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TRANSMISSIBILITY OF SUSPENDED SEAT LOADED WITH PASSIVE MASS AND WITH HUMAN DRIVER - DISCUSSION

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Abstract: *Person sitting on a suspended seat, which is excited by floor motion (f.e. truck cab floor), plays a passive as well as an active role in influencing own vibratory motion. Transmissibility of the floor vibration to a person, occupying a suspended seat, differs therefore vastly from transmissibility of the floor vibration to a passive seat load. Identification of these human reactions could be important, as it could alter vibratory comfort criteria as well as demands on active control of suspended seats. Some hints for further research, which could lead to the identification of force reactions of a person sitting on a suspended seat excited by vibratory floor motion, are discussed.*

Keywords: ***Suspended vehicle seat, vibration transmissibility, human reactions***

1. Introduction

Air-suspended seat with active control, intended for use in trucks, was developed at TU Liberec some years ago (Fig.1). Stages of this development were presented in several papers, e.g. (Kupka et al., 2007; Kupka et al., 2006; Janeček et al., 2005).

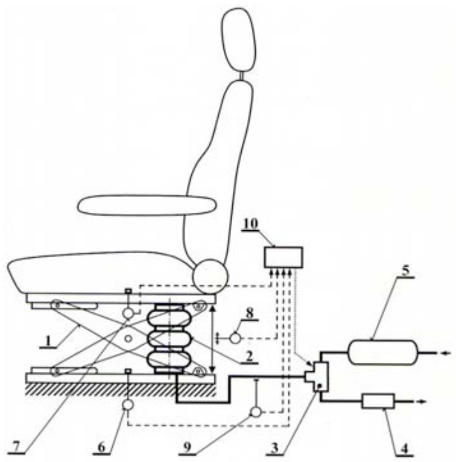

Figure 1. Basic arrangement of the active seat TUL (Apetaur et al., 2009)

Basic philosophy of its control was relatively simple. Important truck cabfloor vertical motion has meaningful frequency content between approx. 0.5 Hz to approx. 12 Hz. It can have (under very hard off-the-road conditions) maximum strokes up to +/-12 cm. The aim of the active seat control was to obtain optimum isolation of the loaded seat from cabfloor vibration. Transmissibility of floor vertical motion to the seat, which would be near to 1 for floor motions with frequency around 1 Hz and which would rapidly fall to lowest achievable values for higher frequencies, was therefore demanded. Excitations with frequencies under 0.5 Hz and over 10 Hz were considered as unimportant.

Seat transmissibility is in the paper defined as frequency dependence of the ratio of seat cushion amplitudes under the load resp. driver to amplitudes of cabfloor vertical motion under the seat.

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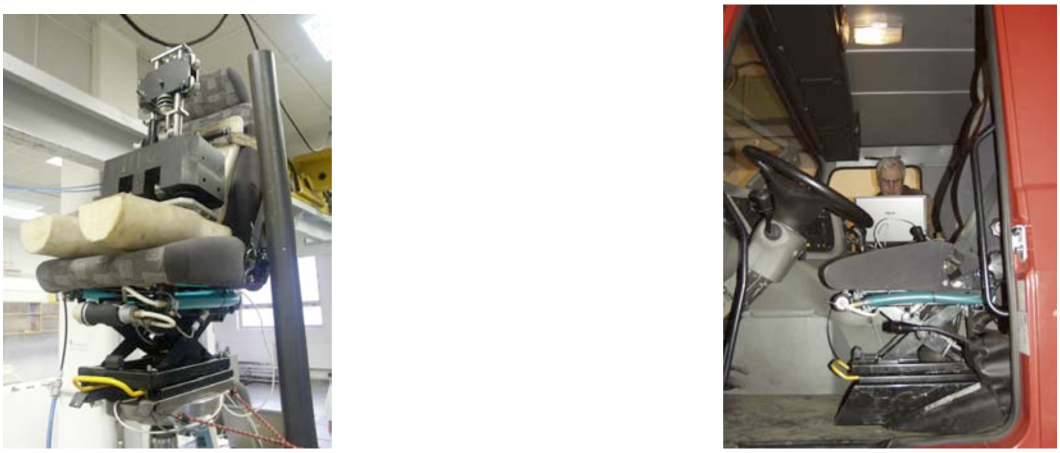


Figure 2. Active seat with a dummy in laboratory and in the truck

Seat transmissibility was tested in the laboratory with passive load, formed both by simple mass and by 3DOF dummy (Fig.2), and excellent fullfilment of this demand was achieved, especially at the latest seat development stage (Fig.3b).

