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Dynamic loading of friction disks in automotive transmissions

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Abstract. The article describes a refined method for design studies of friction disks that are integrated into automotive transmissions. A technique is presented to enable finding the natural frequency spectrum exhibited by disks as distributed mass multicomponent bodies. Grounds are given that explicate the necessity to evaluate the stability of oscillations when high-frequency dynamic processes evolve in a nonlinear system after friction clutches are disengaged and when friction clutches are being engaged and wavelike plastic deformations emerge giving rise to overheated spots. The article also sheds light on specific features inherent in the off-design behavior subsequent to the stopping of the clutch booster and pressure unbalance in the clutch booster plenums. The research studies have produced a number of technical solutions that reduce the amplitude of the high-frequency oscillations, which are generated after friction clutches are disengaged and result in plastic deformations of mating surfaces as well as disturbed axial movability of friction disks. They have substantiated the necessity that the relevant linear velocity should be restricted having determined the boundaries of tolerated linear velocities of revolving friction disks. The article presents results of researching into the processes consequent to pressure unbalance in the friction clutch booster plenums and proposes technical solutions to do away with its adverse effects.

1 Introduction

Development of up-to-date automotive transmissions shows that compact planetary gear trains are in demand. Gears in modern transmissions are shifted by multiple-disk friction clutches; this technical solution has been successfully applied by eminent transmission manufacturers such as Alison, ZF, etc. [1, 2]. On-board information management systems (OIMS) integrated in modern and would-be machinery have the potential to bring about optimized control of friction clutches adequately responding to monitoring technical states of components and required modes of motion. Design methodology provides for achieving proper strength, restricting temperature rises, dealing with wear, warpage, etc. At the same time, available design procedures disregard dynamic loading resulting from specific features inherent in operation and resonant excitation. Analyses of typical damaged friction disks in prototype transmissions and commercial units prove that alongside with familiar destruction patterns there are little-studied ones. In particular, local overheating occurs in friction disk linings, and adhesion layers in the surfaces of mating disks tend to burn out and collapse. This phenomenon induced by bending resonance vibration is termed as thermoelastic instability [3-7]. There are also cases of plastic deformations taking place in the mounting surfaces of drums, which are adjacent to the disks; it leads to disturbed axial movability, incomplete engagement and disengagement and consequently to excessive heating of disks [8]. What is more, transmission components such as management systems operate in a variety of modes under changing conditions and this is likely to adversely affect the processes described above; it may bring forth additional phenomena that have not been studied, yet capable of restricting the functionality of the unit. Specifically, upset pressure balance results in violating the law of pressure variation in the friction clutch booster and leads to inconsistent gear shift duration and growing dynamic loading or increased slippage work.

The purpose of the studies consists in refining a method applied for design computations of friction disks in respect to the little-studied dynamic phenomena that decrease lives of friction clutches.

-The scientific novelty lies in developing new experiment-calculated procedures for determining the natural frequency spectrum of friction disks as distributed mass multicomponent bodies, studying the consistency of disk oscillations under high-frequency dynamic processes in a nonlinear system, and presenting the results of researching into unique features inherent in operational friction clutches functioning in off-design regimes.

The paper describes results of fulfilling the following tasks:

- developing a method for determining the natural frequency spectrum of friction disks as distributed mass multicomponent bodies;
- evaluating the consistency of disk oscillations under high-frequency dynamic processes in a nonlinear system;

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- researching into specific features exhibited by friction clutches operating in off-design regimes.

Available methods, applied in design computation of friction clutches, their management systems are oriented towards imparting adequate strength to structural components. Alternatively, the research, pursued by the authors of the article when developing a variety of transmissions to be integrated into new vehicles showed that operation of friction clutches goes hand in hand with little-studied wave processes in friction disks which lead to limiting their operating capacity. The wave processes come into being when friction clutches are engaged and disengaged as well as in idle running when disengaged, and they are accompanied with excitation of resonant modes. It results in higher dynamic and thermal loading imposed on friction disks; this loading restricts the operating capacity of the transmission as a whole. Eliminating the resonances in the operation modes under study is grounded on managing the parameters of friction clutches and their components (friction disks) relying on precise knowledge of their modal characteristics.

