents of these indicators in frequency domain are roots of vehicle system matrix A, (6), presented in figure 5a, as poles chart. The real part of each pole is an indicator of vehicle (un)stability , depending of sign (+) - , respectively, while the imaginary part indicates oscillating behavior of the vehicle state variable.



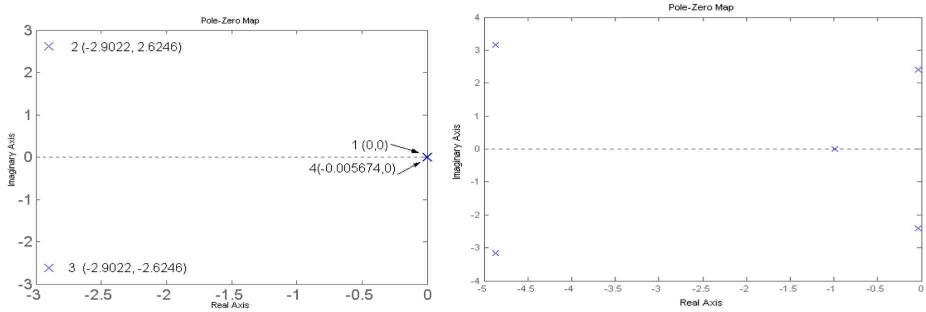
a) *b)*

Figure 3 The time history of the vehicle lateral, a), and angular deviation, b), from desired path during impulse excitation over the steering wheel and vehicle speed of 70 km/h



a) *b)*

Figure 4 The time history of the vehicle lateral deviation a) and angular deviation b), from desired path during lateral impulse excitation and vehicle speed of 70 km/h. a/Δy, b $\Delta \varepsilon$, (according to figure 1)



a) *b)*

Figure 5 Poles chart of a) vehicle lateral dynamics model, b) system driver – vehicle – sight field model

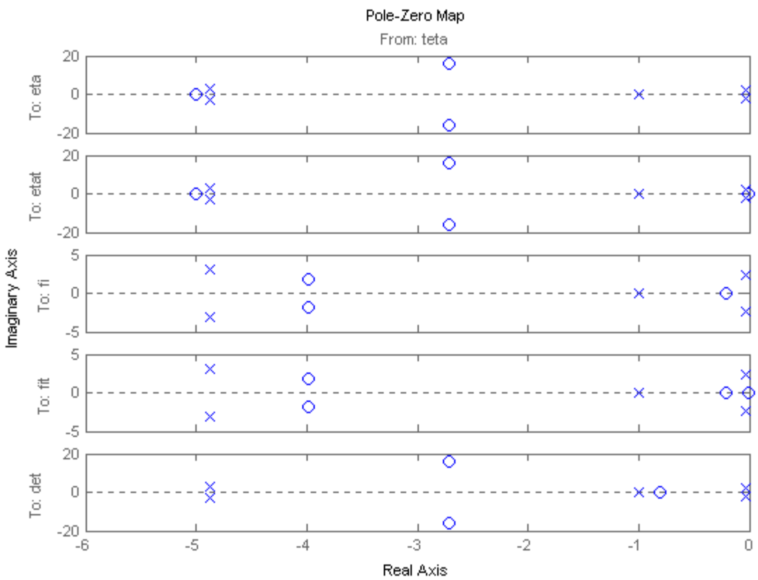


Figure 6 Pole – Zero Map for system driver – vehicle – sight field with five state variables, marked for top to bottom: y, dy/dt, ε, dε/dt, β, respectively, according to figure 1

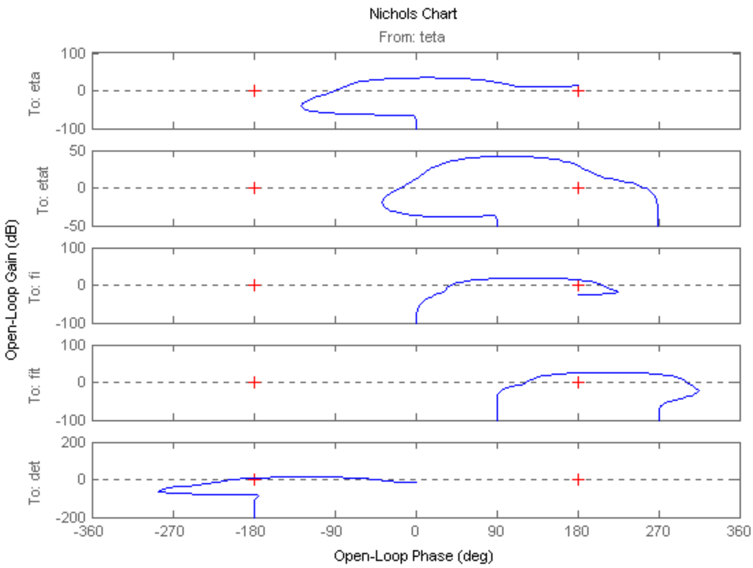


Figure 7 System open –loop gain versa open-loop phase, input ΔY, from (5), output, for top to bottom: y, dy/dt, ε, dε/dt, β, respectively, according to figure 1

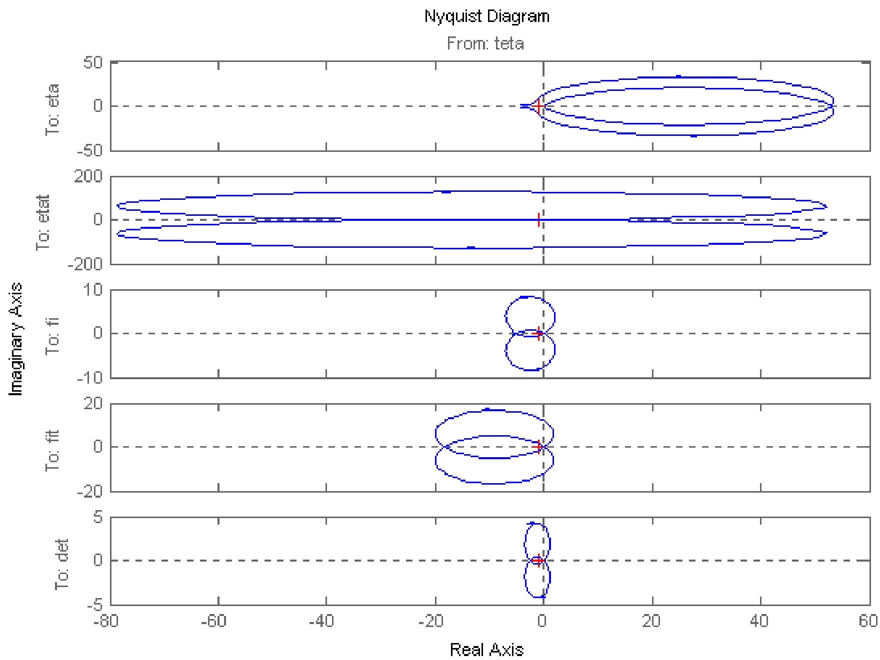
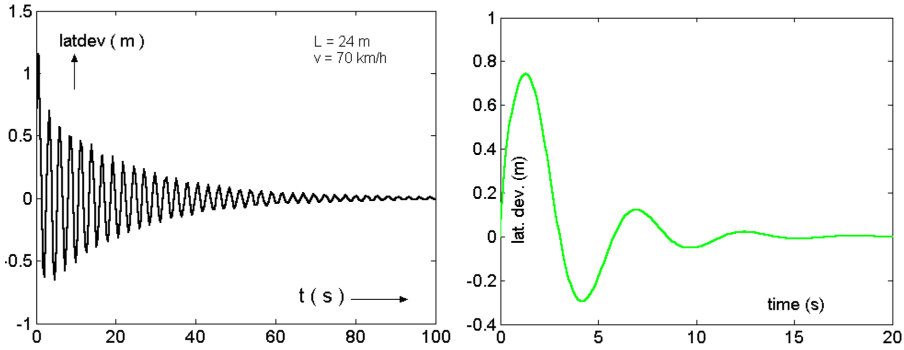
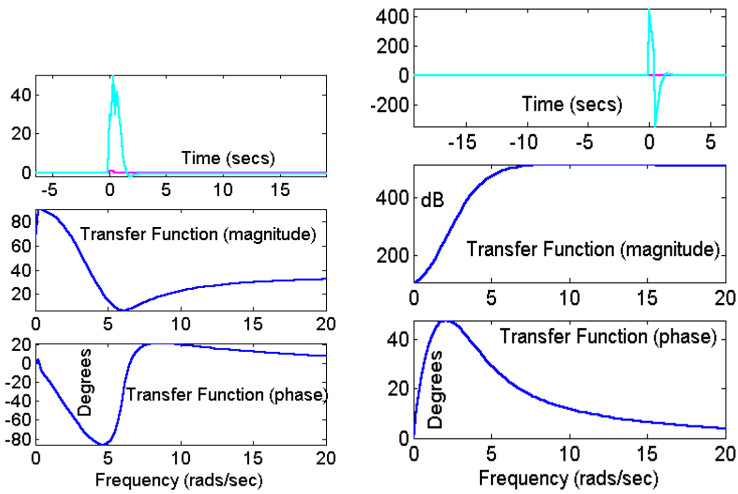


Figure 8 System polar plots, input ΔY, from (5), output, for top to bottom: y, dy/dt, ε, dε/dt, β, respectively, according to figure 1



a) b)

Figure 9 The time history of the vehicle lateral deviation from desired path during lateral impulse excitation of, a) 5m/s, b) 2 m/s, at longitudinal vehicle speed of 70 km/h and distance of driver sight point of 24 m



a) b)

Figure 10 Vehicle transfer function , a) input steering wheel angle, output lateral acceleration, b) input steering wheel angle, output, advanced lateral deviation, for sight point distance of 24m

The pole locations in figure 5a indicate two critical poles, marked with numbers 1 and 4, which are caused unstable motion according to figure 3 and 4.

The results in figure 5b, shown that driver control action improve system performance with respect to stability. The system, driver – vehicle sight field has now five poles, also, one more than vehicle subsystem in open loop, and all poles have negative real parts what indicate stable motion. This fact confirm results in figure 9, presented as time history of the vehicle lateral deviation from desired straight line path at two levels lateral impulse disturbance, a) 5m/s, b) 2m/s, longitudinal speed of 70 km/h, sight point distance of 24 m and by optimal set of driver model parameters, (10). In this case, the change of the vehicle lateral deviation indicates the transient, well damped, stable process, whose parameters depend of the lateral disturbance intensity.

