UDK 629.1–453:629.114.53

Overitev in izboljšava dinamičnih modelov avtobusa

Verification and Improvement of Dynamic Bus Models

FRANCI PADEŽNIK

Dinamični model avtobusa smo preverili z meritvijo avtospektrov pospeškov pri vožnji po različnih cestiščih. Pri izboljšavi modela avtobusa na podlagi izmerjenih avtospektrov smo iskali vzroke za napake v modelu. Naredili smo analizo občutljivosti posameznih parametrov modela. Na koncu smo model avtobusa izboljšali in uporabili za preračun in optimiranje udobnosti in dinamičnih sil na kolesih.

Dynamic model of a bus was verified with measured acceleration autospectra when driving on different roads. Possible errors in dynamic bus model were verified when the bus model was updated. Also the sensitivity analysis for all model parameters was done. In the end the model of the bus was updated and used for prediction of passenger comfort and dynamic forces on tyres.

0 UVOD

Naredili smo dinamični model avtobusa s petimi prostostnimi stopnjami. Izračunali smo lastne frekvence in oblike nihanja avtobusa ter dinamične odzive pri vožnji po različnih cestiščih [1]. Izvedli smo tudi optimizacijo na najboljšo udobnost in na minimalne dinamične sile. Ni pa nam uspelo dinamičnega modela avtobusa preveriti z meritvami – zato so ti rezultati nekoliko vprašljivi. Mogoče je bilo opazovati usmeritve, kaj se dogaja pri spremembi določenega parametra modela. Same vrednosti pospeškov, dejavnikov udobnosti in dinamičnih sil niso bile najbolj zanesljive. Zato smo se odločili izvesti meritve pospeškov med vožnjo po različnih cestiščih. Namen meritev je bil:

– preveriti lastne frekvence vzmetenja avtobusa,

– preveriti rezultate za udobnost v avtobusu,

– preveriti in izboljšati sedanji dinamični model avtobusa,

– določiti potrebno najmanjše število meritev in najboljšo lego odjemnikov,

– optimirati udobnost in dinamične sile na izboljšanem modelu.

1 DINAMIČNI MODEL AVTOBUSA B3 090 T

Dinamični model avtobusa je prikazan na sliki 1. Model je dvodimenzionalen, sestavljen iz štirih togih teles (sprednja in zadnja prema, nadgradnja avtobusa in sedež s šoferjem) ter petih vzmetnih in dušilnih elementov. Postopek reševanja je modalni način v frekvenčnem območju. Zato smo upoštevali linearizirane vrednosti za karakteristike vzmeti in blažilnikov. Najprej smo izračunali lastne frekvence in oblike (zaradi precejšnjega lokaliziranega dušenja so kompleksne).

0 INTRODUCTION

We developed a dynamic bus model with five degrees of freedom. Eigenvalues and mode shapes of bus vibrations, as well as the dynamic response when driving on different road surfaces were calculated [1]. Optimization with respect to driving comfort and dynamic forces was also carried out. However, we did not manage to check the dynamic bus model with measurements, so these results were not quite reliable. It was possible to follow the trends after changing a specific model parameter, but the values of acceleration, factors of riding comfort and dynamic forces, were not reliable. We therefore decided to carry out measurements of accelerations during driving on different road surfaces. The purpose of measurements was:

– to check eigenfrequencies of bus suspension.

– to check the results of riding bus comfort,

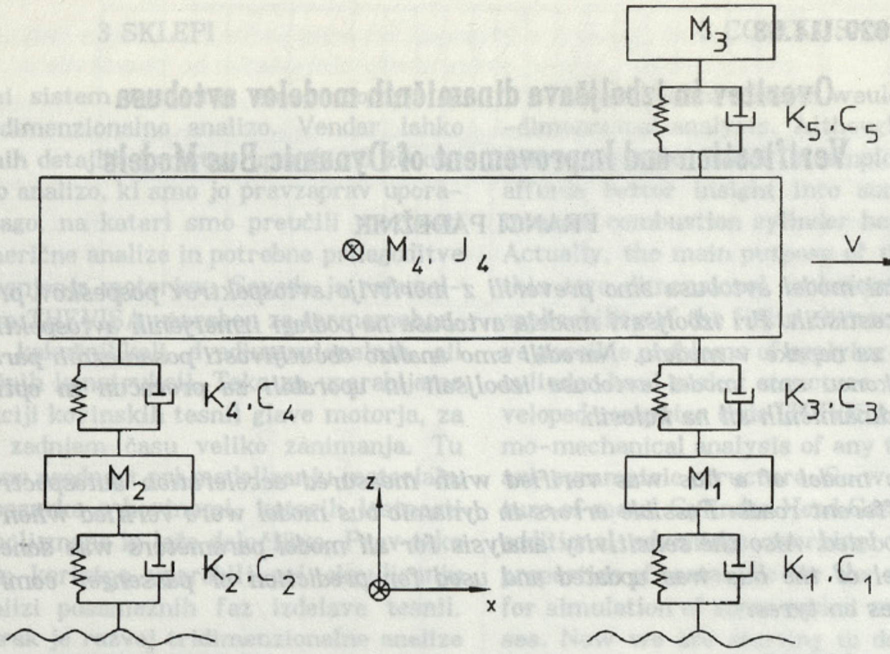
– to check and improve the existing dynamic model of the bus,