2 Determining the natural frequency spectrum of disks as distributed mass multicomponent bodies

Wave theory has been applied to obtain the experiment-calculated procedure to determine the natural frequencies of friction disks. In the first approximation the friction disk is viewed as a circular metal ring. The natural frequencies are found from the equation [9]:

$$\omega = \omega_k = \frac{K(K^2-1)}{\sqrt{K^2+1}}\sqrt{\frac{EI}{m_0 R^4}},$$

where K is an integer giving the number of waves that fits into the length of the ring $2\pi R$ *(K=1,2,..N)*; I - the inertia moment of the rectangular cross-section of the ring; m_o - mass per unit; E - the elasticity module; R - the mean radius of the ring. At the same time, the fiction disk is a multicomponent structure integrating a metal disk, metal-ceramic plates, adhesion layers, i.e. a variety of materials possessing different physical-mechanical properties. In addition to it, one of the end faces of fiction disks has a ring toothing. To find natural frequencies of disks consisting of various materials numerical modeling is employed making use of specialized software packages such as Solid Works, ANSYS Workbench, etc.. The forms that oscillating disks show at *K=2* and *K=3* are given in fig. 1.

As follows from the cited data, these natural frequencies lie in the range of the frequencies disturbing the system, therefore, the resonance is likely to occur. The veracity of modeling is limited by the accuracy of describing a nonlinear interaction between the friction disk components (the steel ring and metal-ceramic or cellocotton lining), this interaction being formed by the adhesion layers. For this reason, it is necessary that the results procured from the numerical evaluation of the natural frequencies of friction disks should be corrected making use of experimental data obtained at a special test stand by a nondestructive inspection technique relying on the response of the disk to a harmonic wave of variable frequency.

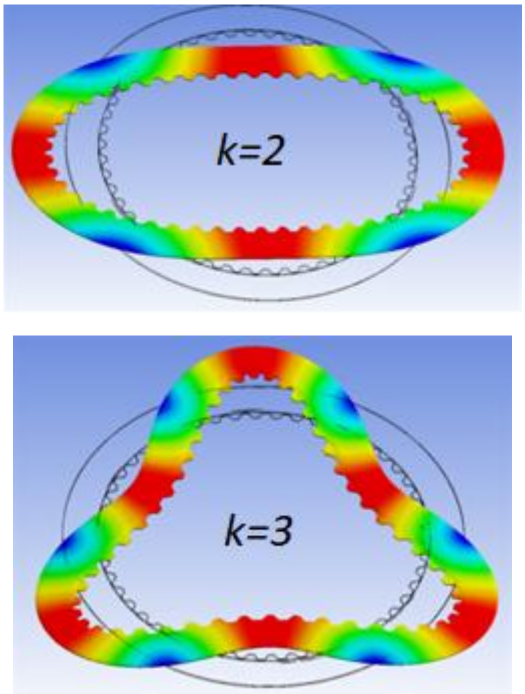


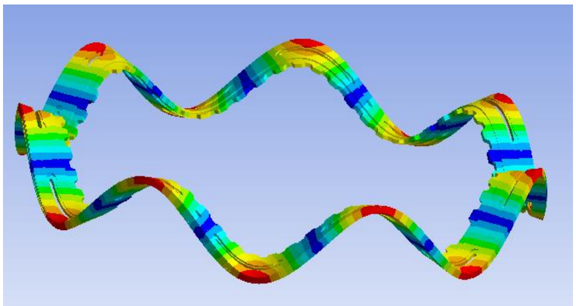
Fig. 1. The eigen forms of the disk.

To evaluate whether correct allowances are assumed for analytical definition of modal characteristics of friction disks it is correlated with experimental data. To do it nondestructive control test stands were developed. The first test stand equipped with piezoaccelerometers (patent RU 122171) is designed for measuring frequencies and waveforms in a single plane. The second test stand employing a laser Doppler vibrometer and equipped with three laser heads was made for defining modal characteristics in space (patent RU 157159).

The results obtained through computational and experimental investigation of modal characteristics are presented in fig.2.

The determined difference between the frequency values (up to 5%) is a basis for refining the parameters of nonlinear characteristics representing the interaction of the friction lining and the metal carrier of the disk and correcting the mathematical model of the nonlinear interaction of the drum and the disk when prognosticating parametric resonances.