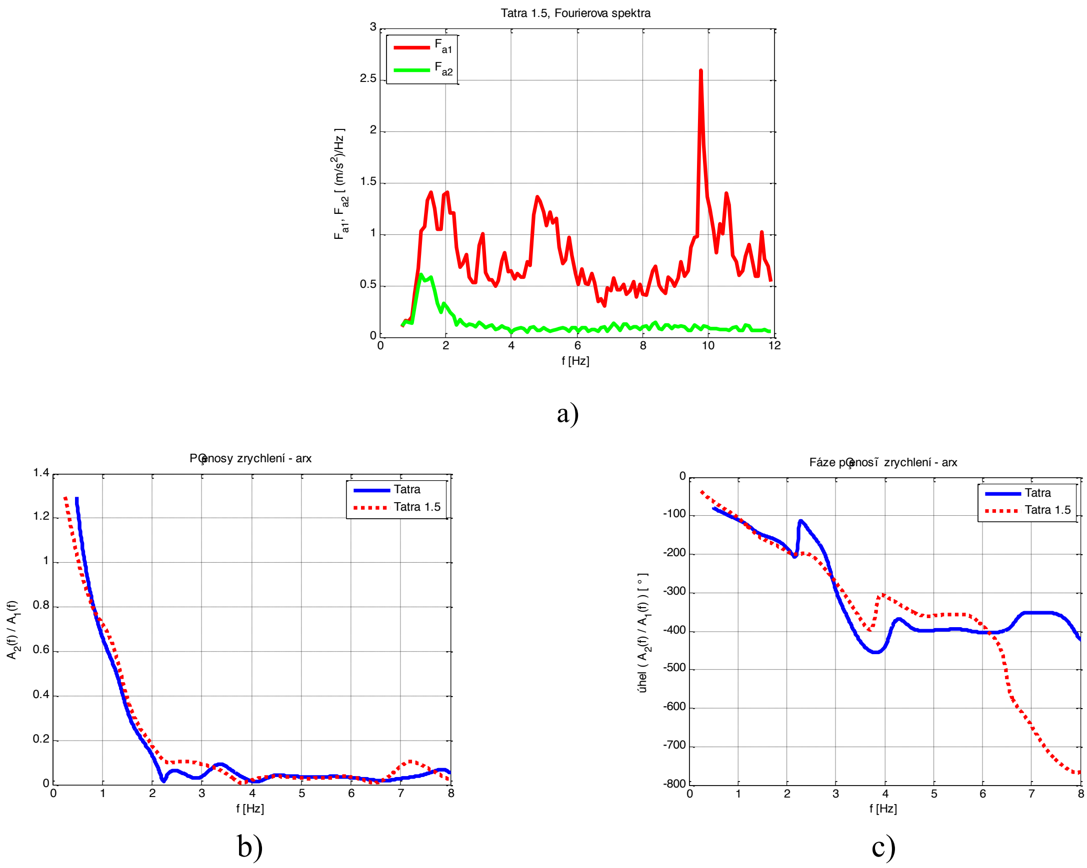


Figure 3. Transmissibility of the active seat TUL (latest development stage) obtained in laboratory with very intensive quasistochastic floor inputs „TATRA 1“ and „TATRA 1.5“ (with maximum total floor stroke of approx. 20 cm): a) Fourier spectrum of the input acceleration „TATRA 1½“and of the resulting seat acceleration, b) amplitude transmissibility, c) phase transmissibility

This result can be compared to the transmissibility of a passive seat from a renown producer, similarly excited (Fig.4).

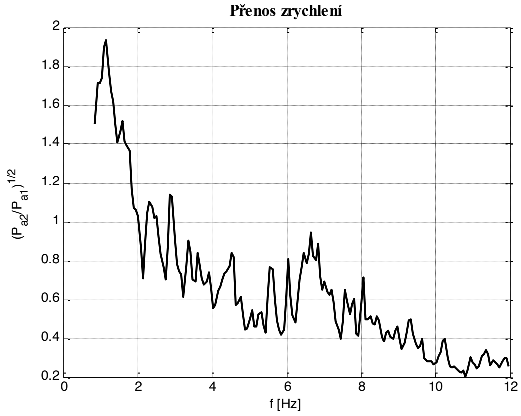
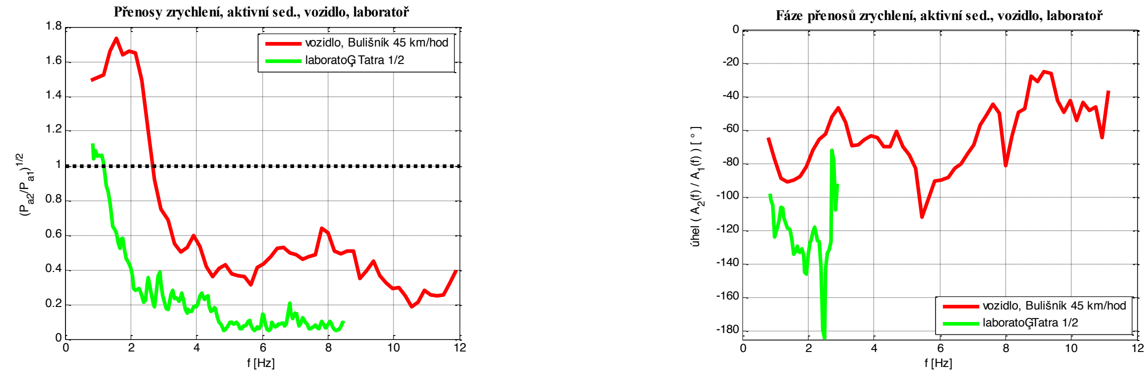