On the basis obtained system pole – zero distribution, in figure 6, are formed typical indicators of system behavior in frequency domain shown in figure 7, as system open loop gain versa open loop phase, so-called Nichols chart and in figure 7, as polar diagram with coordinates: complex transfer function as vector versa phase angle as scalar and circular frequency as parameter, also, presentation so – called Nyquist diagram. These graphs shown five typical modes of system transfer function according to chosen vehicle state variables, vector [x] in model (6), plus added state variable of steering wheel angle, and defined input of » advanced vehicle deviation«. With graphs presented in figure 7 and 8, are functional connected graphs shown in figure 10, as relation magnitude and phase of circular frequency.

The further improvement of the system performance can be achieved by using implemented LQG regulator, according to block diagram in figure 2, and given algorithm, from (11) to (21). But in this paper, the role of the optimal regulator is used for the development of assessment criteria of vehicle dynamics. In this sense, according to a given algorithm are identified the optimal control laws and thus demands that the dynamics of the vehicle sets to driver as a regulator. As an illustrative example are shown the results of this segment of the research for the two speeds of the vehicle, of 70 and 90 km/h and a full format of the vehicle state variables in the open loop, according to equation (18), as follows,

$$\begin{aligned} u(t) &= K * z(t) = 0.7071y + 0.5938\dot{y} + 3.5095\varepsilon + 0.4285\dot{\varepsilon}, \qquad at \quad 70km/h \\ u(t) &= K * z(t) = 0.7071y + 0.6202\dot{y} + 3.9077\varepsilon + 0.4278\dot{\varepsilon}, \qquad at \quad 90km/h \end{aligned} \tag{22}$$

The gain factors identified in the expressions (22) indicate rank the importance of input variables of the optimal regulator. The vehicle speed shows the influence of the factors gain Ky′ and Kε, so, on the speed of lateral movement of vehicles and vehicle turning angle around the vertical axis. Comparing equation (22) with (8) it can be concluded that the obtained gain factors are the good basis to evaluating information for model drivers, therefore the impact of vehicle dynamics on control activity driver.

CONCLUSIONS

For its structural properties and dynamic characteristics of the motor vehicle wheel does not have its own stability of direction in relation to location coordinates. To stabilize the vehicle driver must use visual information from the visual field and mechanical information from interaction system and environment based on them express adequately the effect of the command driving. At the same time, the driver of his action suits a movement and vehicle dynamics which makes a certain degree tiring. A well-trained, experienced and motivated driver acts optimally on command vehicles in terms of demand system performance and ease of management. Therefore, the rational use of available information from the visual field and system interactions, stabilize the movement of the vehicle along with its minimal deviation from the desired trajectory in terms of demands for safe movement and minimal fatigue. According to the results obtained in this paper, the design and implementation of optimal controllers in the vehicle structure, enabled the stabilization of the system, improve the controllability, establishing criteria for assessing the quality of the vehicle in terms of its behavior on the road, the effect on his team and the effect of external influence.

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DEVELOPEMENT OF AUTOMOTIVE RADIATOR COOLING FAN

Branislav Popović[1], *Dragan Milčić, Miodrag Milčić*

UDC: 629.1.06; 62-712.2

ABSTRACT: System for motor vehicle cooling is one of the most important systems for safety of internal combustion engine (IC engine), and engine cooling fan motor is a key subsystem of this system. It ensures that engine operating temperature is within allowed limits and it protects engine from failure of entire internal combustion engine, and vehicle in whole. This engine cooling fan motor is a key subsystem for vehicle air conditioning as well, because it cools air conditioning system cooler at the same time. Radiator cooling fan motor consists from DC engine and radiator cooling fan. DC engine is a subsystem of mentioned systems which has the most important influence on no failure engine cooling fan work, and according to that, on no failure work of engine cooling system and vehicle air conditioning system. The main subject of this paper is development of engine cooling fan from the reliability aspect, in fact, according to required work life of 3000 hours.

KEY WORDS: radiator cooling fan, DC engine, new product development, reliability

RAZVOJ VENTILATORA AUTOMOBILSKOG HLADNJAKA

REZIME: Sistem za hlađenje motora vozila je jedan od najvažnijih sistema za bezbednost motora sa unutrašnjim sagorevanjem (IC motori), i hladnjak motora jeste ključni podsistem ovog sistema. Ovo osigurava da radna temperatura motora bude u dozvoljenim granicama što štiti motor od otkaza i čitav motor sa unutrašnjim sagorevanjem, kao i vozila u celini. Ovaj motor hladnjaka je ključni podsistem vozila sa vazdušnim hlađenjem u vozilu, zato što se isti koristi i kod sistema za grejanje, hlađenje i kondicioniranje vazduha Motor hladnjaka se sastoji od DC motora i ventilatora za hladjenje. Motor DC je podsistem pomenutog sistema koji ima najvažniji uticaj na rad bez otkaza ventilatora motora, i prema tome, na motor sistema za hladjenje i sistem klimatizacije u vozilu. Glavna tema ovog rada je razvoj motora ventilatora sa aspekta pouzdanosti, u stvari, prema potrebi od 3000 časova radnog života.

KLJUČNE REČI: ventilator, DC motor, razvoj novog proizvoda, pouzdanost

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1. INTRODUCTION

For a company to develop, it is pre-requisite to maintain the existing market and expand it, if possible. To achieve this, it is necessary to meet market demands on a continuous basis, whereas the market tends to place more and more complex demands for productivity, quality, reliability, design and rate at which new products are mastered.

Nowadays, the characteristics of the global market are customers' demands domination and market globalization which result in more intense competition. What has become a problem is to sell the product, and not to manufacture the product. To survive, manufacturers need to shorten the product life cycles, improve product quality and reduce the price. This is explicit in the most demanding industries, car and aviation industry.

As an example of a new product development, this paper describes development of a next-generation engine cooling fan, a system consisting of DC engine and radiator cooling fan. The engine cooling fan motor cools air conditioning system cooler of the IC engine and vehicle air conditioning system.

Electro motor with direct current has mass use in car industry and they are with collector. It consist from rotor with shaft, rotor sheet packing, collector, wire coil, stator part of bend frame with ceramic magnets, cover with sinter bearings (bronze or iron) or with so call ball bearings and brush carrier with brushes and wires.

Collector electro motors (DC engines) with brushes apply for wind screen wiper, wind lift, central locking system, seats and back of seats moving systems and on others places in vehicle. Former solutions used one or two electro motors by vehicle, nowadays 20 or 25 by vehicle. These designs differentiate in non-existence or existence of the transmitter-reductor of various types and shapes.

System for motor vehicle cooling is one of the most important systems for safety of internal combustion engine (IC engine), and engine cooling fan motor is a key subsystem of this system. It ensures that engine operating temperature is within allowed limits and it protects engine from failure of entire internal combustion engine, and vehicle in whole. This engine cooling fan motor is a key subsystem for vehicle air conditioning as well, because it cools air conditioning system cooler at the same time.

Engine cooling fan motor and other motor vehicle cooling system components differentiate in load. The motor vehicle cooling system components are stationary and subject to the load of their own weight and vibrations made by the internal combustion engine and vehicle on the move. Besides the above mentioned loads, the engine cooling fan motor has its own heating and rotation which leads to wear and tear of its parts. Thus, the

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potential failure of this component is far greater. Breakdown of the engine cooling fan motor will result in failures due to the engine overheating. Other components breakdown causes failure as well, but rarely a sudden failure of the internal combustion engine.

DC engine is a subsystem of mentioned systems which has the most important influence on no failure engine cooling fan work, and according to that, on no failure work of engine cooling system and vehicle air conditioning system. The main subject of this paper is development of engine cooling fan from the reliability aspect, in fact, according to required work life of 3000 hours.

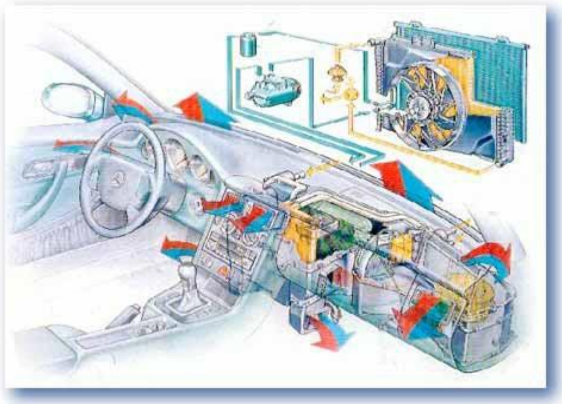

Figure 1 Modern motor vehicle cooling system and IC engine cooling system

TECHNICAL REQUIREMENTS FOR A NEW PRODUCT

According to the prescribed technical requirements, installation data are defined as well:

- Working circuit (engine cooling fan) diameter max 310 mm,
- Engine cooling fan motor length max. 87 mm,
- Stator diameter max. 108 mm,
- Position of three screws for mounting holders, diameter 138 mm, on angle 120°.

The product has to meet TR 9.93160 and it has to be in accordance with regulations and the above said technical requirement. The engine cooling fan motor is tested: in the free air, test chamber and road testing installed in cars. The samples tested according to TR must be fracture or loose free. If there is a fracture or loose, it should be considered that the engine cooling fan motor broke down regardless of being in function and it is regarded as faulty.

Defined functional requirements in free air are:

- Housing temperature, measured after 1 (one) hour work with nominal (V) +15% should be ≤ 45 0C power consumption when nominal voltage is ≤ 8, 5 A, no load,
- Electro motor number of revolutions per minute (rpm) when nominal voltage should be 3000^{+200}_{-100} $\min^{-1}$,
- Airflow over Q = 2000 m^3/h in free space.

