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The design of an inertial testbed for the tests of gearboxes

Marek Jaśkiewicz[1], Jakub Lisiecki[2], Szymon Lisiecki[2], Grzegorz Ślaski[3], Dariusz Więckowski[2]

[1] Kielce University of Technology, Department of Automotive Engineering and Transport
25-314 Kielce, Al. Tysiąclecia Państwa Polskiego 7, e-mail: m.jaskiewicz@tu.kielce.pl
[2] Automotive Industry Institute (PIMOT)
03-301 Warszawa, ul. Jagiellońska 55, e-mail: {j.lisiecki; s.lisiecki; d.wieckowski }@pimot.eu
[3] Poznan University of Technology
60-965 Poznań, ul. Piotrowo 3, e-mail: Grzegorz.Slaski@put.poznan.pl

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Abstract
The paper presents the technical assumptions and the design of a testbed suitable for conducting experimental tests of gearboxes. In the case of drivetrain assemblies, most often they are built on testbeds, much more seldom in vehicles. Experimental tests constitute a broad field due to the differentiation of functions of individual assemblies and their components in the drivetrain system of cars and machines. Conducting simulation tests (on simulation testbeds) consists in the possibly faithful recreation of real operating conditions of an assembly in a vehicle. The testbeds for such tests are complex and expensive but the obtained results are more reliable and more precisely, than in the case of other methods, take into consideration the impact of different operating loads on the durability of the research object. Due to the extent of the topic, this study is only the introduction to the design work whose aim is to prepare the design of a testbed.

Introduction

Vehicle tests can be categorized depending on the adopted criterion [1, 2, 3, 4].

Due to the research object the tests can be divided into:

1) the tests of the whole vehicle;
2) the tests of assemblies;
3 the tests of individual components (parts).

In the case of drivetrain assemblies, most often they are built on testbeds, much more seldom in vehicles. These tests can be divided into:

– functional tests: enabling the assessment of the correctness of assembly operation;
– durability tests: enabling the assessment of the lifespan of an assembly and fatigue phenomena;
– temporary strength tests: enabling the finding of the weakest elements of an assembly, the determination of the strength reserve coefficient and the assessment of deformations of elements in the load function.

Due to the diversity of functions of individual assemblies and their elements in the drivetrain system, testing them is a broad field. Laboratory tests of durability of assemblies are conducted on specially prepared testbeds with the use of different methods of programming them.

The testbeds for those tests can be divided into:

– specialist, for functional tests;
– simulation, for testing the dynamics of the drive system, for durability, optimization tests.

Conducting simulation tests (on simulation testbeds) consists in the possibly faithful recreation of real operating conditions of an assembly in a vehicle. The testbeds for such tests are complex and expensive but the obtained results are more reliable and more precisely, than in the case of other methods, take into consideration the impact of different operating loads on the durability of the research object. Such testbeds are divided into:

– testbeds with power take-off through the brake and with an internal-combustion engine as the prime mover (also inertial testbeds are among them);
– testbeds with circulating power with mechanical tensioners or rotary electrohydraulic exciters.

Simulation tests, carried out based on input signals, conducted on inertial testbeds, are among the methods quite commonly applied for testing durability of the drive system assemblies. The principle of operation of those testbeds consists in recreating real operating conditions and parameters of assemblies in a vehicle. Such testbeds are used for recreating the operation of assemblies in transient states when loads are much greater than when driving with a constant speed.

Programming the tests includes three issues:

1) Selection of dynamic properties of a testbed ensuring the simulation of object operation.

The selection of dynamic properties of a testbed includes the determination of the equivalent reduced moment of inertia of vehicles masses being in progressive and rotary movement, the reduced torsional spring stiffness of the driving system and the attenuation occurring in it. The dynamic parameters which require recreation on a testbed are most often determined experimentally (e.g. diametral stiffness of tyres, torsional spring stiffness of semi-axes, attenuation) or calculated – e.g. the equivalent moment of inertia of a vehicle. The determined values are recreated on a testbed using its adjustment capabilities, however the properties of the testbed itself need to be considered. For example, when recreating the moment of inertia of vehicle masses on a testbed, a set of spinning masses is assumed with the moment of inertia smaller from the calculated equivalent moment of inertia of vehicle masses by the value of the moment of inertia of the remaining spinning elements of the testbed (e.g. spinning brake elements or testbed gearbox). The development conditions of the research object are recreated thanks to the use of the original elements and assemblies, cooperating with the research object in a vehicle (main engine, suspension elements of assemblies, jointed shafts and connectors).