Fig.4 Transmissibility of a a certain production passive seat (low damper adjustment) obtained in laboratory with „TATRA ½" floor input

(Remark: Laboratory tests were carried out with different excitational processes. Laboratory results shown in this paper are mostly achieved on s.c. "TATRA" quasistochatic process, imitating vertical cabfloormovement of loaded TATRA 815 truck running on the "buližník" test track, differently scaled. (1/2, 2/3, 1, 1.5).)

Figure 5. Test tracks on TATRA proving ground, vehicle is riding on the "belgická" test track, "buližník" track in front of the figure (Apetaur et al., 2009)

Active seat, occupied by driver, was then tested in a TATRA truck (Fig.2) on different test tracks (Fig.5) and roads. Transmissibilities completely different from those measured in the laboratory were however obtained (Fig.6) *(Apetaur et al., 2009)*.



a) b)

Figure 6. Comparison of the transmissibilities of active seat TUL (intermediate development stage) passively loaded in laboratory (green) with signal TATRA ½ and with driver on the test track "buližnik" (red) (Fourier spectrum of both vertical excitations is similar): a) amplitude transmissibilities, b) phase transmissibilities

Same behavior was however observed with a passive seat, tested previously to the tests carried out with active seat TUL, so that very strong influence of the driver on his own motions on any, active or passive, suspended seat has to be accepted as a real phenomenon, as already discussed by the authors in a previous paper (Apetaur et al., 2009).

Person, sitting on a suspended seat, can evidently alter consciously or unconsciously his/her (predominantly) vertical position relatively to the floor. This is possible on non-suspended seats to very small extent only because of the limited elasticity of the seat cushion. Activity of the person, which is sitting on a suspended seat, leads to profound change of the seat+person dynamic system in comparison to seat+passive load dynamic system. The fact, that the person sitting on a suspended seat can influence his/her motion, is of course known, but its extent and effects on the total seat/person vibration transmissibility are surprising.

On-the-road comparison of the driver´s comfort, when sitting on a certain passive seat and on the developped active seat TUL, showed relatively small differences between their measured transmissibilities (Apetaur et al., 2009), though laboratory results with passive load and similar excitation showed far better isolation behavior of the active seat. As transmissibility and weighted acceleration evaluation are so far the only characteristics used for comparison of different seat designs, mentioned on-the-road results led unfortunately to loss of interest from the side of the industrial investor in the continuation of the project and practically to the abandonment of further development of the active seat at TUL.

Two questions arise evidently:

- if a person influences very substantially its motions on the suspended seat, it must use for it some muscular as well as mental energy; is it then correct to judge his/her vibratory comfort on a suspended seat by measuring its vertical acceleration only, as it is commonly done to-day (ČSN 14253, 2006; ČSN ISO 2631-1, 1999)?
- optimization of the transmissibility of a suspended seat loaded with passive load alone evidently does not express real development tasks on the dynamics of controlled suspended seats in transport vehicles; is it possible to state the demands on dynamic property of a suspended seat respecting the actual driver´s/passenger´s reactions?

Identification of person´s reactions, when sitting on a suspended seat, would be needed to answer both of these questions.

Under the term "identification" is meant:

- determination of the physical nature of human force reactions, which influence seat vertical motion;

- discovery of the relevant kinematic inputs (cab and body motions) causing these force reactions;
- mathematical description of the relations between the kinematic inputs and resulting force reactions of the person.

Simultaneously following important questions have to be answered:

- how individual are these reactions ?
- are they same for different floor motions, described f.e. by their PSDs?
- how do they depend on the properties of the seat vibratory system?

There is practically no knowledge about any of these items, as experimental as well as theoretical research in this field does not exist.