– to determine the necessary minimum number of measurements and the optimum position of transducers,

– to carry out the optimization of comfort and dynamic forces on the improved model.

1 DYNAMIC MODEL OF BUS B3 090T

The dynamic bus model is shown in fig. 1. The model is two-dimensional and consists of four rigid bodies (front and rear axle, bus body and seat with driver) as well as five suspension and dumping elements. For the solution, a model approach in the frequency domain was applied. We therefore considered linearized values for spring and shock absorber characteristics. First, eigenvalues and mode shapes were calculated (due to considerable localized damping they are complex).



Sl. 1. *Dinamični model avtobusa s petimi prostostnimi stopnjami*
Fig. 1. *Dynamic bus model with five degrees of freedom*

Nato se z upoštevanjem primernega vzbujanja zaradi neravnin cestišča izračunajo avtospektri odzivov v različnih točkah na avtobusu — tako na obeh premah, nadgradnji in sedežu šoferja. Avtospektre pospeškov lahko neposredno primerjamo z izmerjenimi avtospektri pospeškov, iz avtospektrov pospeškov lahko izračunamo dušene frekvence avtobusa ali dejavnike udobnosti.

2 MERITVE NA AVTOBUSU

Pri preverjanju in izboljšavi dinamičnih modelov vozil je treba izvesti precej obširne meritve dinamičnega obnašanja avtobusa. Tako smo izvedli naslednje meritve [2]:

— meritve mase, težišča in vztrajnostnih momentov avtobusa, prenosne funkcije sedeža, meritve značilnosti vzmeti in blažilnikov;

— meritve časovnih potekov pospeškov v več točkah pri vožnji po različnih cestiščih.

Vozili smo po dobrem asfaltu, slabem asfaltu in makadamu. Pospeške smo merili na 16 mestih avtobusa. Vse meritve smo izvedli za prazen in obremenjen avtobus. Merilna mesta pri merjenju pospeškov so prikazana na sliki 2.

Prav tako smo izmerili profile neravnin cestišča. Te potrebujemo kot vzbujanje pri simuliranju dinamičnih odzivov.

Iz posnetih časovnih potekov pospeškov smo na CAT sistem GENRAD 2515 naredili avtospektre pospeškov. Iz avtospektrov pospeškov smo določili dejanske vrednosti pospeškov, dejavnike udobnosti (faktor K) po standardu VDI 2057 [3].

By taking into consideration appropriate excitation due to the unevenness of the road surface, the autospectra of responses at different points on the bus were then calculated - on both axles, on the body and on the driver's seat. The acceleration autospectra can be directly compared with measured acceleration autospectra and from acceleration autospectra, the damped eigenfrequencies of the bus or the factors of riding comfort can be calculated.

2 MEASUREMENTS ON BUS

When checking and improving dynamic vehicle models, it is necessary to carry out extensive measurements of dynamic bus behaviour. The following measurements were carried out:

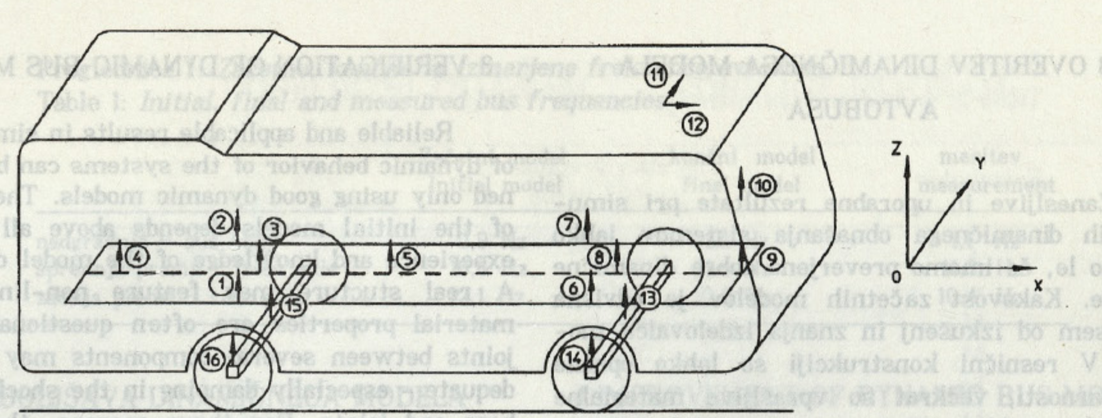
— measurements of mass, centre of gravity and moments of inertia of the bus, transfer function of seat, measurements of characteristics of springs and shock absorbers,

— measurements of accelerations at several points when driving on different road surfaces.

We drove on good asphalt roads, on rough asphalt roads and on macadam road surfaces. The accelerations were measured at 16 points on the bus. All measurements were carried out for a loaded and an unloaded bus. The measuring points of acceleration are shown in figure 2.

We also measured the profiles of road surface unevenness. They are needed for excitation in a simulation of the dynamic response.

From the recorded variation in time of accelerations, we made autospectra of accelerations on the CAT system GENRAD 2515. From the autospectra of accelerations, the effective values of accelerations, factors of comfort (K factor) acc. to standard VDI 2057 [3] were determined.