Also, defined characteristics of the electro motor are:

- Power released in the point of functioning, at test speed in the centre of the specified tolerance in the free air – 50W ±10% with no load,
- Maximum power at speed 3000 min^{-1}- 200, W±10% with load (working circuit),
- Current intensity should be ≥14A ±10 at speed 3000 min^{-1}
- Jerk moment, ≥ 75 daN/mm,
- Current intensity ≤ 32 A at start.
- Fan extrusion force (with mounted plastic fan only), after 4 hours at temperature 80 ±2ºC - ≥ 70 daN,
- Noise max. 40 db,
- Vibration testing should be completed without fractions or distortions of components; the electro motor should function in free air within specified tolerances,
- Thermal cycles, 4 hours at +100±2ºC - 4 hours at +40±2ºC –
- 90 ÷ 95 % relative humidity, + 4 hours at - 40°C - no fraction or deformation, functioning free air, max. drop 10% in comparison to the values measured on a new part, product ,
- Low temperature, class 4, - 40±2ºC - regular jerks, speed in free air within specified tolerances, permissible noise is higher at start,
- Jerks in cold mode, 10 jerks lasting 1 s each with nominal test voltage
- Testing environment -40±2ºC - motor, max.drop 10% in comparison to the values measured on a new part,
- Insulation resistance ≥ 1 MΩ, no abnormalities,
- Work life 3000 hours, nominal voltage with max. Tolerance +15%, at environmental temperature 80±2ºC , 1500 hours of continues work and +1500 hours of intermittent work; every 53 s "ON" +7 s "OFF".
- Insulation resistance ≥ 1MΩ, functioning in free air.
- Max. drop for 15% in comparison to the values measured on a new part.
- Brush worn-out ≤ 95% of useful length.
- Insulations, collector, plastic components, bearings and/or bushes are well maintained,
- Insulation resistance, measured between positive clamper and mass, is ≥ 10 MΩ,
- Disruptive discharge voltage measured between positive clamper and mass is 1000Vef,
- Residual unbalance, quality grade Q = 6,3 ÷ 15 gr mm.

RELIABILTY ENGINEERING IN DEVELOPMENT OF NEW ENGINE COOLING FAN MOTOR

High reliability is a very desirable characteristic of every product, system or facility. In industrial systems and facilities, reliability directly influences inherent availability and return on investment. For commercial products, high reliability can provide to a manufacturer a competitive advantage, which leads to the increase of the market share, and thus to bigger profits.

In all cases, product or system reliability greatly depends on the decisions made during the design and development of the product. The design failures affect all produced objects and designing failures out of the system is more expensive with already developed products. It is not profitable to change design products already released to production. Reliability is a design parameter, and as such, it requires specific design and effort to achieve the required reliability level.

Every suggested solution (whether concept or detail designs) has to be verified before production in conditions defined by regulations or standards. Verification implies analysis and testing which are performed to confirm conformity with the requirements. Reliability engineering is integrated into the product development process. There are two main aspects of the reliability engineering:

1. Reliability engineering is an iterative process.
2. Reliability engineering is a part of the system of engineering processes.

Reliability engineering is a multidiscipline approach simultaneously implemented in each phase of a product life cycle. The design phase includes detail design and design validation before production. All reliability activities performed before production phase are proactive activities. The activities become reactive when the product or system is released to production. Detail design changes made after the product is being released to production is far more expensive and requires more time to implement those changes.

The approach to the product development based on the desired work life, which is used in the development of the engine cooling fan motor, is shown in figure 2.

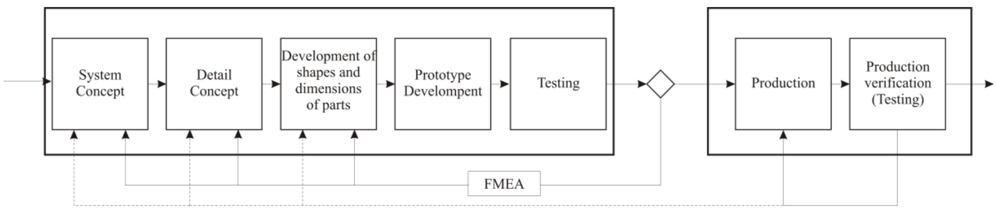

Figure 2 Product development based on the desired work life [1]

In order to prevent, i.e. avoid potential failure effecting the new products, it is necessary to implement the appropriate methods and techniques to minimize the likelihood of those failures in the development phase [4, 5]: FTA (Fault Tree Analysis), design/process FMEA (Failure Mode and Effects Analysis), etc.. In case of development of this new engine cooling fan motor during the development iterative process, it has been used the design and process FMEA, which represents the basis for corrective actions to be carried out on the existing design. The FMEA is the basis for the prototype production as well, after which testing was performed according to the requirements specified in TR.

Figure 3 and 4 show the original and final versions of the engine cooling fan motor.

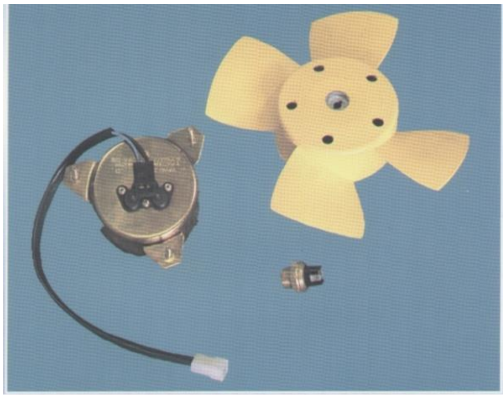

Figure 3 Original version of the engine cooling fan motor

Figure 4 Final version of the new engine cooling fan motor [1]

The test results were verified and the new product was homologated. Homologation was carried out in Zastava Institute, Kragujevac. Three samples were submitted to the testing. Work life test was carried out on the two samples. Test conditions were: 3000h of work at U=13V and T=80°C.

Testing is very important part of the product validation process and it should be conducted before the full production starts. So, every version of the engine cooling fan motor has been tested till failure. Reliability indicator was the work life of the engine cooling fan motor which, as previously said, is to be 3000 hours. The engine cooling fan motor was being developed in the iterative process until the version which fully meets the defined development goal hasn't been developed.

Sample 1 failed after 4100 h due to the worn brush (-), worn out under 2/3 of its length.

Sample 2 failed after 4960 h due to the worn brush (-) as well.

Verification of the newly designed engine cooling fan motor can be performed by parallel testing of the newly developed engine cooling fan motor and competitive engine cooling fan motors. The aim of this testing is to determine similar and different performances of the newly designed engine cooling fan motor and the engine cooling fan motors of similar size, characteristics and use.

The parallel testing included measuring of the physical quantities (pressure and temperature drop) taken at 16 measuring points set up at the safety circuit output, rpm 3000

min^{-1}. The parallel testing was carried out on the newly developed engine cooling fan motor and the engine cooling fan motor rival manufactured. Figure 5 shows the equipment used for the parallel testing.

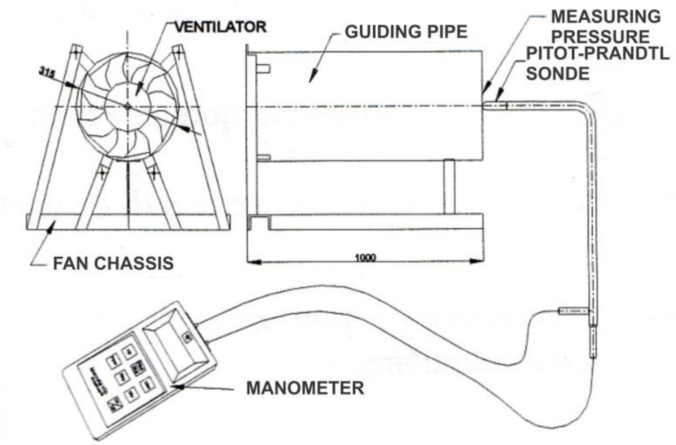

Figure 5 Measuring equipment used for the parallel testing of the engine cooling fan motor

Figure 6 shows the airflow speed values in relation to the measuring points, at n=3000 min^{-1}. The diagram shows the ratio between the airflow speeds of the new engine cooling fan motor and the rival engine cooling fan motor.

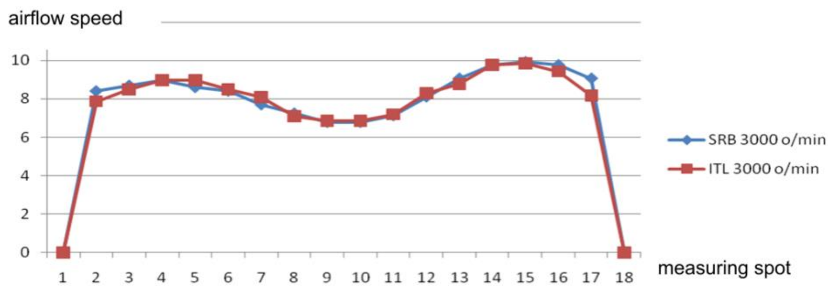

Figure 6 Airflow speed in relation the measuring points

Based on the results of parallel testing [1] it can be concluded that the new product, engine cooling fan motor, doesn't fall behind the similar competitive products, but achieves adequate parameters with the smaller mass.

CONCLUSIONS

On the basis of the realized development of the new product (engine cooling fan motor), which is described in this paper, and results of testing, validation, verification and homologation of the new product at the end of the iteration process, pursuant to the specified work life, it can be concluded:

- New type of DC engine with performance required to be competitive on the world market has been developed.
- New form of the fan and deflector has been developed.

- New type of the engine cooling fan motor with the desired work life of 3000 hours used to cool the IC engine and to regulate the thermal comfort of a vehicle, has been developed.
- Experimental verification of each iterative developmental version of the engine cooling fan motor has been performed until the sample failure in the chambers which simulate operating conditions in service.
- Homologation testing was performed and the final version of the engine cooling fan motor was confirmed in the institution accredited to perform homologation testing.
- New engine cooling fan motor delivering greater power per mass unit has been developed.

This engine cooling fan motor can be installed in cars driven in areas with lots of sunny days (e.g. North Africa, Middle East), and vehicles with air conditioner. The delivered product is highly perspective to be exported to the Russian, European, Far Eastern, etc. markets as well.

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SOLAR VEHICLES AND ROADS

Branko Davidović[1] *, Miroslav Božović, Nikola Maksimović*

UDC:629.331.5; 62.835

ABSTRACT: Solar photovoltaic energy possesses a unique potential for producing a considerable quantity of pure energy which has no part in global warming. This kind of energy has the greatest power (globally 170 W/m²) of all the renewable energy sources. The growing interest for its usage in traffic led to the idea of solar vehicles and solar public roadways development, primarily roads. The long-term objective of solar roads development is the covering of all the concrete and asphalt areas exposed to sunlight by solar panels, which will reduce human dependence on fossil fuels. All the researches move towards the cheap storage of that energy, which still cannot replace the presently dominant fossil fuels to a great extent. The aim of this paper is to provide an insight into the advanced technological solutions which are linked to solar vehicles from the aspect of usage and the ways to use this renewable energy source. Its aim is also to point to the idea of using solar energy on the examples of public roadways and vehicles.