A very elementary attempt was made to get an impression about the possibility of modelling person´ s reactions when sitting on a suspended seat subjected to floor vibration. It is based on results of few available tests, which were not directed to the solution of this problem. This attempt could be therefore directed only to the identification problem in a narrow sense, i.e. to the question whether it seems to be possible to find out relevant kinematic inputs causing such force reactions (of so far unknown nature) of a certain person sitting on a certain seat in a certain truck, which produce vibration transmissibilities similar to those stated in tests.

It must be enhanced, that results shown further must be therefore considered only as an illustration of necessary steps, which could lead to better understanding of this problem.

2. General remarks on the behavior of a person sitting on a suspended seat. Approach to the identification problem

Fig.6 shows comparison of the results gained with the active seat in the laboratory (passive load) and on the testing ground (seat loaded by driver). Difference is significant.

There can be posed an objection, that excitation of the seat with passive load in laboratory and excitation of the seat with driver in the vehicle are different. Whereas the excitation in laboratory is strictly vertical, cab of a riding truck exerts movements in all six DOF, so that the driver in reality does not react on vertical acceleration only. This is to some extent true, but results gained on relatively smooth roads, where cab movements are predominantly vertical**,** show seat/driver system transmissibilities similar to those gained on severe test-tracks and very different from seat/passive load transmissibility (see Fig.10, curves “1” and “4”).

It can be therefore taken as granted, that vertical cabfloor movements form the deciding excitation of the seat/driver system for most driving conditions, even on relatively rough test tracks. Fore-and-aft and tilting motions of the cab should be however taken in further tests into account as potential excitational sources on difficult tracks as well.

Relatively well documented active-seat/driver transmissibilities (measurements TUL) unfortunately cannot be taken as a base for the driver´s effort interpretation, as the controlled seat itself forms a highly non-linear time-dependent dynamic system.

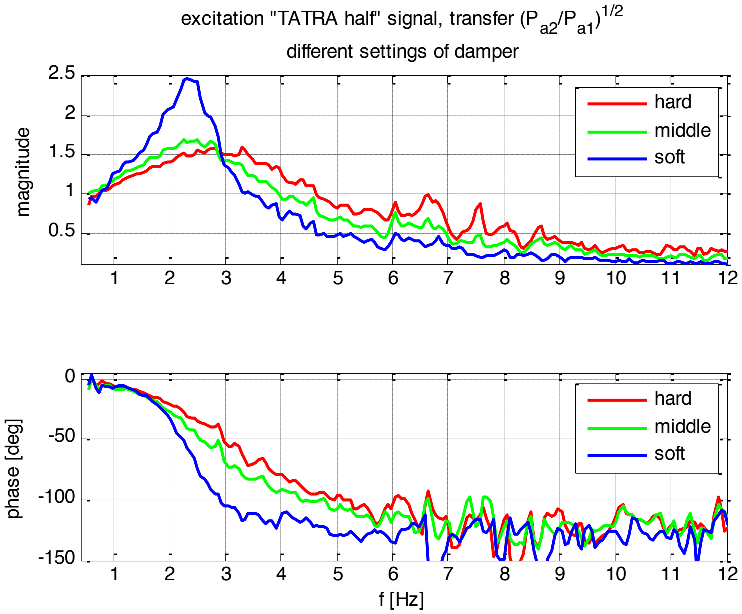


Figure 7. Amplitude and phase transmissibility of a certain passive seat with passive load, „hard“, „middle“,„soft“ damper adjustment, laboratory measurements, quasistochastic “ TATRA ½“ input; (some difference in natural frequency, seen on the figure, between “soft”,”middle” and “hard” damper adjustments is caused by the damper properties, as the damper exerts some “stiffness” property, especially in “hard” adjustment)

Following discussion is therefore directed to persons sitting on passively suspended seats. Dynamic behavior of these seats, loaded with passive mass, is very near to that of a linear 1DOF model in practically all so far measured cases (Apetaur et al., 2009). Seat suspension non-linearearities (air spring characteristics, damper characteristics, friction) seem to play a secondary role only. An example is shown on Figure 7.

Measurements, on which following discussion is based, were conducted by another laboratory with a certain passive seat (natural frequency approx. 1.25 Hz for (seat+passive load) mass equal to approx. 80 kg), which could not be tested by us, so that complete data were not available (see Apetaur et al., 2009).

The only possibility for a person, sitting on a suspended seat, to change his/her vibrational behavior is by exerting some time-changing force acting on the seat structure in vertical direction.

It can be produced in different ways.