2) Selection of forcing signals specifying the simulation of the loads of an object on a testbed (programming of a single operating cycle).

The selection of forcing signals consists in measuring, in the conditions of road tests, the values describing the operation of mechanisms controlling the engine and the assemblies of the drive system which comprises the examined object. The forces and displacements are measured in control systems: the gearbox, clutch and engine damper. Moreover, rotary speeds of the drive system elements are measured at which individual gears are switched. The simultaneous registration of all those values in the function of time enables to determine the dependencies conditioning the cooperation of individual control mechanisms. Many repetitions of such tests allow for determining average values of sought after values which are next recreated in the system of controlling mechanisms on a testbed.

3) Selection of the number of cycles of simulation loads of a given mileage.

The number of activations of individual gears is assumed as the quantity allowing for specifying the correlation between the time of tests conducted on the testbed and the mileage. During experimental tests the average number of activations of each gear is determined in relation to the mileage of a given vehicle. A test cycle is repeated on the testbed till a number of activations corresponding to the assumed mileage will be achieved for each gear.

In order to undertake the above tests, one needs to have such research potential that would allow to prepare such a testbed. This paper pertains to the design of an inertial testbed for the tests of gearboxes (Fig. 1).

Assumptions and structure of an inertial testbed

Purpose of a testbed

A testbed is intended mainly for examining drivetrain assemblies – manual gearboxes – cars and machines:

– manual gearboxes;
– drive axles;

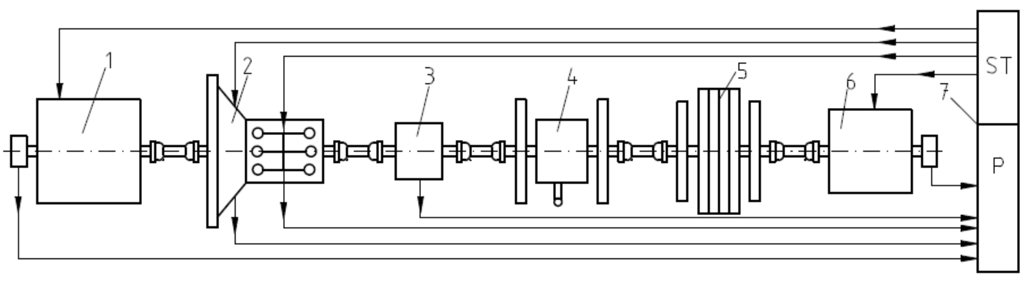

Fig. 1. The diagram of an inertial testbed for the tests of gearboxes; 1 – main engine, 2 – tested gearbox with a clutch, 3 – torquemeters, 4 – susceptibility and attenuation adjustment assembly, 5 – inertial mass assembly, 6 – brake, 7 – measurement and control assembly, P – measurement systems, ST – control systems

– friction clutches used in the system (in feasible cases).

The design of a testbed should consider the needs and requirements connected with:

– building prototypes;
– changes introduced in already existing structures;
– preparing and verifying new programmes and research methods;
– testing consumables.

Due to the above reasons, the testbed should allow for conducting a significant part of the tests for which there was a demand, and on such a basis they could be forecasted in the future.

Computational models of vehicles and their drive systems, modelled on real vehicles, were adopted as the basis for design.

A testbed should fulfil research programmes (or their selected elements) which are the forecasted or recreational simulation of drivetrain assemblies operation in use, including transient states, determined rotary speeds and loads in the system. In the case of gearboxes with gears activated through friction clutches operating in the wet environment, we are dealing with:

– conducting a test simulating operating conditions of an object: accelerating with the use of gears, steady states, transient states on individual gears, changes of gears, braking;
– fulfilling the object operation with a cyclical change of the direction of output rotations with the use of internal return gearbox (machines).