KEY WORDS: solar energy, panels, vehicles, roads

SOLARNA VOZILA I PUTEVI

REZIME: Solarna fotonaponska energija poseduje jedinstveni potencijal za proizvodnju značajne količine čiste energije koja nema nikakvu ulogu u globalnom zagrevanju. Ova vrsta energije ima najveću snagu (globalno 170 W/m²) od svih obnovljivih izvora energije. Sve veće interesovanje za korišćenje ove energije u saobraćaju vodi do ideje razvoja solarnih vozila i javnih puteva, pre svega puteva. Dugoročni cilj razvoja solarnih puteva je pokrivanje solarnim panelima svih površina betona i asfalta izloženih suncu, što će smanjiti čovekovu zavisnost od fosilnih goriva. Sva istraživanja se kreću ka jeftinim skladištenjema te energije, koja još uvek ne može da zameni trenutno dominantnu upotrebu fosilnih goriva u velikoj meri. Cilj ovog rada je da pruži uvid u napredna tehnološka rešenja koja su u vezi sa solarnim vozilima sa aspekta upotrebe i načina korišćenja ovog obnovljivog izvora energije. Takodje, cilj je da ukaže na ideju korišćenja solarne energije na primerima javnih puteva i vozila.

KLJUČNE REČI: solarna energija, paneli, vozila, putevi

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SOLAR VEHICLES AND ROADS

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1. INTRODUCTION

Although the direct conversion of solar energy into electric, the so-called «photovoltaic effect», was noticed almost two centuries ago, it's in the recent years that the photovoltaic conversion of solar energy has become the primary branch of solar devices industry because of its numerous technological advantages. Solar energy can produce 1700 kWh/m^2 of electrical energy on average day (in Europe about 1000 kWh/m^2, in the Middle East about 1800 kWh/m^2, in Africa even more). In Serbia, that value is about 1400 kWh/m^2. The solar energy application can be performed in two ways: by converting solar energy into heating energy and by converting the solar radiation into electrical energy, which can be applied in almost all spheres of social life.

The standard components of photovoltaic systems are the FN modules-panels, controllers and battery charging regulators, accumulators or batteries, cables and mounting systems, as well as the convertors of direct current into the alternating current – the inverters (autonomous and network). The direct current produced in the solar cell is taken to the controller by cable which prevents the excessive battery charging, but it also has other roles, depending on the specific applications. The application in traffic is becoming more important since radical changes are expected in the traffic managing systems on the roads through an active communication «with the roads» by applying virtual systems. In this paper, the technical elements of solar vehicles and roads were displayed, their intercommunication and ways of developing.

The growing popularity of this type of energy, the solar panels production will cause their price reduction, so it is realistic to expect its mass application with vehicles in the near future. Momentarily, the FN module prices are €2,5 – €3,5/W and the complete systems are installed at €4-6/W and, depending on the system type and power, the prices of panels are about €300 per vehicle [4]. Panels can produce the power between 750 kWh and 1500 kWh a year, per installed kW, which creates the solar electricity price from 20 eurocents/kWh to 40 eurocents/kWh.

2. SOLAR VEHICLES

Numerous researches are directed to solar vehicles designing, to material and equipment such vehicles should possess. From testing and verification of characteristics to the mass production there are only a few the requests which, together with normative regulations, make this vehicle application very complex. The basic structure of a solar vehicle is: the chassis, the body shape and material, the battery, the engine, the electronics,

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the solar panels, the total vehicle dimensions, the number and arrangement of operating wheels etc.

Most solar vehicles should use the tube-frame chassis as a truss or a one-piece chassis made of composite materials, figure 1.

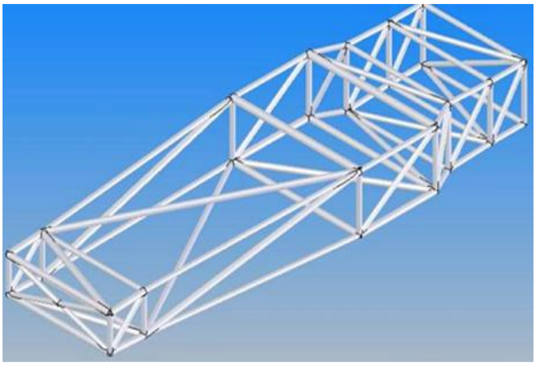

Figure 1 Chassis shapes

The tube-frame chassis is generally cheaper and easier to be designed than the one-piece composite chassis. On the other hand, the one-piece chassis is of lighter mass than the tube- frame one and it enables us to disassemble the vehicles easily into components so the mechanical and the electrical subsystems could be separated. The vehicle mass influences directly on the rolling resistance, on lateral forces in road bends so the smaller the vehicle mass is, the less kinetic energy it needs, which enables the improvement of other characteristics. Vehicle mass isn't equally important for the aerodynamics, the kinetic energy needed or the chassis construction since it has different effects on some vehicle performances.

The vehicle's exterior is also very important when designing a vehicle because of the aerodynamic air resistance which appear at considerable speeds should be reduced. This aerodynamic resistance directly results from the vehicle's shape (the front part of the vehicle is especially important), and it influences the vehicle as the normal projection of force in relation to the air flow direction. Because of this, solar vehicles generally have very low profiles and are completely closed.

Besides the obvious aerodynamic advantages, the vehicle exterior supplies support for the solar modules which are usually placed on the roof of the vehicles. A typical solar module has the power of 80 W to 100 W and the voltage of 12 V. Its dimensions are 100 cm – 50 cm. Although there is a great number of photovoltaic materials, most often the solar (photovoltaic) cells are, as semiconducting structures, made of amorphous silicium (Si) or of gallium -arsenide compounds (GaAs) or some other materials (CIS, CdTe, InP). There have been many investments in the development of silicium heterocell (SANYO solar cell) lately. Silicone (Si) cells parts represent a great majority of all solar modules, and, consequently, they are the cheapest solution. However, even the most efficient Si cells can reach only 20% of energetic efficiency, while the GaAs cells own the possibility and efficiency of 40%.

On the other hand, the GaAs cells production is much more expensive and that's why they are presently used only in space applications. However, the Si cells have their advantages over the GaAs cells (except for their price) because they proved to be more efficient in the conditions of bad light or of the low wavelengths spectrum.

By connecting more photovoltaic cells, a photovoltaic module is produced, with common operating unidirectional voltages of 12 or 24 V, the power of which depends on the total area of all the cells. The unidirectional voltage of the photovoltaic module is changeable and, to control it precisely, it is conducted into the voltage reducer. The battery is charged by a regulated voltage or the unidirectional (DC) consumers are supplied. Voltage from the battery goes into the inverter (a device which turns the DC into the alternating current (AC), and the unidirectional voltage of 12 v into an alternating of 220V) so the alternating consumers (DC) could be supplied. The portable modular chargers can be connected (attached) to a classical electric energy source (in special stations for charging, garages, SSG or landings by the road) when the vehicle is not moving or during the drive for maintaining the battery current level (1A to 2A) through the so-called «super-fast chargers». Batteries can also be charged by solar energy via solar cells placed on the roof of the vehicle. The degree of solar cells usage is 16% and they can Ni-Cd batteries completely in five days at constantly good weather.

Although the subsystem for energy (battery) storage isn't indispensable in solar vehicles, it is recommended that it should be so there wouldn't come to the decline of vehicle performances in the bad light conditions or in the surroundings which aren't ideal for solar vehicles, considering that the power needed for the drive varies depending on the vehicle's speed, wind strength, state of roadways etc. An efficient battery or other systems for energy storage management can considerably minimize the influences on vehicle's performance, the influences which resulted from some of the variations mentioned. The capacity of this storage system varies and it is directly dependant on the speed of drawing electricity from the battery, and the current battery state is calculated by a Pojkert law equation.

The present prototypes of solar vehicles use lithium-ion (Li-ion) or lithium-polymer (Li-Poly) batteries because they represent the latest generation of batteries, and they have an important role in the big technological progress of solar vehicles in recent years. Lithium battery cells provide about six times more power per a mass unit than the accumulator lead batteries. These batteries enabled the vehicles of 180 kg to reach the speed up to 100 km/h. However, this lithium technology requires a special maintenance and an active survey of the voltage, current and cell temperature so the chemical instabilities and the battery life degradation could be avoided.

To maximize the performance and the range of solar vehicles, it is necessary to maximize the efficiency of the vehicle's electrical components and, at the same time, minimize the power needed for moving. The power necessary for keeping constant speed (v) and, thus, overcoming the aerodynamic resistance power, the rolling resistance and the road decline can be calculated from:

$$P(v) = P_{aero} + P_{rolling} + P_{slope} \tag{1}$$

$$P_{aero} = 0{,}5\rho C_d A_f v^3 \tag{2}$$

$$P_{rolling} = mgzC_r \tag{3}$$

$$P_{slope} = mgzv \tag{4}$$

where: ρ - the air density; C_d - the aerodynamic vehicle resistance coefficient (depends on the area and the shape of a vehicle); A_f - the surface of the front part of the vehicle; v - the vehicle speed; m - the vehicle mass; g - the Earth's gravity acceleration; z - angle of road's longitudinal slope; C_r - rolling resistance coefficient.

Regardless the environment, ρ, g and z are the constants which do not depend on the vehicles. The greatest power losses are the consequence of the air resistance power Paero, which is in the direct function from v^3. The aerodynamic vehicle resistance coefficient C_d depends on the vehicle area and shape. The vehicle's shape is certainly very important for the undisturbed air circulation and for avoiding the air swirling (turbulence), figure 2.

The total vehicle mass m is very important because it influences the Pslope and Prolling and it also reduces the power needed for accelerating. Because of that, it is important to minimize the vehicle mass, which was one of the reasons for adopting the new generations of batteries. Using aluminium and composite materials for making the chassis is also recommended because it considerably reduces the vehicle mass. Unfortunately, this tendency for minimizing the vehicle mass led to the fact that designers often exclude the vehicle accessories and thus directly reduce the driver's comfort. However, these discomforts are just temporary until their adequate alternatives are found.

The only mobile parts on solar vehicles are the wheels. The wheels' diameter is very important because big wheels increase the vehicle mass, they are better over the roughnesses and they require a higher gear relation in the transmission. Previous models use wheels of 40 mm to 50 mm diameter, although solutions for up to 70 mm were suggested, and then it was observed that the rolling resistance increased for about 0,07 N. The wheel diameter influences the speed of wheel rotation and, thus, on the gear transmission relation and the speed of rotation per minute and it must be chosen carefully.