First, and most probable, is force originated by the sitting person in the contact of its body with the cab, by driver by legs (but he must be able to operate the pedals) and by arms (but he must be able to operate the steering wheel), by passenger by legs only (Remark: in extreme off-road circumstances he can stabilize himself by holding some appropriate handle in the cab; this is often the case.). Reactions of the driver and of the passenger to the floor vibration will be therefore most probably different.

Second possible force origin is dynamic, by near-vertical motion of “free” body parts. Especially motions of head and of upper arms with shoulders can be effective in producing near-vertical forces even without causing notable relative motion of the back to the backrest.

Mentioned forces can have either purely passive, inertial, origin, or can be caused or initiated by subconscious muscular actions of the person.

Motions of body´s chest and internal organs seem to play a secondary role only. Results gained in seat laboratory tests with 3DOF dummy (Fig.2), which imitates passive vibrational properties of a human body, and with simple passive mass, showed very similar transmissibilities.

Basic computations, as well as measurements (Fig.8), have further shown, that flexibility of the seat cushion does not play any substantial role on the seat transmissibility.

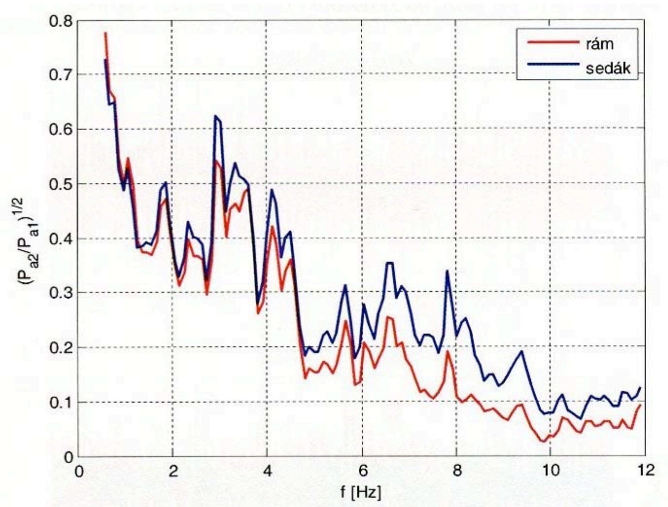


Figure 8. Comparison of the transmissibility from the cabfloor to seat structure ("rám", red) and to seat cushion ("sedák", blue) – active seat TUL (intermediate development stage), laboratory measurement with a dummy, "TATRA ½" input

Simple dynamic model was therefore taken as basis for a very crude "identification" (in narrow sense) attempt.

It was assumed, that the torso of the person, who sits on the seat, is a passive mass joined with movable seat structure mass, linearilly suspended on the cab floor.

The dynamic equilibrium equation of the seat+body dynamic system under these simplifying assumptions is

$$m.(d^2x/dt^2) + b.(dx/dt- dz/dt) +k.(x-z) = F \quad (1),$$

where x(t) is the vertical seat/body motion, z(t) floor vertical motion, F(t) force influence exerted by person sitting on the seat, acting in vertical direction, m (kg) total mass of (seat+body), k (N/m) stiffness of seat spring, b (Ns/m) damping coefficient of seat damping. This equation describes a linear 1DOF system, whose properties need not to be discussed.

Force reaction F(t), influencing motion of the sitting person, must be excited by some input signals $v_i(t)$ perceived by him/her. It can assumed, that these signals induce individual force processes $F_i(t)$, so that the actual reaction force F(t) is composed as their sum

$$F(t) = \Sigma F_i(t) \quad (2a).$$

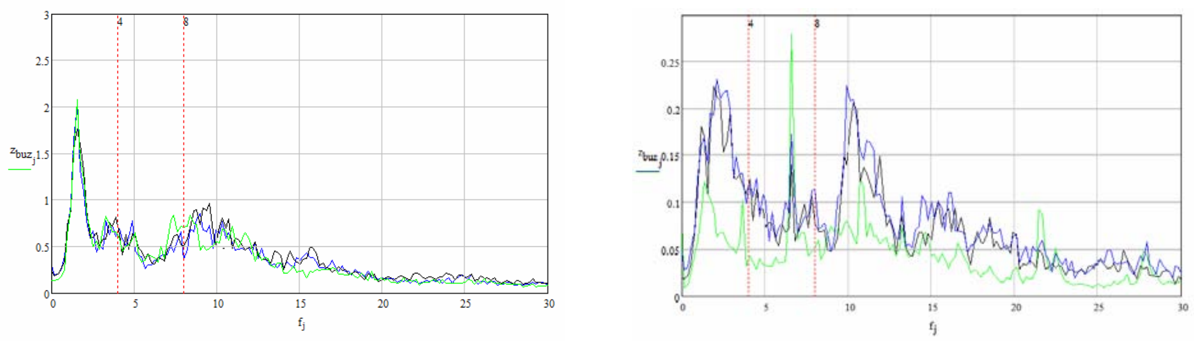
It is so far unclear, which inputs $v_i(t)$ are causing actual force reactions $F_i(t)$. Evidently all kinematic parameters of cab and seat motions can be taken into account, i.e.:

- stroke, velocity, acceleration, jerk of the floor motion z(t),
- stroke, velocity, acceleration, jerk of the relative seat to floor motion (x(t)-z(t));
- stroke, velocity, acceleration, jerk of the seat motion x(t).