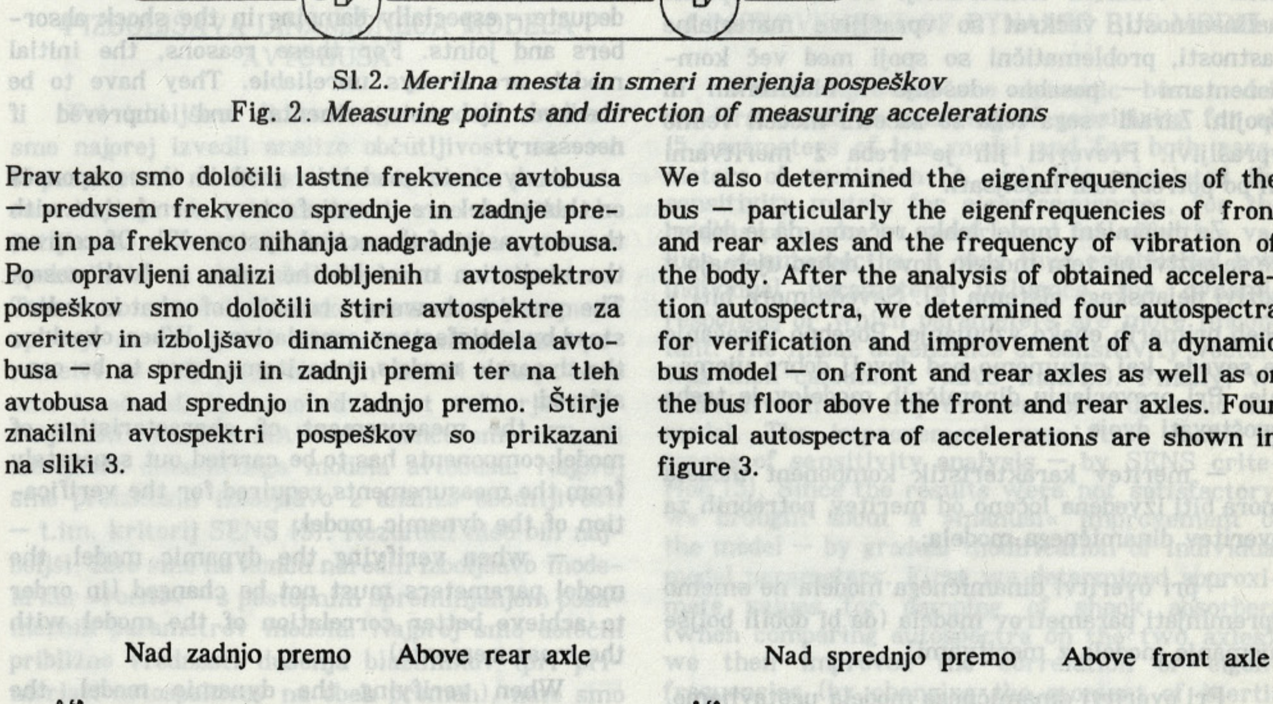


Sl. 2. *Merilna mesta in smeri merjenja pospeškov*

Fig. 2. *Measuring points and direction of measuring accelerations*

Prav tako smo določili lastne frekvence avtobusa — predvsem frekvenco sprednje in zadnje preme in pa frekvenco nihanja nadgradnje avtobusa. Po opravljeni analizi dobljenih avtospektrov pospeškov smo določili štiri avtospektre za overitev in izboljšavo dinamičnega modela avtobusa — na sprednji in zadnji premi ter na tleh avtobusa nad sprednjo in zadnjo premo. Štirje značilni avtospektri pospeškov so prikazani na sliki 3.

We also determined the eigenfrequencies of the bus — particularly the eigenfrequencies of front and rear axles and the frequency of vibration of the body. After the analysis of obtained acceleration autospectra, we determined four autospectra for verification and improvement of a dynamic bus model — on front and rear axles as well as on the bus floor above the front and rear axles. Four typical autospectra of accelerations are shown in figure 3.



Sl. 3. *Štirje izmerjeni avtospektri pospeškov na slabem asfaltu pri 60 km/h*

Fig. 3. *Four measured autospectra of accelerations on rough asphalt at 60 km/h*

3 OVERITEV DINAMIČNEGA MODELA AVTOBUSA

Zanesljive in uporabne rezultate pri simuliranjih dinamičnega obnašanja sistemov lahko dobimo le, če imamo preverjene dobre dinamične modele. Kakovost začetnih modelov je odvisna predvsem od izkušenj in znanja izdelovalca modela. V resnični konstrukciji so lahko opazne nelinearnosti, večkrat so vprašljive materialne lastnosti, problematični so spoji med več komponentami — posebno dušenje v blažilnikih in spojih. Zaradi vsega tega so začetni modeli vedno vprašljivi. Preveriti jih je treba z meritvami in po potrebi tudi izboljšati.

Za dinamični model lahko rečemo, da je dober, če se odzivi na tem modelu dovolj dobro ujemajo z odzivi dejanskega sistema [3]. Seveda mora biti v obeh primerih enako vzbujanje. Posebno vprašanje je seveda, kaj razumemo pod dovolj dobro ujemanje. Pri preverjanju dinamičnih modelov je treba upoštevati dvoje:

— meritev karakteristik komponent modela mora biti izvedena ločeno od meritev, potrebnih za overitev dinamičnega modela;

— pri overitvi dinamičnega modela ne smemo spreminjati parametrov modela (da bi dobili boljše ujemanje modela z meritvami).

Pri overitvi dinamičnega modela ugotavljamo, kako dober začetni model imamo. Na podlagi tega se nato odločimo, ali je treba izvesti izboljšavo oziroma optimizacijo modela.

Overitev dinamičnih modelov lahko naredimo na več načinov, in sicer:

— z modalno metodo — po tej se najprej izračunajo lastne frekvence in oblike modela. Nato se opravi eksperimentalna modalna analiza na dejanski konstrukciji. Kakovost dinamičnega modela tukaj ugotavljamo po primerjavi lastnih frekvenc in oblik;

— s primerjavo odzivov dinamičnega sistema lahko primerjamo časovne ali frekvenčne odzive dinamičnega sistema. Ta metoda ima v našem primeru določene prednosti, saj lahko primerjamo avtospektre pospeškov (prav to, kar nas zanima), avtobusa ni treba vzbujati z velikimi hidravličnimi vibratorji. Pomanjkljivost te metode pa je, da je med neznanimi veličinami tudi vzbujanje.

Izbrali smo torej primerjavo avtospektrov pospeškov in veličin, ki jih lahko preprosto odberemo iz avtospektrov pospeškov.

3 VERIFICATION OF DYNAMIC BUS MODEL

Reliable and applicable results in simulations of dynamic behavior of the systems can be obtained only using good dynamic models. The quality of the initial models depends above all on the experience and knowledge of the model designer. A real stucture may feature non-linearities, material properties are often questionable, the joints between several components may be inadequate - especially damping in the shock absorbers and joints. For these reasons, the initial models are always unreliable. They have to be checked by measurements and improved if necessary.

A dynamic model is good if the responses on this model are in satisfactory correlation with the responses of the actual system [3]. Of course, the excitation must be the same in both cases. The question, however, remains of what is understood by satisfactory correlations. When checking the dynamic models, two items have to be considered:

— the measurement of characteristics of model components has to be carried out separately from the measurements required for the verification of the dynamic model,

— when verifying the dynamic model, the model parameters must not be changed (in order to achieve better correlation of the model with the measurements).