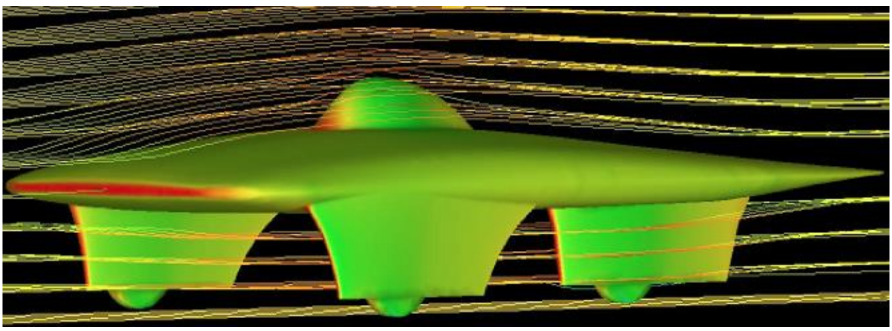

Figure 2 Display of the air flow in relation to the vehicle body

To reduce the abrasion, closed ball bearings are suggested as the protection from the impurities. It is recommended that the disc wheels should be of aluminium or of polyurethane with rubber only on drive wheels. All the inner vehicle components (including the brake system and the supporting system) are enclosed by special materials which don't disturb the flow of air. There are only few smaller openings on the vehicle for batteries' cooling and for driver's ventilation inside the vehicle.

2.2. Experience in Solar Vehicles Development

Solar vehicles have existed for a long time now, and although we cannot find them in retail at the moment, there is much interest for such vehicles. Many countries in the world develop their own models of solar vehicles with their own homologation and that shows how much they are interested in this type of vehicles. As for the current researches and solar vehicles development, it is important to mention the Ford and Mazda companies which tested the solar hybrid vehicles a few years ago and since then they have been actively working on perfecting these technologies.

Ford Reflex is a vehicle presented in public in 2006, and it's distinctive by its solar panels which are placed in the headlights themselves. This vehicle is also equipped by an advanced electro-diesel hybrid engine with lithium-ion batteries which provide that the vehicle will use 3,6 L/100 km diesel fuel, and accelerate from 0 to 97 km/h in 7 seconds. Ford presented one more solar vehicle prototype, called C-MAX, at this year's CES 2014 Fair, figure 3. Ford claims that it has reached the stage in which this vehicle gets 75% of the energy needed for its daily functioning from the solar plates placed on the roof of the vehicle. They achieved this by coating the panels with lenses which focus and increase the solar energy, so this vehicle functions even in bad weather conditions. The vehicle should be exposed to sunlight 7 hours a day to be charged completely. With such charged battery, the vehicle can travel up to 33,8 km with no problems before the battery empties.

Figure 3 Ford C-MAX

Mazda Senku is a vehicle presented to the public as a concept in 2005, and its solar panels were on the roof, too. This Mazda hybrid system is one of the first possessing the START-STOP function which enables less fuel consumption in urban areas, and thus a reduced emission of greenhouse gases. In this vehicle, solar cells are placed on the far end of the glass roof which enables the uninterrupted flow of light to the layers with the solar cells. These cells represent the next generation of the technology which provides the low costs of the whole solar system on one side, and on the other is very convenient for installation and because of the transmitted light percent. This whole system is actually the evolution of solar roofs (first of the kind) which Mazda developed and applied on its vehicle Sentia in 1991. The purpose of these roofs is to provide help in the form of additional electrical energy to the hybrid system in the vehicle. While the vehicle is parked, or stationed for any other reason, this system is the primary source of electrical energy. Cadillac Provoq is a vehicle presented in 2008, which uses solar panels to power the on-board accessories, such as and the audio system, the interior lighting etc.

It is also necessary to mention the French automotive manufacturer Venturi which made considerable efforts in creating the vehicle of the future. One of these prototype vehicles was presented at the Paris Motor Show in 2006. This electric vehicle uses, in combination, solar energy, wind energy and batteries, which power the vehicle together. Solar panels are placed on the roof of the vehicle, while the vehicle also uses the wind energy which the turbines automatically transform into electricity used for powering the vehicle and its batteries. However, this vehicle is relatively slow because it cannot go faster than 48 km/h.

Application of solar panels is also expanding in the field of load vehicles, buses, motorcycles and other vehicles in road traffic. At load vehicles, there are great capacities for battery and panel storage, both in the passenger and the load part of the vehicle, figure 4.

Figure 4 An example of placing solar panels on a lorry

Although batteries occupy a certain space, there is still enough load space for basic needs in all the parts of the vehicle. At the moment, the following types of commercial vehicles powered through solar panels with one charging are developed:

- Balqon, maximum speed – 110 km/h, 240 km range;
- Boulder EV, maximum speed – 104 km/h, 320 km range;
- Zero Truck, maximum speed – 90 km/h, 160 km range;
- Enova, maximum speed – 105 km/h, 240 km range;
- EVI Trucks, maximum speed – 96 km/h, 145 km range;
- E-Star EV, maximum speed – 80 km/h, 160 km range;
- Smith Electric Vehicles, maximum speed – 80 km/h, 160 km range.

When designing a solar vehicle, the simplest possible components arrangement should be applied. With batteries laid out correctly, the vehicle stability in new generations could be improved. It primarily refers to the vehicle gravity centre which influences the vehicle stability when it passes the curves. This should be taken care of considering that the new types of solar vehicles are becoming bigger and more massive.

3. SOLAR ROADS

In December 2008, the first solar photovoltaic system was released on a highway in the state of Oregon, in the USA. That 104 kW system of 594 solar panels produces one third of energy needed for interstate highway lightning, which showed that the solar panels could be installed into the roadways. The solar road is an intelligent road which supplies pure renewable energy and it's safer for driving. There are examples in the world of installing panels on the parking lots where batteries could be charged.

Now the powering of electric vehicles while they are crossing over the solar panels by mutual inductivity is being researched. Although it cannot supply enough electrical energy (in the current investigation phase) to power the moving vehicle completely, it will surely increase its autonomy.

If one fast food restaurant chain places solar panels on its parking lots throughout the country, electric vehicles will be powered on these parking spaces, which can considerably increase these vehicles' autonomy and make them more practical. It will also attract more users who will eat or shop in their while the electric vehicles are being powered on the parking spaces. As the number of buyers grew, the electric vehicles would become more practical. That way the other enterprises will see the advantages of paving their parking lots which enables them to stop paying for the electrical energy from the classic sources.

3.1.The non-contact Magnetic Charging

Scientists from the Korean Advanced Institute of Science (KAIST) developed an electrical transport system (the so-called OLEV - Online Electric Vehicle) where vehicles get their energy from cables places underneath the road surface (30 cm under it), and the energy itself is wirelessly sent to the vehicle on the road. This system was applied for the first time in the Korean city of Guma, where the first wireless electronic bus has been operating since July, 2013, figure 5.

Figure 5 A bus being supplied from the road

Of course, in the current state, this system is powered from the city electrical power supply. However, this is just the first step towards the further technology development. The ways to make this system work together with solar roads are being considered. That way this system would become self-sustainable and independent of the city power supply.

3.2. Management and Traffic Safety

Each solar panel is 4 x 4 m, it contains a microprocessor which monitors and controls the panel, which then communicates with the surrounding panels and vehicles passing over it. This means that there is a communication device on the road at every 4 metres. With this kind of control, the possibilities of managing the road by dotted lines are great since you can 'travel' along the vehicle at a certain speed limit. If a car moves faster than the lines, it means that it moves faster than the limits. If the line is faster than the vehicle, the vehicle moves too slow. You can keep the desired speed without looking at the speedometer. The road can warn you about the upcoming congestions and even recommend the way to avoid them. The destination can be entered into the GPS device and the arrow appearing on the road can navigate the driver, instead of the previous audio navigation.

Unlike the non-lit roads by which we drive at night, solar roads will have the LE diodes which will 'colour' the lanes, and they can be instantly changed if needed. Many people have the problem of vision, especially when they are blinded by the headlights of a car coming from the opposite direction or when it's raining. If the vehicle crosses the dividing line several times at a certain section, the LED ring, which will travel with the vehicle unlimitedly, can be formed around it. This will warn the other drivers about the potential danger and the law enforcement officers about the potential problem. Solar roads can considerably reduce the number of casualties, the night driving will be safer and, thus, the number of accidents caused by the speed unadjusted to the road conditions reduced. This can result in reduced insurance proceedings for all the traffic participants.

There is no need for the roads to use the electrical energy in the periods when there are no cars, so the intelligent roads would activate the LE diodes just if they sensed a car on its surface – for example, 1000 m before the vehicle and 500 m behind the moving vehicle. In this way, the drivers will know that a car is approaching from the opposite direction by seeing the light on the road. The LE diodes can be programmed to move parallel with the vehicles at the limited speed, warning the driver if he moves too fast. Diodes can also be used for writing the letters on the road, for warning the driver about the animals on the road, about the detour, the accident, the road works, etc. The central control station will be able to change the lines and letters instantly, thus reducing the traffic digestion and making roads safer and more efficient. The cities will be able to change the road and parking space signalization to adjust them to their needs.

3.3. Economical Aspects of Solar Roads Construction

The price of constructing highways with classical roadway construction has increased several times in the last few years. In our country, the price of liquid asphalt is relatively low and it is about 70 E/t at the production site and about 60 E/m^3 depending on the concrete brand. The price of material for solar road construction is very high for now. There are some ways to realize more income: by energy generating, transporting purified water from the local communities or agro-centres, for lightning commercials, payments at parking lots, payments of vehicle charging on them or at special stations etc.

It is hard to determine what could be expected from revenue collection, but it is definitely true that electric energy generation provides the best effect, as following:

- average price of electrical energy was 12 cents a kWh in the USA in April 2009,
- the electrical energy price increased in the previous period for 35% till 2009,
- the target price for a solar panel is 10 000 dollars and its lifetime is 20 years.

At a present price in the USA, which is 12 cents a kWh, a solar panel could generate 10000/0,112=83,333 kWh, so it would pay for itself in 20 years. This is the longest possible scenario because it suggests that the price of energy will not increase significantly in the next 20 years. To generate 83,333 kWh, which is the figure a solar panel needs to pay off, the daily production of 11,4 kWh is needed (by current prices).

When the energy of sun reaches the earth's surface, it has declined for 1000 W by a square meter at noon on a sunny day. All over the planet, in average, 24 hours a day in a year's time, each square meter gathers energy equivalent to a barrel of oil every year, ie, 4.2 kWh energy every day (average for the whole year). If the solar panel dimensions are 3,66 m, and the surface 13,4 square meters, at the average energy of 4,2 kWh per square, we get 56,28 kWh per panel. If we use panels of 18,5% efficiency, we get 10,41 kWh per panel theoretically. At the given values, it takes a bit less than 22 years to pay off a solar panel without a significant increase in price of electrical energy during the panel exploitation. If the panels had a little better coefficient of sun energy exploitation, it would shorten the payoff deadline. One of the important characteristics of solar panels is that majority of them can be reused while some components (solar cells, condensers, LE diodes…) and must be replaced.