A testbed should recreate the operating conditions of drivetrain systems of vehicles and have the following parameters:

– maximum total vehicle mass (also including a trailer);
– maximum rotary speed at the inlet of the examined drivetrain system.

The mechanical system of the testbed – modular structure allowing for the configuration of its assemblies depending on the needs. Fundamental assemblies of a testbed include:

– electrical drive engine of specified rated power (alternatively, a DC or AC engine);
– a gearbox between the drive engine and the examined drive system as the assembly used optionally (adjusting the characteristics of the drive to the parameters of the examined system);
– assemblies of inertial masses reproducing the moments of inertia of masses of vehicles in movement;
– gearbox (gearboxes) between the examined object and a brake (brakes);
– electrical brakes (eddy current brakes or electrical engines);
– friction brakes (option);
– drive shafts or flexible couplings;
– assemblies securing the operation of the testbed against excessive rotary speed;
– auxiliary assemblies (option), e.g. hydraulic power units used for controlling the elements of examined objects.

The measurement and control system of the testbed should ensure the measurement of the following quantities: rotary speed, (braking) torque, (oil) temperature, force, (oil) pressure, length (displacement), tension, time. Because of that, a suitable number of measurement channels is required, which depends on the variant of a testbed layout. The measurement and control assembly should ensure the control of objects according to the set research program of the testbed due to the following quantities:

– the rotary speed of the electrical drive engine, electrical brakes, disc brakes according to the test schedule;
– braking torque (force) of electrical brakes;
– braking torque (force, pressure) of friction brakes;
– pressure, length (displacement) in the system of control of the clutch and gear changing;
– the temperature of testbed objects in the system of control of the cooling fans;
– the time of individual periods and the whole test schedule.

The measurement and control system should:

– ensure automatic supervision over the testbed and the examined objects by systematic control of the values of measured physical quantities;
– react in the case of irregularities by signalling alarm states and deactivating the testbed.

The data acquisition system should enable the registration of records of chosen physical quantities in real time, with a specific frequency and the length of a period of time, and enable their visualization and reading of the measured data. The acquisition of data may take place simultaneously for controlling a testbed as well as for recording measurement data.

As one of the variants, we can assume that the basic assemblies of the testbed deciding about the possibility of fulfilling the main research parameters are: electrical drive engine, brakes, gearboxes.

The balance of vehicle motion resistance was assumed as the basis for calculating the parameters of the testbed. Total motion resistance was divided into two groups:

- inertial resistance used for specifying the moments of inertial masses of the testbed;
- other motion resistance.

Pursuant to the technical data of drive systems of real vehicles, one can determine the required parameters of the drive engine, brakes, gearboxes and inertial masses of the testbed assuming that the drive systems of those vehicles are correctly chosen and proven in use. Therefore, the following items are considered:

- inertial resistance used for specifying the parameters of inertial masses of the testbed;
- total motion resistance fully overcome by the vehicle drive system in order to specify the optimum parameters of testbed assemblies.

Considering the remaining motion resistance can be skipped due to the fact that they constitute only a small part of total resistance.

The forces working on a vehicle are in motion.

On a vehicle moving along a straight line forces are working counteracting its movement and they are called motion resistance, and there is a longitudinal reaction of the base counteracting them, which is caused by the driving torque led from the engine to driving wheels [5, 6, 7, 8].

The equation constituting the motion resistance balance:

$$F_n = F_t + F_w + F_p + F_b + F_u \quad (1)$$

where:
F_n – driving force of the vehicle at each moment equal to the total of all motion resistance;
F_t – rolling resistance;
F_w – up resistance;
F_p – air resistances;
F_b – vehicle mass inertia resistance;
F_u – pull resistance.

In the case of inertial experimental tests, the equation (1) can be presented in the following form:

$$F_n = F_b + F_{op} \quad (2)$$

where: $F_{op} = F_t + F_w + F_p + F_u$ – the total of the remaining motion resistance.