Determination of most important inputs and of their influence will be evidently one of the crucial problems in future proper investigations. It can be expected, that relations between $v_i(t)$ and related force components $F_i(t)$ can be quite complicated.

"Identification" of the human reactions is here understood in a very narrow sense as finding most relevant inputs v_i which excite reaction forces F_i, and laws describing their mutual $F_i(v_i)$ relations. Actual origins of the reaction forces F_i are not discussed, as experimental data are not available.

Proper identification will be evidently complicated by its subjective nature. Results gained by experiments with one driver performing only one drive on a specific track with one damper adjustment are further used. The driver had a perfect knowledge of the test tracks and of the truck, i.e. he was



a) b)

Figure 9. Fourier spectrum of the vertical cabfloor motion:
a) on "pavé" test track, b) on good public road "silnice"

perfectly aware what vibratory conditions he has to expect, he was prepared to sustain vibrational exposition with a level known to him in advance.

Vehicle rides on three surfaces were taken as basis for further discussion:

- ride on a good public road „silnice" (Fig.9b), vehicle speed 80 km/h, length 1000 m,
- ride on test track „belgická", imitating very bad road, vehicle speed 15 km/h, length 400 m,
- ride on test track „pavé", imitating extremely bad road (Fig.9a), vehicle speed 25 km/h, length 400 m.

Intensity of the vibration of the cabfloor on these tracks can be very roughly scaled:

- "silnice" 1 : "belgická" 2.5 : "pavé" 8, at frequency around 1.5 Hz,
- "silnice" 1 : "belgická" 2 : "pavé" 4, at frequency around 10 Hz,

i.e. intensity of vibrations of the cabfloor on these tracks was vastly different.

Transmissibilities cabfloor/seat, gained by original investigations (partially described in Apetaur et al., 2009), are used in further discussion.

Following observations can be made:

- Floor motion spectra have two distinctive peaks at frequencies approx. 1.5-2 Hz and approx. 10 Hz, corresponding to the natural frequencies of the vehicle suspension and one less pronounced at approx. 6.5 Hz, corresponding to cab suspension; excitation at frequencies below 1 Hz is relatively low, which of course influences accuracy of the determination of the transmissibility at theses frequencies; shown transmissibility values for frequencies under 0.5 Hz should not be taken into account.
- transmissibility at frequencies over 5 Hz is near to 0.5 and is very slightly dependent on the excitation intensity (track properties) as well as on the seat damper adjustment ;
- resonance of the seat+(passive load) dynamic system (at approx. 1.25 Hz) is practically always suppressed;
- transmissibility for frequencies 0.5 to approx. 1.5 Hz is extremely high on all rough tracks.

Measured seat transmissibilities, gained on mentioned three very different tracks, were approximately simplified as indicated on Fig.10. Transmissibilities, gained on other test tracks, lie in the hatched area.