To compare the construction expenses between the present road constructions and the solar roads more precisely, we should compare the prices of asphalt and/or concrete surfaces, the expenses of thermal power plants operation, the system for transmission and distribution of electric energy with the prices of constructing a solar road. Besides, the elimination of power plants which use fossil fuels will cut the carbon dioxide emission in half and thus create an indirect effect which mustn't be neglected in cost analysis. Providing stations for electric vehicles charging anywhere by the road will open the door for eliminating the internal combustion engines which are responsible for most emission of pollutants. Besides, solar roads convey energy, not from a centralized spot, as with power plants, but from its own network for electrical energy production and it can also transmit signals for cable TV, telephone, fast internet to every home and the institutions connected to the network by access roads and parking lots. Basically, a solar road becomes a transmitter for all the electro signals and signals carrying data.

3.4. Some Dilemmas about the Solar Roads

Are solar roads a utopia or not? Wouldn't it be wiser to build canopies over the roads to hold the solar panels? Or just to place the panels on the north side of the road, facing the sun?

No, it would be much more expensive because we would still have to pay for the existing road infrastructure. Spending the money already designated for classical roads on the solar roads is being planned. If we built roads with classical road construction and canopies over them or if we put the side panels, the price would multiply. Most characteristics of solar roads would also be lost, such as the LE diodes lighting in night rides. Side panels wouldn't help in road protection from snow and ice, so the cities in the north would still have expenses for cleaning the snow and the accidents caused by unsafe road conditions. Many other features would be lost, such as saving lives of millions of animals, self-healing decentralized powering net, all aspects of an intelligent road, reporting potential problems, crime and terrorism reduction etc.

What is the adhesion like? Automobiles slide on the wet asphalt, not to mention the wet glass. What will happen to the solar roads surface when it rains?

Everybody figures a car sliding and losing control on the wet glass. But, one of many technical characteristics of the upper layer is that its texture provides adhesion, at least the same as the existing asphalt, even when it rains.

How to keep a solar road surface clean?

There is something called the self-cleaning glass. It is a special type of glass with the surface which cleans itself by natural processes. It cleans itself in two phases: the photo catalytic stadium of the process breaks the organic dirt from the windshield using the ultraviolet air spectrum in the sunlight and makes the glass hydrophilic (otherwise it is hydrophobic). During the glass hydrophilic state, the rain washes the dirt away leaving the surface clean, since the hydrophilic glass distributes water evenly on its surface.

It is yet to be seen whether this process could keep the solar roads clean in operational conditions, but it will certainly help in solving the problem. There will be obstacles, such as the oil spill, sand storms, etc. The worst possible scenario is: if everything else fails, the snow plows can be replaced by street sweepers (vehicles with rotating brushes). This is for the case of the worst possible scenario and only in the case when the self-cleaning glass cannot perform its function well enough.

Some of the roads in the environment never see the sunlight. Does it mean that we shall never see solar roads in our neighbourhood?

No, it doesn't. Solar roads will be installed in tunnels and under the bridges, regardless the fact there won't be any sunlight there. By the calculation, three times more energy than needed would be produced. Theoretically, it means that only one third of panels should be exposed to sunlight. They would still glow, melt ice and snow, report problems, using the energy collected by the lighted panels.

4. CONCLUSION

Sunlight is the greatest potential source of renewable energy in the world, but it can easily happen that this whole potential remains unrealized. Not only that solar panels do not function at night, but during the day their power rises and falls if the clouds pass over them. That's why most solar panels are connected to the power supply network. During the sunny days, when the conditions for the panels are ideal, the users can sell the extra energy to an electricity distribution company, but generally, all of them have to be in the network during the night or when the clouds darken the panels.

There are many applications showing that the electronic vehicles are more convenient for using than the classical ones. Although investing in solar panels for the vehicles seems expensive, this investment pays off through great fuel savings, savings for the reduced maintenance etc. However, the prices of solar panels still aren't low enough to justify their usage with automobiles and other vehicles, so these panels are mostly used in construction works.

Moving to solar energy (instead of using fossil fuels for getting electrical energy) and choosing electric vehicles by a growing number of users, means that the beginning of the end for fossil fuels usage is at reach. The greatest advantages of solar vehicles are: the zero emission of harmful gases, the solar vehicles engine makes no noise, the dependence on fossil fuels is greatly reduced, the servicing and maintenance of these vehicles is much simpler, and thus cheaper. The batteries developed so far are already capable of satisfying 80% of our daily needs for transport. It should also be mentioned that the next generations of batteries are being developed and they will be capable of competing with the mileage realized by vehicles with reservoirs full of fuel.

A solar road will pay off through electric power generating. The same amount of money now being used for classical roads production will be used for building solar roads. The demand for electrical energy produced in hydro and thermal plants will decline and all the money invested in them could be redirected to solar roads. In addition to that, the price of energy distribution should be calculated (transmission lines, transformer stations etc.)

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AN APPROACH TO VEHICLE RESEARCH

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UDC:629.113:519-7

ABSTRACT: Vehicle's performance is in relation with its structure, design parameters and interaction with the environment. The domain of the vehicle research is a typical example of interconnectedness and interdependence of theory and experiment. In this paper, problems of combining mathematics - simulation and experimental research of vehicles are considered. The appropriate simulation models are formed and necessary preliminary experiments were carried out. A concept of augmented system with extended Kalman filter is realized and used. Some illustrative results of the research done by this methodology are presented and discussed.

KEY WORDS: vehicle, research, estimation, Kalman filter

PRISTUP ISTRAŽIVANJU VOZILA

REZIME: Performanse vozila su u vezi sa svojom strukturom, parametrima dizajna i interakcijom sa okolinom. Domen istraživanja vozila je tipičan primer povezanosti i međuzavisnosti teorije i eksperimenata. U ovom radu, razmatrani su problemi kombinovanja matematike – simulacija i eksperimentalnog istraživanja vozila. Formirani su odgovarajući modeli simulacija i sprovedeni su potrebni eksperimenti. Koncept augmentovanog sistema sa proširenim Kalmanovim filterom je realizovan i korišćen. Neki ilustrativni rezultati istraživanja urađeni ovom metodologijom su predstavljeni i duskutovani.

KLJUČNE REČI: vozilo, istraživanje, procena, Kalmanov filter

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1. INTRODUCTION

With the advent of the first vehicle on the road there were also some problems of its use and, thus, the requirements for design and performance improvement. In today's conditions, the customers and legislation force the stringent requirements to manufacturers of motor vehicles. In light of these requirements, the two main objectives may be pointed out: 1) to increase the efficiency of vehicle use through increased productivity, 2) to increase safety while using the vehicle. In this sense - to define, investigate and optimize the structure and performance of the vehicle relevant to its quality.

The requirements outlined above are often contradictory and demand compromise solutions. For example, a request to increase the speed of movement in order to increase the productivity of the transport task is contradictory to requirements of a stable and safe movement. In addition, the increase in speed of movement leads to increased mechanical and thermal loads on the parts and components of the vehicles, loads on the driver, the environment and, particularly, road. Another indicator of the productivity of the transport task is a useful payload. Request for increasing the vehicle payload leads to increase of gross vehicle weight that exerts a complex effect on the relevant performance. Vehicles performance is in relation with its structure, design parameters and interaction with the environment [7], [11].

When carrying out the transport task, the vehicle is exposed to road roughness, aerodynamic environment and the effects of the driver control. The results of these disturbances are dynamic processes, which, depending on the research objectives, can be considered independently or coupled in the reference planes of the longitudinal, vertical and lateral dynamics [10]. Increasingly stringent requirements for improvement of motor vehicles performance lead to an increasing share of the active control components for drive regimes and work processes [3]. This extends the basic structure of the vehicle and significantly affects the mechanical and functional couplings in comparison to the classical concept of construction.

Trends in the development and improvement of vehicle design follow the trends of the development of theoretical and experimental research methods at all stages of vehicle life cycle, from development, design, production, use, to recycling. Vehicle domain research is a typical example of interconnectedness and interdependence between theory and experiment. Namely, the theoretical studies of dynamic processes based on the vehicle modeling are good basis for design of the appropriate experimental systems, then for creation of identification models or processing and interpretation of experimental results. On

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the other hand, mathematical modeling and simulation of the dynamic processes of the vehicle are caused by the knowledge on the input data from previous experiments on similar objects, prototypes and on the appropriate databases. In addition, the dependence between the mathematical simulation and the experimental study demonstrates the need to verify the structure and parameters of used simulation models. In addition, a matter of choice of the reference level for verification of research results is always part of the problem.

New opportunities offered by the intensive development of numerical methods, computer technology, electronics and their relevant disciplines are a growing challenge and encouragement in the creation of modern methods for vehicle research based on an efficient combination of theory and experiment. Realizing the importance of solving the above-mentioned problems and following the trends in this area, an approach to explore the dynamic characteristics of the vehicles based on simultaneous use of the results of modeling and experiments is presented in this paper.

PAPER OBJECTIVE AND USED METHODOLOGY

This chapter highlights the general remarks and a short review regarding the formation of the model.

Based on the discussion in the previous section, it can be concluded that the two main segments of vehicle research, both theoretical and experimental, are each coupled in some way to the combined classical approach to their use. A number of serial, parallel and feedback connections can be made between them, to adjust the stages of work, but not in the time course of the individual stages. However, in terms of increasing the efficiency of the vehicle research, which means to use the advantages and eliminate the disadvantages of afore mentioned segments, it is advisable to implement them, ie. to combine them simultaneously in real time (online proceedings). This method of achieving a number of positive effects, such as: 1) ability to determine immeasurable or difficult measurable variables, 2) significant simplification of the simulation model and the experimental system, 3) increase of accuracy of the previously obtained results through iterative determination of reference levels for verification of the results, 4) reduction of research costs, 5) creating the database and the conditions for the expansion and upgrade of the basic structure of the vehicle passive components, 6) introduction of active control, 7) formation of virtual sensors and interfaces of GPS and INS systems, 8) revitalization of previously performed experiments in terms of efficient use of the obtained results.

Models

The general problem of combining mathematics (simulation) and experimental research of vehicles in order to achieve some of the goals stated above, is reduced in this chapter by working on specific problems of vehicle dynamics and its interaction with the environment, expressed in terms of lack of information, input data for modeling and simulation, as well as the difficulties of measuring these data. In order to highlight and solve the task, a physical model of the vehicle was created and shown in Figure 1a).