When verifying the dynamic model, the quality of the initial model can be established. On the basis of this, we can decide on the need for improvement or optimization of the model.

The verification of dynamic models can be carried out in several ways, i.e.:

— by the model method, where first the eigenfrequencies and mode shapes are calculated. An experimental modal analysis on a real structure is then performed. The quality of the dynamic model is established on the basis of comparison of eigenfrequencies and mode shapes of vibrations;

— by comparison of the results of responses of a dynamic system - time or frequency responses of the dynamic system can be compared. In our case, this method has certain advantages, since the autospectra of accelerations can be compared (the very subject we are interested in) and the bus need not be excited with large hydraulic vibrators. A disadvantage of this method is that the unknown quantities include also excitation.

We thus decided on the comparison of autospectra of accelerations and quantities that can be determined simply from the autospectra of accelerations.

Preglednica 1: *Začetne, končne in izmerjene frekvence avtobusa*
Table 1: *Initial, final and measured bus frequencies*

	Začetni model Initial model	končni model final model	meritev measurement
nadgradnja – bus body	0,9 Hz	1,2 Hz	1,1 Hz
sprednja prema – front axle	10,6 Hz	11,4 Hz	11,3 Hz
zadnja prema – rear axle	12,1 Hz	10,0 Hz	10,4 Hz

4 IZBOLJŠAVA DINAMIČNEGA MODELA AVTOBUSA

Pri izboljšavi dinamičnega modela avtobusa smo najprej izvedli analizo občutljivosti za vseh 15 parametrov modela avtobusa in za oba parametra vzbujanja (A, w). Izračunali smo matriko občutljivosti za lastne frekvence, za višine vrhov v spektrih in za dejanske vrednosti avtospektrov. Tako smo ugotavljali, kako posamezni parametri vplivajo na dinamične odzive oziroma, kateri parametri so bolj pomembni in kateri manj. Nato smo izračunali linearno odvisnost vektorjev občutjivosti (matriko MAC). Na koncu smo se lotili izboljšave dinamičnega modela avtobusa. Najprej smo preizkusili izboljšavo z analizo občutljivosti – t.im. kriterij SENS [5]. Rezultati niso bili najboljši, zato smo na koncu naredili izboljšavo modela kar »ročno« – s postopnim spreminjanjem posameznih parametrov modela. Najprej smo določili približne vrednosti dušenja blažilnikov (pri primerjavi avtospektrov na obeh premah), nato smo izboljšali ujemanje lastnih frekvenc (s spreminjanjem vztrajnostnega momenta avtobusa in obeh nevzmetenih mas). Zanimivo je morda, da nismo mogli dobiti zadovoljivega ujemanja, dokler nismo dopustili spreminjanja parametrov vzbujanja. Tako smo nazadnje spremenili pet parametrov modela in oba parametra vzbujanja. V preglednici 2 so prikazane začetne in končne vrednosti parametrov modela avtobusa pri vožnji po slabem cestišču s hitrostjo 60 km/h.

Vidimo, da je bilo najbolj potrebno spremeniti vztrajnostni moment vzmetene mase avtobusa. Menimo, da je bil ta parameter slabo izmerjen in bi bilo v prihodnje te meritve treba ponoviti. Pa tudi meritve neravnin profilov cestišča bi bilo treba ponoviti oziroma izmeriti profile neravnin cest, na kateri smo merili avtospektre pospeškov. Končno ujemanje modela z meritvami je prikazano na sliki 4. Vidimo, da je ujemanje avtospektrov odzivov dokaj dobro.

Ko imamo dober dinamični model avtobusa, se lahko lotimo optimiranja udobnosti v avtobusu in dinamičnih sil oziroma izbire primernih vzmetnih in dušilnih elementov. Tukaj je treba izbrati spodnjo in zgornjo mejo vseh parametrov