The vehicle mass inertia resistance in the unsteady motion:

$$F_b = F_{b1} + F_{b2} + F_{b3} \quad (3)$$

where:
F_b – total inertia resistance;
F_{b1} – resistance of the whole mass of the vehicle in the progressive motion;
F_{b2} – resistance on the diameter of driving wheels coming from spinning masses of the engine and the driving system reduced onto the axle of driving wheels and from the masses of driving wheels;
F_{b3} – resistance on the diameter of rolling wheels, where:

$$F_{b1} = m \cdot \frac{\mathrm{d}v}{\mathrm{d}t} \quad (4)$$

where:
m – total vehicle weight;
$\mathrm{d}v/\mathrm{d}t$ – linear acceleration of the vehicle,

$$F_{b2} = \frac{M_{b2}}{r} \quad (5)$$

$$F_{b3} = \frac{M_{b3}}{r} \quad (6)$$

where:
M_{b2} – moment of inertia resistance coming from the spinning masses of the engine and the spinning parts of the driving system and from the driving wheels;
M_{b3} – moment of inertia resistance coming from the rolling wheels;
r – circle radius (respectively: driving or rolling).

Based on the above dependences, one can write:

$$M_{b2} = M_{bs} + M_{bn} + M_{bkn} \quad (7)$$

where:
M_{bs} – moment of inertia resistance coming from the spinning masses of the engine;
M_{bn} – moment of inertia resistance coming from the masses of spinning drivetrain assemblies;
M_{bkn} – moment of inertia resistance coming from driving wheels,

$$M_{bS} = I_S \cdot \frac{\mathrm{d}\omega_k}{\mathrm{d}t} \cdot i_c^2 \cdot \eta_c \quad (8)$$

where:
I_s – mass moment of inertia coming from the spinning masses of the engine;
ω_k – angular speed of the driving wheel;
i_c – total switching of the drivetrain system;
η_c – total efficiency of the drivetrain system,

$$M_{bn} = \frac{\mathrm{d}\omega_k}{\mathrm{d}t} \sum_i^n I_n \cdot i_n^2 \cdot \eta_n \quad (9)$$

where:
I_n – mass moment of inertia from the n-th part of the drivetrain system;
i_n – switching from the n-th part of the drivetrain system to the driving wheel,

η_n – efficiency of the drivetrain system from the n-th part of the drivetrain system to the driving wheel,

$$M_{bkn} = I_{kn} \cdot \frac{\mathrm{d}\omega_k}{\mathrm{d}t} \tag{10}$$

where:

I_{kn} – mass moment of inertia of driving wheels,

$$M_{bkt} = I_{kt} \cdot \frac{\mathrm{d}\omega_k}{\mathrm{d}t} \tag{11}$$

where:

I_{kt} – mass moment of inertia of rolling wheels.

Having substituted the above dependences to equation (3) we get:

$$F_b = m\frac{\mathrm{d}v}{\mathrm{d}t} + \frac{M_{b2}}{r} + \frac{M_{b3}}{r} \tag{12}$$

hence:

$$F_b = m\frac{\mathrm{d}v}{\mathrm{d}t} + \frac{1}{r}\left(I_s \frac{\mathrm{d}\omega_k}{\mathrm{d}t} i_c^2 \eta_c^2 + \right. \\ \left. + \frac{\mathrm{d}\omega_k}{\mathrm{d}t} \sum_i^n I_n \cdot i_n^2 \eta_n + I_{kn}\frac{\mathrm{d}\omega_k}{\mathrm{d}t} + I_{kt}\frac{\mathrm{d}\omega_k}{\mathrm{d}t} \right) \tag{13}$$

Having converted, we get:

$$F_b = \\ = m\frac{\mathrm{d}v}{\mathrm{d}t}\left[1 + \frac{1}{mr^2}\left(I_s i_c^2 \eta_c + \sum_i^n I_n \cdot i_c^2 \eta_n + I_{kn} + I_{kt} \right)\right] \tag{14}$$

Isolated segment of equation (14):

$$\delta = 1 + \frac{1}{mr^2}\left(I_s^2 i_c^2 \eta_c + \sum_i^n I_n \cdot i_n^2 \eta_n + I_{kn} + I_{kt} \right) \tag{15}$$

where: δ – the coefficient of spinning masses (the coefficient of reduced masses) in the case of driving or braking, when the drivetrain system is not disconnected from the engine.