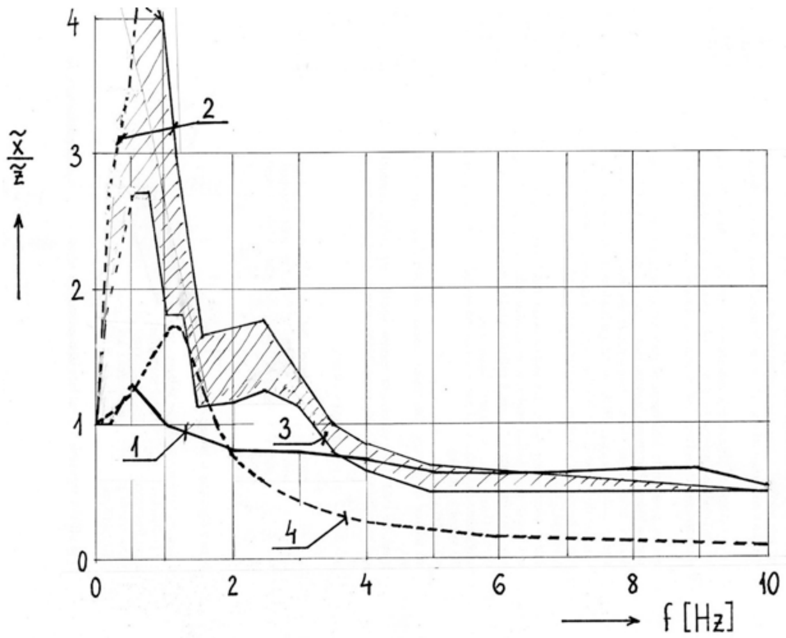


Figure 10. Simplified transmissibilities of seat/driver system measured in on-the-road experiments: "1" silnice=road, 80 km/h;"2" belgická test track, 15 km/h; "3" pavé test track, 25 km/h; "4"(dashed) expected transmissibility of seat/passive load system, medium damping

These simplified transmissibilities were formed as medium ones for "medium" damping of the measured passive seat. Expected amplitude transmissibility of the passive seat, used in the measurements, loaded with passive load is shown on the figure as well. Difference, between the "passive load" transmissibility and the "driver load" transmissibilities, is evident.

Equation (1), with constants m=80 kg, b=480 Ns/m, k=4960 N/m, was used as base for the identification attempt. Forces $F_i(t)$ were arbitrarilly supposed to be described by linear second order differential equations with inputs $v_i(t)$. Because of the linearity of the model, its transmissibility could be computed by using harmonic input z(t).

The task was to achieve transmissibilities of this model similar to those shown on Fig.10.

This was done purely empirically, trial and error style, by changing inputs, control laws and constants. Following relations were found at the end:

$$F(t) = F_1(t)+ F_2(t)+ F_3(t)+ F_4(t) \qquad (2b),$$

with individual forces $F_i(t)$ computed as:

$$(dF_1/dt) = -1.F_1 - \beta.(dz/dt);$$

$$(d^2F_2/dt^2) = -60. (dF_2/dt) - 4000.F_2 + 128000.(d^2z/dt^2);$$

$$(d^2f_3/dt^2) = -8.(df_3/dt) - 300.f_3 + 200.(d^2x/dt^2);$$

$$F_3=(df_3/dt);$$

$$(d^2F_4/dt^2) = -6.(dF_4/dt) - 62.F_4 - 2400.(6.(dx/dt-dz/dt)- 62.(x-z)) \qquad (3).$$

These equations could be used for all three excitational conditions. It is interesting to note, that even for such extremely different excitational conditions only constant β, which directs the transmissibility at low excitational frequencies, had to be changed to get reasonable results. It was stated as:

„road“ β=4800; „pavé“ β=10400; „belgická“ β=16000.

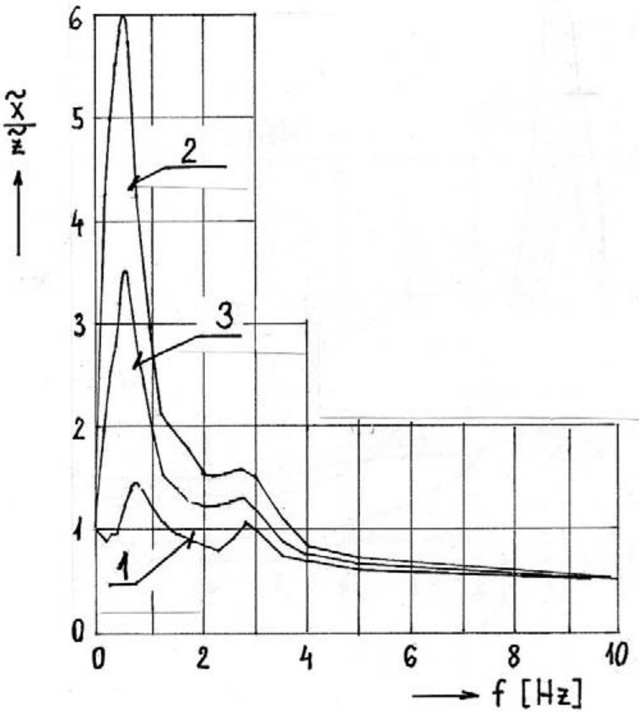


Figure 11. Transmissibilities gained by seat+driver model (Eqs.1,2b,3): "1" silnice=road, 80 km/h;"2" belgická test track,15 km/h; "3" pavé test track,25 km/h

Amplitude transmissibilities gained by this seat/driver model are shown on Fig.11. Computed transmissibilities correspond fairly well with measured ones (Fig.10).