4 IMPROVEMENT OF DYNAMIC BUS MODEL

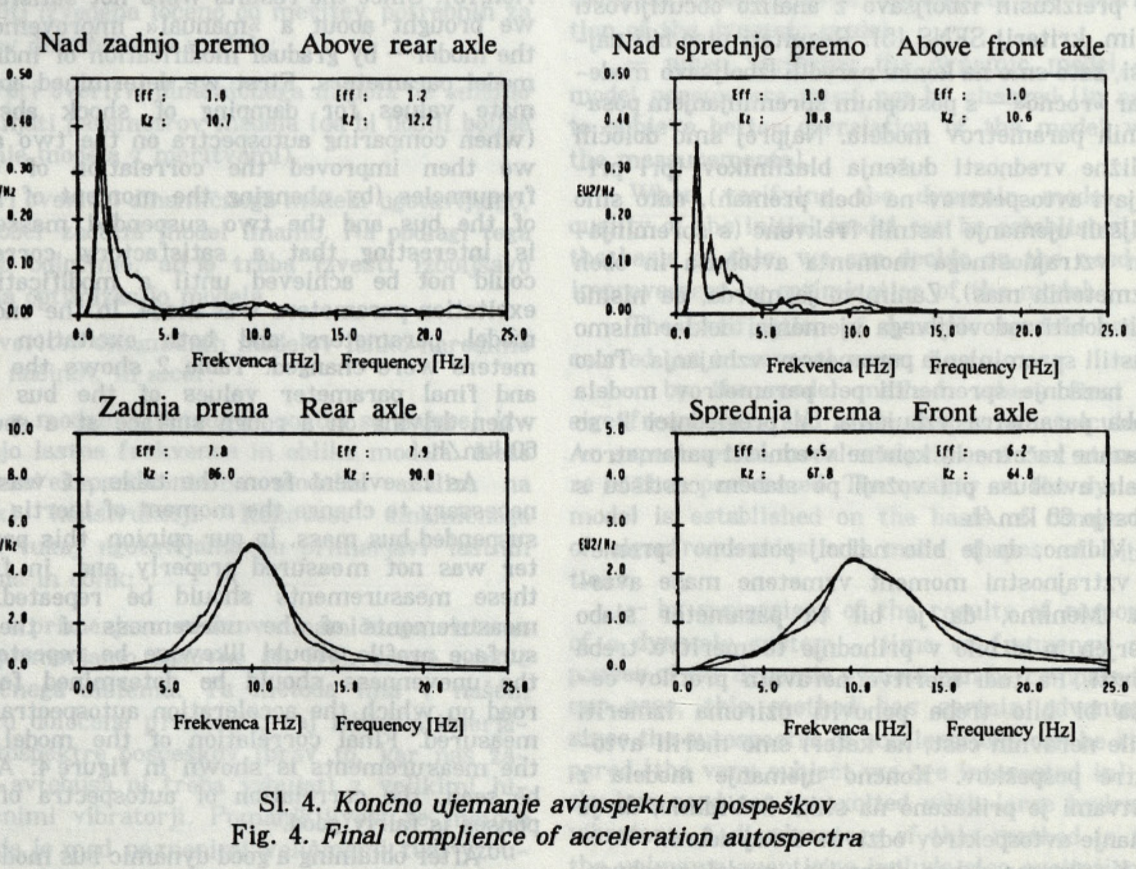
When improving the dynamic bus model, we first made an analysis of sensitivity for all 15 parameters of bus model and for both parameters of excitation (A, w). We calculated the sensitivity matrix for eigenfrequencies, for the heights of peaks in spectra and for effective values of autospectra. It was thus established how individual parameters influence the dynamic responses or which parameters are more important. The linear dependence of sensitivity vectors was then calculated (MAC matrix). Finally, we started with the improvement of a dynamic bus model. The improvement was first made by means of sensitivity analysis – by SENS criterion [5]. Since the results were not satisfactory, we brought about a »manual« improvement of the model – by gradual modification of individual model parameters. First we determined approximate values for damping of shock absorbers (when comparing autospectra on the two axles), we then improved the correlation of eigenfrequencies (by changing the moment of inertia of the bus and the two suspended masses). It is interesting that a satisfactory correlation could not be achieved until a modification of excitation parameters was made. In the end, five model parameters and both excitation parameters were changed. Table 2 shows the initial and final parameter values of the bus model when driving on a rough surface at a speed of 60 km/h.

As is evident from the table, it was first necessary to change the moment of inertia of the suspended bus mass. In our opinion, this parameter was not measured properly and, in future, these measurements should be repeated. The measurements of the unevenness of the road surface profile should likewise be repeated and the unevenness should be determined for the road on which the acceleration autospectra were measured. Final correlation of the model with the measurements is shown in figure 4. As can be seen, the correlation of autospectra of responses is fairly good.