In general case, a two-axle vehicle with four wheels and four tracks is presented as a spatial physical model with five masses: sprung mass, M, and four unsprung masses, m11, m_{12}, m_{21}, m_{22}, and a total of ten degrees of freedom, x, z , y, θ, ψ, ε, z_{11n}, z_{12n}, z_{21n}, z_{22n}. Characteristics of stiffness and damping of suspension are marked by c_{ij}, k_{ij}, i = 1,2, j = 1,2, respectively, and characteristics of stiffness and damping of the tire by c_{ijp}, k_{ijp}, i = 1,2, j = 1, 2, respectively .

Potential properties of excitation effects of the environment on a vehicle are marked by vectors as follows: N - the uneven road, F - by changing the conditions of adhesion, A - from the air environment, V - from the effects of the driver control. In doing so, a distinction is made between the term of "potential properties of excitation effects ..." and the term "realized excitation interaction between the vehicles and the environment, ie. with a driver". A simple explanation for this is found in an example of excitation of vehicles from road roughness. The potential characteristics, in this case, are actual macro- and micro-roughness of the road, and the excitation resulting from the interaction between the road and the vehicle is carried out in the course of the movement, which is affected by numerous factors. The main problem is that it is difficult to directly measure the properties of the potential and realized excitation of the environment on the moving vehicle. These issues can be discussed and resolved based on the vehicle oscillatory model shown in figure 1a), with the use of an adequate algorithm, the method of combined research shown in Figure 1b), obtained by synthesis of following mathematical model, presented in the state space:

$$\begin{aligned} \dot{x} &= [A]x + [B]r \\ y &= [C]x + v \end{aligned} \qquad (1)$$

$$\dot{x} = [A_i]x_i + [B_i]w \qquad (2)$$

$$\begin{aligned} \dot{x}_p &= \lfloor A_p \rfloor x_p + \lfloor B_p \rfloor r \\ y_p &= [C_p]x_p + v_p \end{aligned} \qquad (3)$$

Equation (1) represents the state space mathematical model for the determination of the state vector, x, and output vector, y, of the vehicle, where r - is a vector of excitation due to road roughness and v - a vector of immeasurable inputs. Equation (2) represents a mathematical model of the implements involved in the structure of the vehicle in terms of improving performance, or in an experimental system in terms of expanding the measurement capabilities, while equation (3) shows a mathematical model of the extended system with the included structure models of vehicles, implements and estimators.

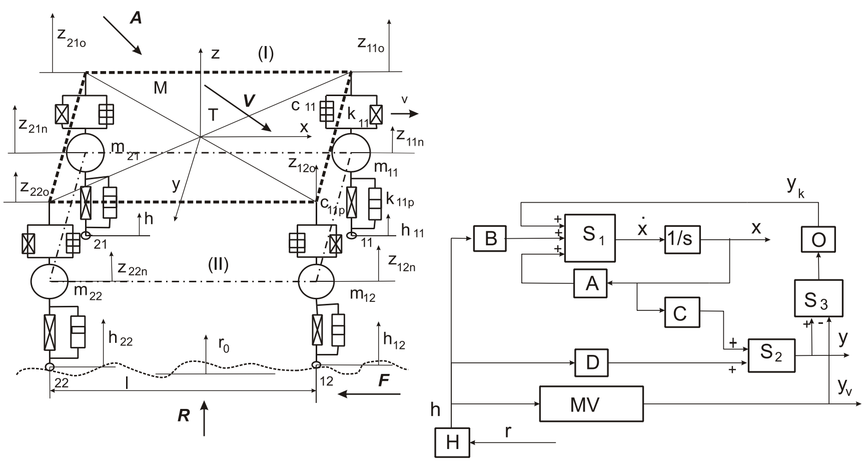


Figure 1 a) Vehicle simulation model, b) Block diagram of the extended system "vehicle – simulation model – estimator"

Block diagram of the algorithm of the research method used in this study is shown in figure 1b). As noted above, the method is based on the iterative use of the simulation results of the vehicle mathematical model and the experimental results obtained on the vehicle for which that model is formed. Thus, the observed complex couplings between the blocks in figure 1b) represent the structure of an integrated system of vehicle - a simulation model vehicle - estimator of state variables and parameters. Designations in figure 1b) are: A - dynamics matrix, B - matrix interface of inputs, C - matrix interface of output and state variables, D - matrix interface of inputs and outputs, MV - real vehicle as measuring object, O - observer, as a component estimator, x - state vector, h - vector of excitation due to road roughness, y - vector of outputs of the simulation model, y_v - vector of measured outputs of the real vehicle, y_k - output vector from the observer. Within this generalized block display, the structure, parameters and iterative procedure estimators are not specified in detail, but only the basic contours of the couplings between basic components, vehicle - model - estimator. A detailed specification is given in the selection of a particular type of estimator and its formation depending on research task and set of demands [2].

Experimental systems

For experimental research, two experimental passenger vehicles were used, marked as “vehicle 1” and “vehicle 2”, respectively. Details of the measuring points on the “vehicle 1” are shown in figure 2, in the following order: a) vertical acceleration sensor of front left wheel unsprung mass (set of four identical sensors on all four wheels), b) three-axis acceleration sensor placed on the engine mount, c) dynamometric steering wheel with sensors to measure the angle, angular velocity and torque on the steering wheel. In figure 2d), a detail of connection of the vertical acceleration sensor to the right rear wheel of the “vehicle 2” is shown.

a) b) c) d)

Figure 2 Measurement devices on the experimental “vehicle 1”: a) acceleration sensor on the front left wheel, b) three-axis sensor on the engine mount, c) sensors on the steering wheel, on “vehicle 2”, d) acceleration sensor at the rear right wheel

Figure 3 shows the testing “vehicle 1” in conjunction with a measuring device for recording the characteristics of road roughness [9] and details of this measuring device platform with vertical acceleration sensor on the experimental stand in the laboratory.

Figure 3 Two single axle trailers for road profile measurement on the experimental stand and towed by experimental "vehicle 1"

RESULTS

As pointed out, the proposed methodology presented in the previous chapters is applicable to different segments of the research of vehicles and engines, as well as of the structure, dynamics, identification, diagnosis, control, optimization, etc. However, starting from the formed vehicle models in the previous chapter and conducted research in the context of the present work, the results of this chapter are related to oscillatory processes caused by the interaction between the vehicle and the road roughness. In order to present the efficiency of the proposed methodology, the simulation model of the vehicle, shown in figure 1a), can be reduced to equivalent models in accordance with the modes of movement and dominant dynamics levels (longitudinal, lateral, vertical) or broken down into a number of sub-models, depending on the specific problem being emphasized.

Some illustrative results of this study are shown in figures 4 to 6:

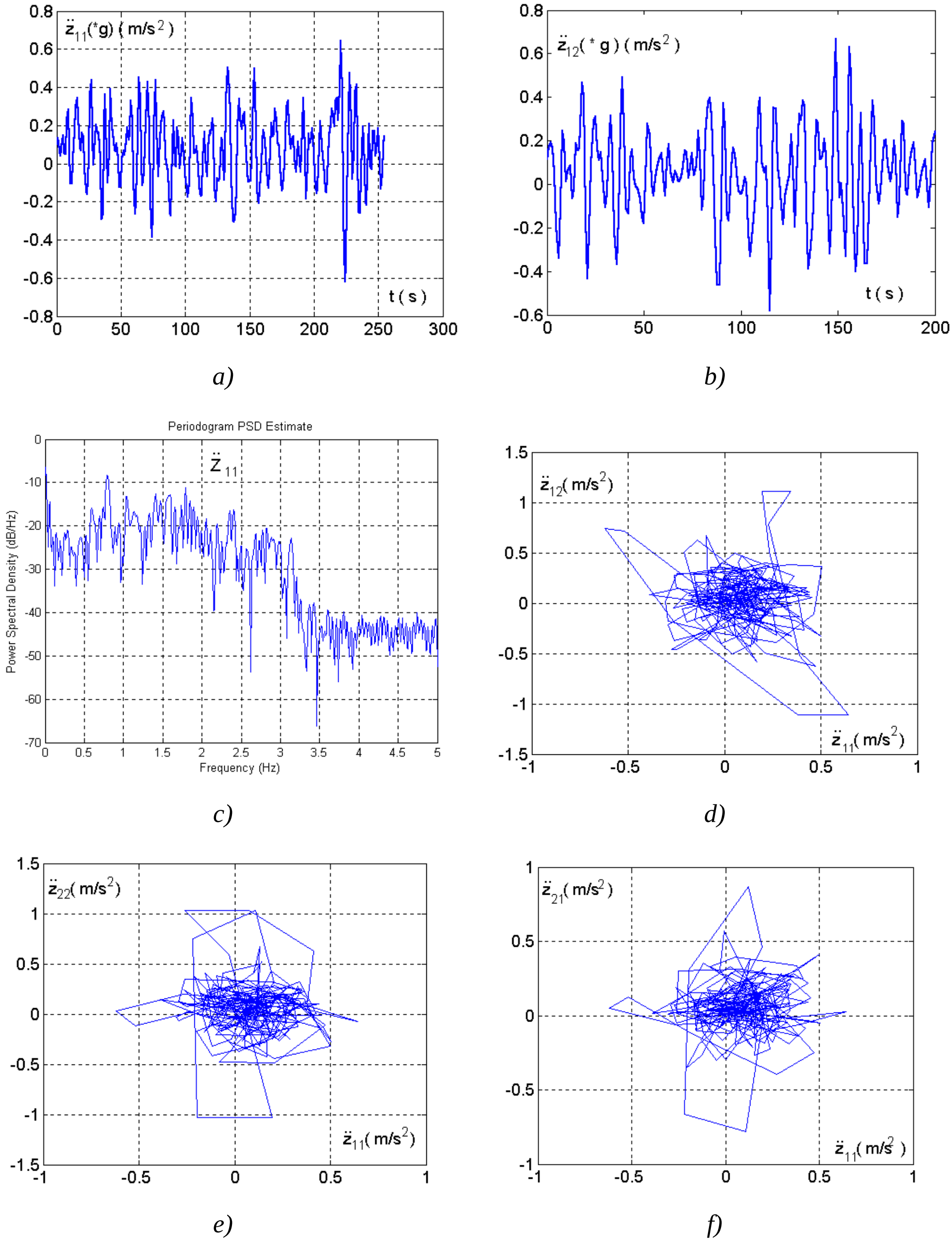


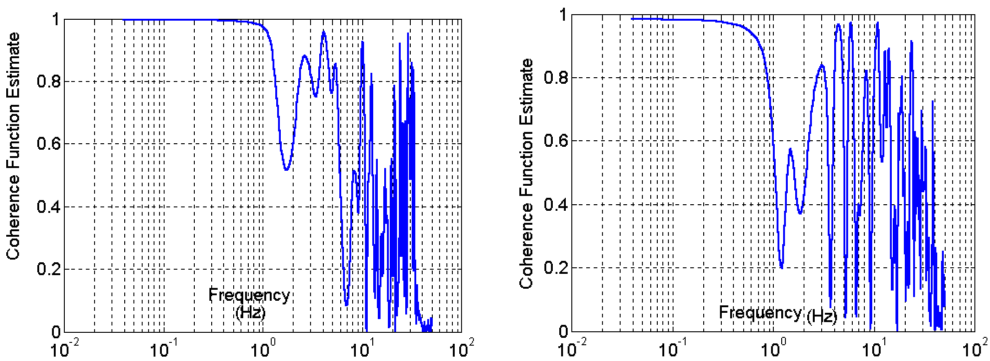
Figure 4 a), b) time records of vertical acceleration of the front wheels of "vehicle 1", c) the power spectrum density of the front left wheel vertical acceleration, d), e), f) mutual dependence between the front left wheel vertical acceleration and vertical acceleration of the front right wheel, the rear left wheel and the rear right wheel, respectively