Analyzing the results obtained from numerical computation and their correlation with experimental data makes it possible to forecast the possibility for evolving resonant modes of friction disks in transmissions, to perfect design computation procedures and to solve the inverse problem of eliminating resonances in various operation regime.



a)

b)

Fig. 2. Spatial modal characteristics of the disk: a – computationally determined result (natural frequency – 1169 Hz), b – experimentally discovered result (natural frequency 1100 Hz).

3 Evaluating friction disk loading under evolving high-frequency dynamic processes in a nonlinear system

Eliminating wave processes in resonant modes rests on solving the following problems:

- studying the conditions of exciting parametric oscillations of disks in plane and finding ways to exclude resonances;
- studying the conditions of exciting high frequency oscillations of disks in their plane and finding ways to exclude resonances;
- analyzing conditions of forming thermoelastic instability of disks affected by bending oscillations (in transverse plane).

3.1 Analyzing conditions of forming and eliminating thermoelastic instability of bending oscillations under transient processes occurring in engagement and disengagement of friction clutches

Methods applied in designing of friction disks involve a number of calculations, some of them covering thermic aspects [4]. Technical literature which describes research studies of friction elements explicates the necessity of substantial refinement in thermal (thermodynamic) design. Well-known procedures rest on the assumptions that pressure is evenly distributed throughout the disk surfaces. In reality deviations of geometric parameters from their nominal values, wave-like bending oscillations of disks redistribute applied pressure and temperature fields. The thermal flow generated by rubbing disks is proportional to contact pressure. Local pressure in contact points exceeds the mean value; therefore, in the area affected with high pressures the temperature tends to grow making the local pressure still higher due to thermal expansion. Heating of the disks, which are experiencing bending oscillations, in antinodes causes termoelastic instability (TEI) to emerge at the time when the friction clutch is engaged. The TEI mechanism discovered by J.R. Barber explicates a macroscopic process of heating and thermal deformation of parts when heated by friction. The TEI leads to an additional increase of local contact pressures caused by thermal deformations. As a result, the so called hot spots appear on disks as shown above.

In individual cases the TEI results in plastic deformations of steel disks going which might initiate cracking. As the certain local temperatures affect the lining of friction disks, it wears out. The wear debris decreasing filter capacity are likely to cause failures of the lubrication systems and hydraulic controls as a whole. Formally a thermodynamic process that takes place in a linear elastic system is described by a matrix equation, its right side including external loads and forces resultant from thermal expansion. The model characterizes the heat transfer which is formed by conductivity and convection dependent on structural parameters of the disks and their relative rotational velocity. To analyze a stressedly-deformable state the system is discretized with the finite element method. As a result, there appears a possibility to solve the thermoelastic problem by means of describing the process with first order equations and analyzing the interaction of elastic and thermal processes. Meanwhile, the real components of the solution are correlated with the sliding velocity of disks. The solution is regarded as stable if the real side is negative, and vice versa, the thermodynamic process is unstable if the real part is positive. The initial system includes from several hundred to several thousand normal differential equations, at the same time, just one or several of them may turn out to be unstable. Hence, a problem with an approximated answer needs to be solved. The abbreviated model has the potential to prognosticate formation of hot spots on clutch disks and take preventive measures in the framework of the management system by varying the duration of engagement of friction elements. Fig.3 illustrates the dependence between the real part of the periodic solution and the speed as established by P. Zagrodzki P. [7].

Occurrence of the TEI caused by bending oscillations, the latter being perpendicular to the disk plane, is to al large extent aggravated by the parametric oscillation in the disk plane. In particular, high-frequency oscillations result in plastic deformations of the disk surfaces which are adjacent to other parts in the unit. It, in its turn, leads to incomplete engagements and disengagements of the disk pack; consequently, the disks are overheated due to intensive slippage work and upset thermoelastic stability.

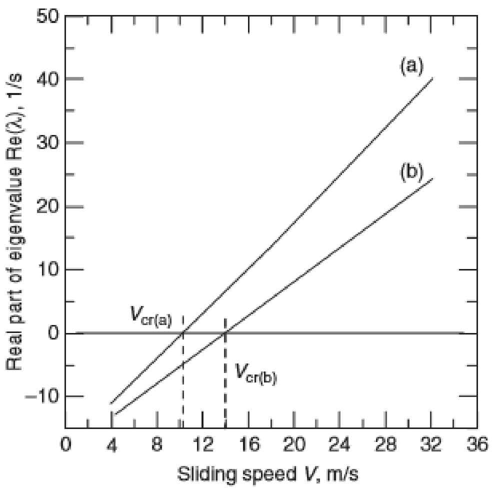


Fig. 3. Dependence of the real part of the eigenvalue on the function of the linear sliding speed of the disk.