After obtaining a good dynamic bus model, we can start with optimization of comfort in the bus and dynamic forces, or rather, with the selection of suitable suspension and damping elements. It is necessary to choose the upper and lower limit for all optimization parameters. The situation is best

Preglednica 2: *Začetne in optimirane vrednosti parametrov*
Table 2: *Initial and optimized parameter values*

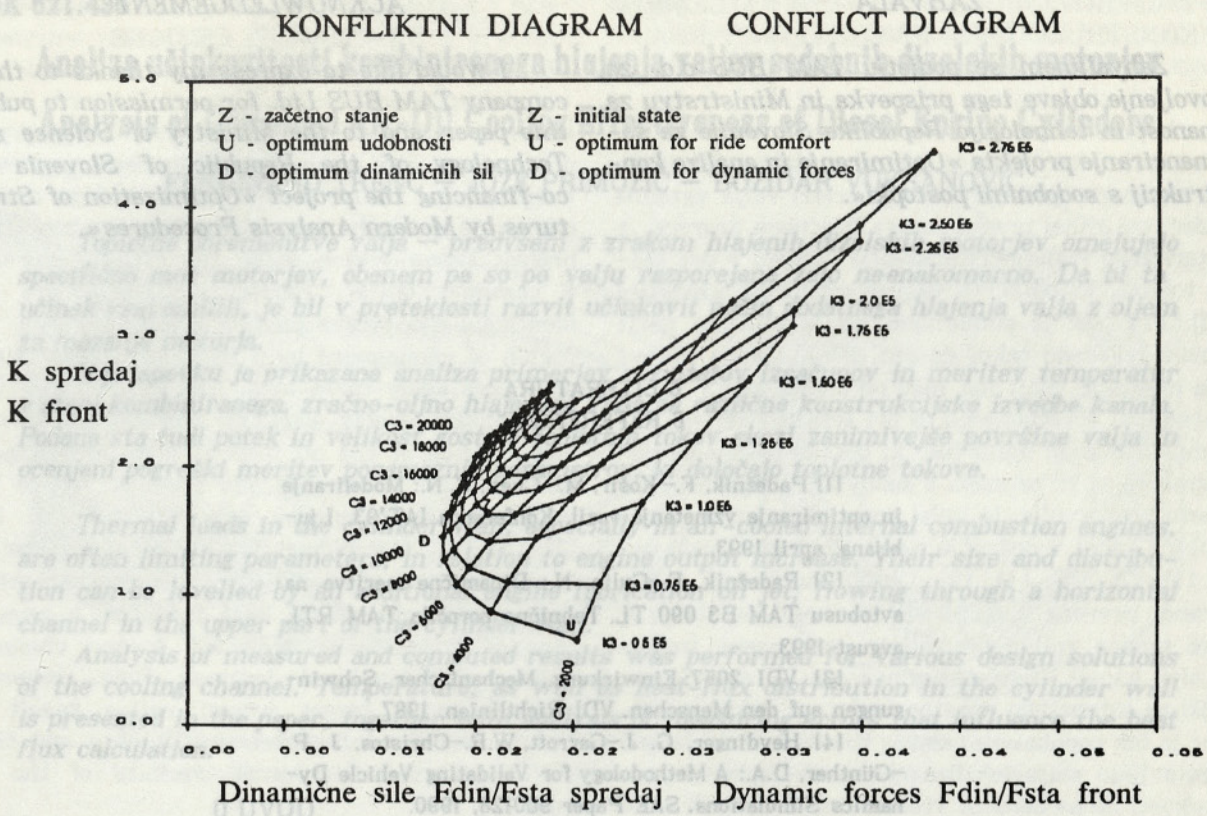
Parameter	začetna vrednost initial value	končna vrednost final value
A	$2 \cdot 10^{-6}$	$0{,}35 \cdot 10^{-6}$
w	2,0	2,5
M_1	400 kg	400 kg
M_2	1 000 kg	1 000 kg
M_3	70 kg	70 kg
M_4	11 200 kg	11 200 kg
J_4	100 000 kgm^2	46 000 kgm^2
K	$1 \cdot 10^6$	$1 \cdot 10^6$
C	1 000 Ns/m	1 000 Ns/m
K_2	2 MN/m	2 MN/m
C_2	2 000 Ns/m	2 000 Ns/m
K_3	0,1 MN/m	0,1 MN/m
C_3	7 000 Ns/m	9 000 Ns/m
K_4	0,20 MN/m	0,25 MN/m
C_4	11 000 Ns/m	11 000 Ns/m
K_5	20 000 N/m	20 000 N/m
C_5	1 500 Ns/m	1 500 Ns/m



Sl. 4. *Končno ujemanje avtospektrov pospeškov*
Fig. 4. *Final complience of acceleration autospectra*

optimiranja. Najlaže si stvari predstavimo s konfliktnim diagramom (sl. 5), kjer je narisana udobnost v odvisnosti od dinamičnih sil za različne vrednosti parametrov vzmetenja avtobusa.

presented with a conflict diagram (Fig. 5), in which the comfort is drawn as a function of dynamic forces for various parameter values of bus suspension.