In the case of braking, when the drivetrain system is disconnected from the engine:

$$\delta_h = 1 + \frac{1}{mr^2}\left(I_{kn} + I_{kt} + \sum_i^n I_n \cdot i_n^2 \eta_n \right) \tag{16}$$

The total inertia resistance of a vehicle on the circumference of driving wheels:

– in the case of driving or braking, when the drivetrain system is not disconnected from the engine:

$$F_b = m\delta \frac{\mathrm{d}v}{\mathrm{d}t} \tag{17}$$

– in the case of braking, when the drivetrain system is disconnected from the engine:

$$F_{bh} = m\delta_h \frac{\mathrm{d}v}{\mathrm{d}t} \tag{18}$$

Moment of inertia resistance in the case of driving or braking, when the drivetrain system is not disconnected from the engine:

$$M_b = F_b \cdot r = I_b \cdot \frac{\mathrm{d}\omega_k}{\mathrm{d}t} \tag{19}$$

where: I_b – moment of inertia of resistance on driving wheels:

$$F_b \cdot r = m \cdot r\delta \frac{\mathrm{d}v}{\mathrm{d}t} \tag{20}$$

$$M_b = m \cdot r \cdot \delta \frac{\mathrm{d}v}{\mathrm{d}t} \tag{21}$$

where: $\frac{\mathrm{d}v}{\mathrm{d}t} = \omega_k \cdot r$

$$I_b = mr^2\delta \tag{22}$$

Moment of inertia resistance in the case of braking, when the drivetrain system is disconnected from the engine:

$$I_b = mr^2\delta_h \tag{23}$$

Moment of inertia masses of a testbed on an inlet hub of the drive axle:

$$I_{b1} = \frac{I_b}{i_m^2 \cdot \eta_m} \tag{24}$$

where: i_m – complete switching of the drive axle, mechanical effectiveness of the drive axle.

Moment of inertia masses of a testbed on a clutch roller of a gearbox:

$$I_{b2} = \frac{I_b}{i_m^2 \cdot i_b^2 \cdot \eta_m \cdot \eta_b} \tag{25}$$

where:

i_b – switching a given gear on a gearbox;

η_m – mechanical efficiency of a gearbox on a given gear of the drive axle.

Inertia masses of a testbed.

Regardless of the location of masses in a given test, considering the possibility of broadening the scope of the research on the drivetrain system, the value of those masses was calculated for two points: on the driving wheels axis, at the outlet of a gearbox.

The moment of inertia of masses was calculated based on the following:

- the total mass of a vehicle in progressive motion;
- moments of inertia of driving and rolling wheels of a vehicle;
- switching of the drive axle transmission;
- mechanical efficiency of the drive axle transmission;
- the moment of inertia of the drive shaft;
- mechanical efficiency of the drive shaft.

Hence, the moment of inertia masses are determined according to the following dependences:

1) On driving wheels axis:
   - the coefficient of (reduced) spinning masses

$$\delta = 1 + \frac{1}{mr^2}\left(I_{kn} + I_{kt}\right) \tag{26}$$

   - moment of inertia of masses (total)

$$I_b = mr^2 \cdot \delta \tag{27}$$

2) On outlet hub of the gearbox
   - moment of inertia of masses (total)

$$I_{bsp} = \frac{I_b}{i_m^2 \cdot \eta_m \cdot \eta_w} + I_{m\mathrm{red}} + I_w \tag{28}$$

   where: $I_{m\mathrm{red}}$ – moment of inertia of the spinning elements of the drive axle reduced to the inlet (drive) hub of the axle.

Parameters of the main engine and the brakes of the testbed and moments of inertia of the elements of the drivetrain system assemblies

Points of characteristics of an internal-combustion engine driving a model vehicle adopted for the considerations.

In order to assess the necessary testbed parameters of the driving and braking assemblies, the points of characteristics were adopted for the considerations of the engines of real reference vehicles.

M_M – maximum engine torque;
n_M – engine rotary speed at maximum torque;
N_M – engine power at maximum torque;
M_N – engine torque at the rotary speed of rated power;
n_N – engine rotary speed at rated power;
N_N – engine rated power.