3.2 Investigating excitation of high-frequency oscillations of disks in plane and substantiating the means to eliminate resonances

The reason for exciting resonant oscillations in disks lies in a nonlinear characteristic of their interaction with the driving drum. The behavior of these oscillations are dependent on the dynamics of a system, which includes the intertia masses of the engine, transmission components, friction disks and drums interacting with the disks [8,10].

In the design model the friction disks are connected to the drum by means of a loose fit; it is aligned in reference to the pitch circle diameter with a minimum positive allowance to provide for shifting the disks relative to the drum for engagement and disengagement to take place.

The nonlinear function which is a correlation of the moment and the angular coordinate is assumed to be symmetrical to the allowance, i.e.

$$M(\varphi) = \begin{cases} 0 \text{ at} |\varphi| \leq \beta \\ c_0 \cdot (|\varphi| - \beta) \cdot \text{sign}(\varphi) \text{at} |\varphi| > \beta, \end{cases}$$

its parameters are determined as per technical documentation (β=0.003 rad) and c_0 is the rigidity of the disk tooth – drum tooth couple.

A numerical solution of the system shows that a nonlinear high-frequency impact interaction of the disk and the drum as solid bodies, initiates a bandwide spectrum of excitation frequencies (from 0 to 6000 Hz) having a considerable amount of power, this spectrum exceeding the range of natural frequencies. It leads to resonant oscillations of the disk. To find ways to eliminate possible resonances a consistency analysis of the periodic solution is made. This problem is solved on the basis of finite element modeling of the disk which is regarded as a distributed mass multicomponent system, the system being subjected to a broadband impact induced by the nonlinear interaction of the disk and its adjacent drum.

4 Researching into specific features of friction clutches operating in off-design regimes

The effect of unbalanced centrifugal pressures in the compensation chamber of steering friction clutches was discovered in final tests of automotive transmissions. It is a consequence of a variety of factors, one of them being the rpm of the booster. It appears to bring about two control process patterns. In the first case a self-engagement of the friction clutch occurs being resultant from centrifugal forces; it is likely to be companioned by high dynamic loading, extensive slippage work leading to a temperature increase and destruction of structural components. In the second case, due to a pressure unbalance in the booster plenums and violation of the pressure change law, the duration of engagement varies considerably, and the dynamic loading or slippage work grows. The research study that has been completed proves that observation of relevant control laws for friction clutches is related to a large number of parameters.

A mathematical model was devised to describe the travel of a piston in the control booster which manages the engagement of separate gears. It made it possible to evaluate the influence of the following parameters on the quality of observing the related control law. They are: the fullness of the compensation chamber; the features inherent in the operation of the electromagnetic valve; the stiffness of the spring in the compensation chamber; the number of friction pairs. A complex mechanotronic dynamic system was modeled to establish a dependence of the required volume of oil in the booster related to the piston travel and the inner diameter of the oil ring in the compensation chamber. A technical solution to stabilize the pressure in the compensation chamber was proposed and implemented in a transmission.

5 Conclusion

The research studies have proved that poorly explored wave processes are inherent in the operation of friction clutches restricting their working capacity. The wave processes, attended by exciting resonant modes, come into being when friction clutches become engaged and disengaged and when they idle. It results in increased dynamic and thermal loading of friction clutches and limited efficiency of the transmission as a whole; it sets forward a necessity for perfecting the relevant calculation method. An experiment-calculated technique has been developed to determine the natural frequency spectrum of disks as distributed mass multicomponent bodies, substantiation has been made available explicating the relevance of evaluating the stability of oscillations of disks under high-frequency dynamic processes in a nonlinear system when friction clutches are disengaged as well as when they are in the process of engagement and wave plastic deformations emerge initiating overheated spots. Research has been done into the features of friction clutches functioning in off-design modes of operation with the rotational speed of the friction clutch booster changing within a large range and thus resulting in unbalanced pressure of working fluid in the plenums in the friction clutch booster.

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