Sl. 5. *Konfliktni diagram sprednjega dela avtobusa*

Fig. 5. *Conflict diagram for bus front end*

5 SKLEPI

Menimo, da smo naredili dovolj dober dinamični model avtobusa, ki se lahko uporabi za nadaljnje analize. Začetni model je bilo treba izboljšati na podlagi meritev dinamičnih odzivov in vzbujanja. Narediti je bilo treba dva modela avtobusa — enega za vožnjo po slabši cesti, drugega pa za vožnjo po gladki cesti. V drugem primeru je treba upoštevati vzbujanje zaradi vrtenja koles — večkratnike frekvence vrtenja koles.

Pri izbiri parametrov optimiranja je treba izvesti analizo občutljivosti. Pri optimiranju je treba upoštevati najznačilnejše parametre. Spoznali smo, da včasih tudi izmerjeni podatki niso najbolj zanesljivi.

V prihodnje je treba ponovno izmeriti vzbujanje zaradi neravnin cestišča, vztrajnostne momente avtobusa itn. Zanimiva bi bila primerjava dobljenih rezultatov z nelinearnim modelom, ki računa v časovni odvisnosti. Preizkusiti bi bilo dobro tudi preprost tridimenzionalni model in prenesti program za dinamični preračun vzmetenja vozil na osebni računalnik.

5 CONCLUSIONS

We developed a fairly good bus model that can be used for further analyses. The initial model had to be improved on the basis of measurements of dynamic responses and excitations. We had to develop two bus models - one for driving on a rough road and the other for driving on a smooth road. In the second case, the excitation due to the rotation of wheels has to be considered — the multiples of wheel rotation frequencies.

When choosing the optimization parameters, an analysis of sensitivity has to be made. In optimization, the most significant parameters must be considered. We found that even the measured data were sometimes not quite reliable.

In future it will be necessary to remeasure the excitation due to road surface uneveness, the moments of inertia of the bus, etc. It would be interesting to compare the results obtained with a non-linear model calculated in the time domain. It would also be advisable to check the simple three dimensional model and to transfer the programme for dynamic calculation of vehicle suspension to personal computer.

ZAHVALA

Zahvaljujem se podjetju TAM BUS d.d. za dovoljenje objave tega prispevka in Ministrstvu za znanost in tehnologijo Republike Slovenije za sofinanciranje projekta »Optimiranje in analiza konstrukcij s sodobnimi postopki«.

ACKNOWLEDGEMENT

I would like to express my thanks to the company TAM BUS Ltd. for permission to publish this paper and to the Ministry of Science and Technology of the Republic of Slovenia for co-financing the project »Optimization of Structures by Modern Analysis Procedures«.

6 LITERATURA
6 REFERENCES

[1] Padežnik, F.–Košir, M.–Chen, S. N.: Modeliranje in optimiranje vzmetenja vozil. Konferenca IAT'93, Ljubljana, april 1993.

[2] Padežnik, F.–Gulin, N.: Dinamične meritve na avtobusu TAM B3 090 TL. Tehnično poročilo TAM RTI, avgust 1993.

[3] VDI 2057: Einwirkung Mechanischer Schwingungen auf den Menschen. VDI Richtlinien, 1987.

[4] Heydinger, G. J.–Garrott, W.R.–Christos, J. P. –Günther, D.A.: A Methodology for Validating Vehicle Dynamics Simulations. SAE Paper 900128, 1990.

[5] Padežnik, F.: Verifikacija in optimizacija dinamičnih modelov. Magistrsko delo, TF Maribor, januar 1992.

Avtorjev naslov: mag. Franci Padežnik, dipl. inž.
TAM – Razvojno tehnični inštitut d.o.o.
Ptujska cesta 184
62000 Maribor

Author's Address: Mag. Franci Padežnik, Dipl. Ing.
TAM Ltd. Development Institute
Ptujska cesta 184
62000 Maribor, Slovenia

Prejeto:
Received: 13.6.1995

Sprejeto:
Accepted: 31.8.1995