Two points of engine characteristics were assumed:

1) N_N, n_N;
2) M_M, n_M.

Based on those two points, the following values will be calculated on individual gears of a gearbox in chosen points of the drivetrain system:

- maximum motion resistance moment;
- maximum rotary speed.

Below are the basic (general) computational formulas used for the calculations on an outlet roller of a gearbox on a given gear:

$$n_{b\max} = \frac{n}{i_b} \tag{29}$$

$$M_{b\max} = n \cdot i_b \cdot \eta_b \tag{30}$$

where:

n – the rotary speed of engine: n_N or n_M;
$n_{b\max}$ – maximum rotary speed on an outlet roller of a grearbox on a given gear;
i_b – total switching of a gearbox on a given gear;
$M_{b\max}$ – maximum torque on an outlet roller of a grearbox on a given gear;
η_b – total efficiency of a gear box on a given gear.

For drivetrain assemblies of the drive and drive wheels of the adopted models of vehicles, the calculations of mass moments of inertia of spinning elements can be made using the general formula of the moments of inertia of such figures as: cuboid, full circular cylinder, hollow circular cylinder, circular cone – using at the same time Huygens-Steiner theorem.

Conclusions

The paper presents the technical assumptions and the design of a testbed suitable for conducting experimental tests of gearboxes. Due to the extent of the topic, this study is only the introduction to the design work whose aim is to prepare the design of the testbed. Due to the quality of the conducted tests, the design of such a testbed should consider:

1) The introduction of the designed automated inertial testbed for use means increasing and modernizing the research potential allowing for conducting dynamic tests recreating the real operation of the drive train system, and simultaneously increasing the number of the potential orders for the tests for which there is the demand but which cannot be conducted in the Laboratory currently.
2) Ensuring a much quicker reaction than in the case of manual operation by a person to any changes appearing in test conducting systems also to disruptions.
3) The simultaneous consideration of the results of a big number of tests of the accuracy exceeding many times the capabilities of human senses.
4) The capability to introduce quick changes impossible to be directly recreated by manual operation by a person.

5) The possibility to build, use and take advantage of the proposed algorithms of control of a testbed, and to carry out (suitably to the performed task) modifiable algorithms or operation allowing for maintaining, without changes, the basic layout of the testbed.
6) Direct programming of the testbed operation as well as the individual chosen test parameters.
7) Registration of data, archiving and reconstructing information.
8) Memorizing individual measurement configurations in the computer system (creating the libraries of ready "scenarios" of test courses).
9) The possibility to use automatic control of peripheral devices, such as printers, alarms, etc.
10) When needed there is the possibility to expand the supervision systems.

Due to the safe operation and ergonomics, experimental tests should consider:

1) Automatic devices of the testbed may operate for a long time without breaks – a human brain works in impulses and becomes tired quickly.
2) After many hours of operation (especially at night), in increased temperatures in laboratory rooms, human reaction time is much longer and external stimuli (visual, sound and thermal) are received differently than by a rested person.
3) Automatic operation and automatic supervision over it enable much shorter and less frequent visits of personnel in the area of the testbed – decreasing the risk of an accident.
4) Incomparably faster operation of automatic systems in the scope of measurements and information acquisition does cause human exhaustion.

The impact of economic factors:

1) The possibility to conduct the tests for which there is the demand and which currently cannot be conducted in the Laboratory due to the lack of a suitable testbed.
2) Quick and high volume operation of automated systems of the testbed allowing for great savings of personnel time of work.
3) Quick detection of irregularities which may arise during tests and stopping in time the tests of the whole facility before damage of the scope hindering a careful identification of causes occurs, what creates the possibility to avoid cost increases caused by the necessity to repeat tests or pay compensation to the ordering party.
4) Power savings thanks to the use of drives with power return to the mains and thanks to automatic supervision controlling rationally the operation of the research testbed.
5) Decreasing the costs of building the testbed in the case of using driving and braking AC engines what enables to eliminate some gears of the testbed.
6) Automatic protection of the testbed whose expensive assemblies are exposed to the risk of damage.

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