The time records in figure 4a), and 4b) indicate random nature of the vertical acceleration which is in accordance with road excitation random properties. An approach was used for signal processing and preceding data presentation. Namely, the time records were used for estimation of corresponding spectral characteristics. The three algorithms were used to realize this objective [1], [5], [7]:

$$S_{\ddot{z}}(f)=\lim(1/T)[\ddot{Z}_T(f)]^2, T\to\infty,\ \ S_h(\Omega)\approx S_{\ddot{z}}(f)v(2\pi)^{-5}f^{-4},$$
$$\log S_z(\Omega)=\log S_z(\Omega_0)+w(\log\Omega_0-\log\Omega) \qquad (1)$$

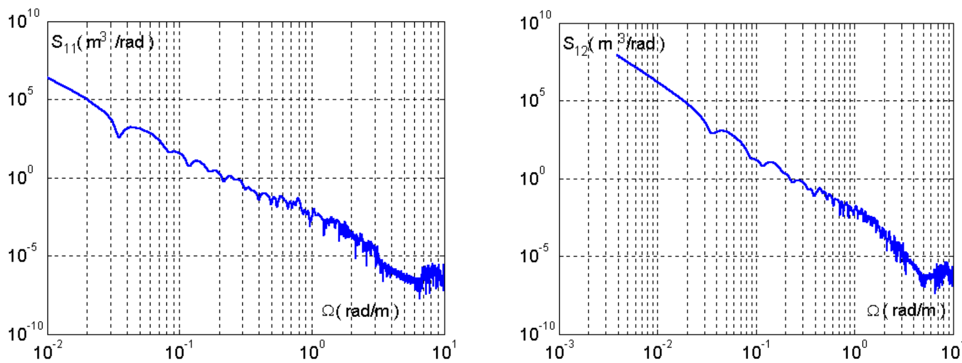
where: $Z_T(f)$ is a spectrum of the wheel centre vertical acceleration complex amplitude, $S_z(f)$ is corresponding power spectrum density, $S_z(\Omega)$ is excitation spectrum of road roughness estimated by above given inverse method, and w, Ω_0 are parameters of road excitation spectrum.

Figure 6 shows these spectra for all four wheels of the "vehicle 1". The shapes of these curves and the estimated parameters confirm the hypothesis of homogeneity and isotropy of the road surface given in papers [4], [6], [8]. The results shown in figure 4d), 4e) and 4f) indicate wheels excitation dependence in time domain, while, in figure 5, dependence in frequency domain is shown. The frequency content of the measurement record from figure 4a) is presented in figure 4c).

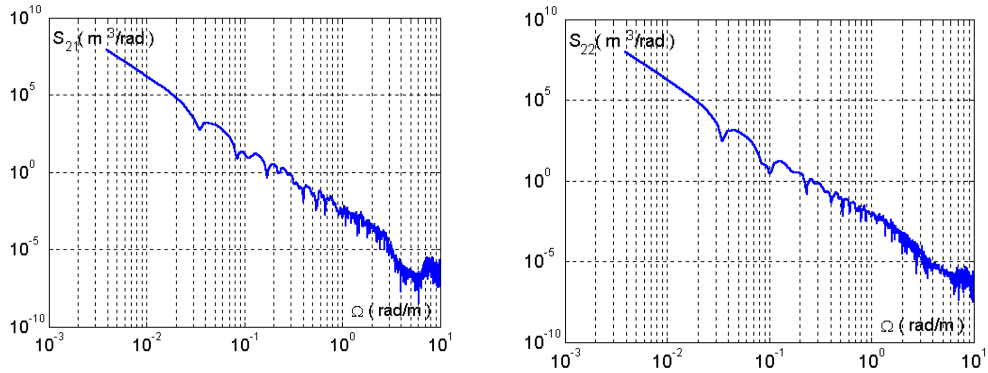


a) *b)*

Figure 5 Coherence functions between: a) front wheels, b) front left wheel – rear left wheel



a) *b)*



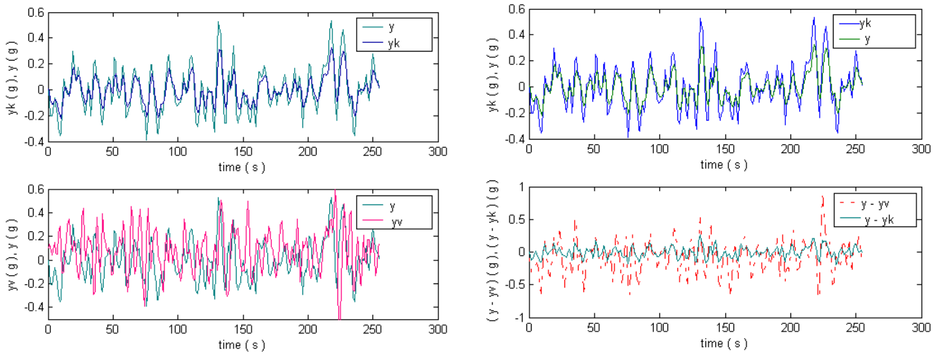
c) d)

Figure 6 Excitation spectrum of the front wheels: a) left, b) right and of the rear wheels: c) left, d) right, for: "vehicle 1", speed 50 kmh^{-1}, the straight-line road section

Previously presented results served as a basis for implementation of procedure shown with algorithms in figure 1b).

In accordance with the structure and physical parameters of the oscillatory model of the vehicle, shown in figure 1a), a quarter model with two masses in the domain of the left front wheel is formed and included in the algorithm of the integrated system for estimation of state variables and the measured outputs of the system in Figure 1b). In addition, the state vector contains five variables as follows: vertical displacement and vertical acceleration of sprung mass, M11, as part of the total mass of the vehicle (M11=M/4), then the vertical displacement and acceleration of unsprung mass, m11, and vertical excitation of front left wheel from road, h11. Vector of the measured output contains one variable - vertical acceleration of the front left wheel, which can be expanded with the vertical displacement of the wheel. In this case, the primary input of the system formally has zero value and the secondary input, as process noise, is defined by the vector of the basic features of the uneven road. These are formed by using the random signal generator of uniform spectral characteristics, then by using the shaping filter and database on identified characteristics of the uneven road, the shape and parameters as in Figures 6a), 6b), 6c), 6d). Other, secondary input of the integrated system is noise measurement contained in the measured output, or the vertical acceleration of the wheel. In the first stage of the procedure, the structure and parameters of the estimator are identified, as a sub-system with two input vectors (measured and simulated output system of the vehicle) and two vector outputs (estimates of the outputs and estimates of the vehicles state space variables). Thus, the procedure can be used to obtain unknown state variables, immeasurable inputs and outputs, increasing the accuracy of the results of simulation and experiment.

For the basic data of the "vehicle 1": total mass of 1235 kg, sprung mass of 1123 kg, wheel base of 2.449 m, wheels tracks of 1.3 m, coordinates of the centre of mass relative to the front axle - 1.13 m and above the ground plane - 0.5 m, and the previously obtained results in this paper, a quarter simulation model of the front left wheel with suspension and a quarter of the vehicle mass was formed. This model is included in the extended system shown in Figure 1b), with Kalman filter as estimator, and then the research is conducted in accordance with above presented algorithm of iterative combination of simulation and experimental results. The illustrative examples of these results are given in Figures 7a) and 7b).



a) *b)*

Figure 7 Estimates of the vehicle front left wheel vertical acceleration:

a) yv – measured output, yk – filtered output, y – true output, b) yk – filtered output, y – true output: y – yv – measurement error, y – yk – estimation error, experimental "vehicle 1", asphalt road, speed 50 kmh^{-1}, Cov(y–yv)=0.0689, Cov(y–yk)=0.0070

In figure 7a) below, the measured time history of the vertical acceleration of the front left wheel and its true value are compared and, in the same picture above, the filtered and the true value of this variable are compared. Figure 7b) below shows measurement and estimation error, respectively, and figure 7a) above shows the comparison between the filtered and true value of the left wheel vertical acceleration. The efficiency of the implemented estimation procedure for example given above is evaluated by mutual flow graphics – qualitative and their numerical indicators - quantitative. One such indicator is the error covariance - value of 0.0689 is obtained for measured series, as measurement error, value of 0.0070 for estimation series, as estimation error (values given in figure 7b) below). This shows that the used estimation procedure has significantly increased the accuracy of the previously measured results.

CONCLUSIONS

Combining the theoretical and experimental methods in an appropriate manner can significantly improve the efficiency of vehicles research. The special contribution is to make modern methods of identification of dynamical systems and methods for estimation of state variables and parameters of the system. Optimally chosen structure of an extended system with estimator provides a number of positive effects, such as: ability to determine immeasurable or variables difficult to measure, significant simplification of the simulation model and the experimental system, increase of the accuracy of the previously obtained results through iterative determination of reference levels for verification of the results, creating the database and the conditions for the expansion and upgrade of the basic structure of the vehicle passive components, introduction of active control, revitalization of previously performed experiments in terms of efficient use of the obtained results. One example of increasing accuracy of the previously obtained experimental results using the proposed estimation algorithm is presented in this paper.

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