Some initial supposals about the nature of the driver´s reactions were to some extent confirmed by the model:

- reaction (force F_2) of the driver to relatively higher frequency floor excitation (over 5 Hz) seems to be caused by floor acceleration (d^2z/dt^2); its description is qualitatively and quantitatively same on all roads;
- driver tries to diminish relative floor to seat movements in the frequency range 1 to 3 Hz (force F_4), seemingly as reaction to relative body to cabfloor movement (x–z) and its velocity (dx/dt-dz/dt) ; force F_4 seems to suppress pronouncedly resonance effect of the original passive mass dynamic system; its description is qualitatively and quantitatively same on all roads;
- some destabilizing effect (force F_3), caused probably by phase delayed body reactions, can be clearly seen around 2 to 4 Hz; its description is qualitatively and quantitatively same on all roads; force F_3 seems to be dependent on body jerk (d^3x/dt^3).

But:

- origin of the force F_1, which substantially increases transmissibility in the range 0.5 to 4 Hz, is difficult to explain; its stated first order dependence on the floor velocity (dz/dt) is surprising; its description is qualitatively same but quantitatively different (constant β) on different roads; necessary change of constant β cannot be so far explained (excitation intensity in vertical direction is highest on „pavé 3" track, lowest on „silnice 1" track).

(Remark: discussed transmissibilities in the very low frequency range under 1 Hz must be considered very carefully, as cabfloor vibration intensity with frequencies under 1 Hz is in all tests, which were carried out, very low (see Figs. 3 and 9) and the time of observation (around 50 s) of individual rides is for their evaluation relatively short; values shown can be therefore relatively inaccurate.)

The fact, that transmissibilities of the seat+driver system stated for very different input intensities, could be successfully mathematically modelled by linear differential equations with change of one constant (namely β) only, was unexpected and is certainly surprising.

It must be enhanced that shown equations <u>cannot</u> be considered as meaningful solution of the identification problem as:

- experimentally stated transmissibilities were gained from measurements with one subject (driver) performing one drive on a certain track only;
- approximation of the actual transmissibilities on Fig.10 was very crudely done from insufficient data;
- very crude models of the seat system and of the human body were used;
- validity of Eqs.1, 2, 3 was not checked by:
    - phase relations comparison, as no experimental data were available;
    - computation of total correcting force F(t) , which would show, whether the driver is physically able to generate it;
- origin of the individual correcting forces in Eq.3 is unknown; hence validity of their shown differential description is doubtful.

Most probably, other scenarios are possible as well.

The authors see actual value of the shown "identification" attempt in providing some starting points for further research. Its sole positive result can be seen in the fact, that it seems to be possible to find some general mathematical model of force reactions, which correct vibratory motion of a person sitting on a suspended seat which is excited by floor motion.

However, without further research, including relatively costly and time consuming experiments as well as sophisticated identification of their results, there is no chance to enlarge the very limited knowledge presented here.

3.Conclusions

Person, sitting on a suspended seat, influences radically his/her own vibratory motion by exerting time-dependent forces of so far not cleared origin. This is valid for very different floor vibration levels, reaching from very low to extreme ones. Identification of the processes, which cause such muscular and mental involvement of the sitting person in directing his/her vibration, would lead:

- very possibly to the change of vibratory comfort evaluation of persons sitting on suspended seats, as some further conditions, f.e. evaluation of forces between legs and arms and vehicle cab or evaluation of relative motions of different body parts (head to spine, etc.), evidently should be added to the usual method of weighted acceleration evaluation (ČSN 14253, 2006; ČSN ISO 2631-1, 1999);
- to the gain of information for further development work regarding actual demands on active seat control, important for improving driver/passenger/operator vibrational comfort in vehicles and heavy machinery.

Proper identification would demand to distinguish physical nature of the forces, exerted by the sitting person, determination of kinematic inputs, which provoke them, and mathematical description of their relations.

Attempt to identificate reactions of driver sitting on a suspended seat, discussed in the paper, was done in a narrower sense. It had the purpose to find out, whether a mathematical description of the driver´s reactions to kinematic inputs, formed by floor and body motions, seems to be possible at all. Its result is encouraging, though many questions are left open.

Some observations, gained from the identification attempt discussed, about roles of individual kinematic inputs on the origin of human reaction forces are however interesting, though experimentally unconfirmed.

The authors consider the possibility of empirical description of force reactions of a person sitting on a suspended seat, their "identification" in a narrow sense, as realistic.

Proper identification of human reactions, which would lead to its practical exploitation, is however a much more complicated task, demanding laboratory measurements with a group of individuals and their statistical evaluation. Laboratory means as well as theoretical background are at disposal at TUL (see Apetaur et al., 2009) and other laboratories, though evidently new identification algorithm would have to be created because of the multitude of possible inputs.

No interest to support work in this exciting field, dealing with man/machinery interaction, was however found so far.

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