Diagnostics of dissipative characteristics of friction damper

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Abstract. The aim of our study was to broaden current knowledge of characteristics of friction damper that acts to dissipate the energy of small translational oscillations in friction pairs and to convert it into significant angular shaft movements. We have devised a novel methodology to evaluate elastic-dissipative characteristics of the damper, which provides real-time identification of the stability of these characteristics, as well as running-in periods, stable operation, and catastrophic wear. It is shown that plan bearings made of antifriction self-lubricating organic-fiber composite are more effective than plain bearings made of metal-fluoroplastic tape since their use causes less high-frequency noises that affect the quality of transient response.

1. Introduction

One of the core problems of ensuring a high level of safety in both civil and military aviation is increasing the strength, durability, and damage tolerance of an aircraft structure by diverse methods, including damping technologies for aircraft vibration attenuation. From a technical point of view, the most optimal points for mounting a damper are the points of the damped unit since then its displacements have the highest vibration amplitudes, and the load on the damper is minimized. However, the design features of the damped unit (for instance, podded engines, landing gear assemblies, etc.) do not often meet these requirements. In this case, the only possible points for mounting the damper are the points, characterized by small vibration amplitudes of the structure (for example, near the mounting supports of the damped unit), and large loads on the damper. Under these conditions, the use of well-known devices, in particular hydraulic dampers, appeared to be ineffective. With this in mind, we tried to find an innovative solution.

The research team of Federal State Unitary Enterprise “Central Aerohydrodynamic Institute” (hereafter TsAGI) has developed an innovative type of damper (figure 1) based on sliding friction pairs [1]. Due to the conversion of small translational movements caused by the vibration of the damped structure, the vibration energy of the structure is dissipated into significant angular shaft displacements in the friction pair. It ensures effective damping of vibrations with small amplitudes in a broad range of frequencies. The most important demand for a friction pair is a high level of stability of its tribological properties in the required period of operation.
After the application of load $F_v(t)$, the eccentric shaft moves around the axis of rotation through the angle $\alpha(t)$ and the axis of load application is displaced vertically a small distance from the initial position. With a relatively small eccentricity of the load application, small translational movements of the vertical thrust correspond to large angular displacements of the eccentric shaft with relatively large frictional moments in rotating pairs, which always prevent rotation. As proved, it ensures effective vibration damping in a broad frequency range.

2. **Aim of the study**

We initiated this research to develop a strong coating for dry friction bearings to be used in a friction damper for reducing vibration of aircraft structures. Besides, we have examined the mechanical properties of coatings and a damper with plain friction bearings to pre-estimate the influence of various technological factors on the tribological properties of coatings.

3. **Methodology**

We have devised a cutting-edge methodology to diagnose the tribological properties of a damper with rotating friction pairs [2]. It includes the analysis of the known load amplitudes and friction forces, calculation of the frequency transfer function and the transient function of the dynamic coefficient of friction [3]. Moreover, we have employed the analysis of the amplitude-phase characteristics of the dynamic coefficient of friction to determine the dependence of the change in the integral quality criteria on the ratio:

- elastic-inertial components that contribute to bringing up friction pairs together, increasing stresses and temperatures;
- inertial constituents that lead to the loss of stability of the friction bonds;
- inertial-dissipative components of the resistance to relative sliding;
- inertial-dissipative components of resistance, causing frictional self-excited oscillations.

The analysis of the obtained characteristics made it possible to select the recommended values of the dimensionless damping coefficient in the range from 0.08 to 0.38 and its optimal value equal to 0.25. It is worthwhile noting that we have devised a novel methodology of dynamic monitoring of the
damper, which allows to keep its technical condition under observation, as well as to predict the degradation of the tribological properties of the materials used.

Experiments on dissipative characteristics of a damper with plain bearings possessing diverse tribological properties were performed on a test bench in 2018 (figure 2). Carrying out experiments, we recorded the amplitude values of the load and the amplitude of the relative displacement at an oscillation frequency ranged from 4 to 15 Hz. In order to analyze the results obtained, we applied the previously developed methodology of dynamic monitoring of the elastic-dissipative characteristics of the damper.

![TsAGI damper](image)

**Figure 2.** Test bench for conducting experiments on the TsAGI damper.

The dissipative characteristics of the damper were analyzed based on the hysteresis energy loss loop and the method of tribospectral identification of friction processes [4].

4. Results

Figure 3 reports the data on the damper bench tests. It details the analysis of the 2nd, 100th, and 200th loading cycles for three types of plain bearing coatings: a new and worn-out coating made of metal-fluoroplastic tape (figure 3 (a), (b)); a new coating made of antifriction self-lubricating organic-fiber composite (figure 3 (c)). The vibration amplitude of the damper thrust was 0.5 mm at a frequency of $\omega = 4$ Hz. As seen, the damping characteristics of all damper constructions much vary, especially in the area of zero forced displacement amplitudes. A damper with new plain bearings made of antifriction self-lubricating organic-fiber composite (figure 3 (c)) when passing through zero displacement amplitude demonstrates the greatest resistance and, probably, has the highest damping characteristics.

The elastic-dissipative characteristics were assessed based on the analysis of frequency (figure 4), transient (figure 5) and integral functions to support the hypothesis.
The experiment with new plain bearings made of a metal-fluoroplastic tape (figure 4 (a)) shows that an aperiodic link was effective in suppressing the oscillations in the area of lower frequencies in the frequency range from 0 to 17 Hz. The maximum inertial characteristics are observed at a resonant frequency $\omega_r = 141.6$ and 379.6 Hz with a maximum dynamic coefficient of friction $f_{fr\text{ max}} = 0.24$ in the 200th and 2nd test cycles (point B and C, respectively). The dynamic coefficient of friction is characterized by the value of gain margin $L = 18.3$ dB. Significant speeds of relative sliding at higher
frequencies lead to the destruction of the metal at the interface of the contact surfaces of rotating friction pairs and notable strain amplitudes of plain bearing bonds.

Figure 5. Loading cycling-dependent transient characteristics of a damper.

Figure 4 (b) indicates the unstable operation of a damper with worn-out plain bearings made of metal-fluoroplastic tape, caused by medium (100 ... 130 Hz) and high-frequency (220 ... 500 Hz) vibrations. Along with high values of the dynamic coefficient of friction $f_{\text{fr max}} = 3.53$ at a frequency of 345 Hz (point D), forces of inertia and resistance (the velocity vector is co-directed with $v_{\text{vel}}$, the velocity vector of friction bond deformation), frictional self-excited oscillations, and significant kinetic energy greatly contribute to the convergence of friction pairs. Moreover, it leads to an increase in contact stresses and the temperature of the friction pairs, the emergence of plastic deformation and
local areas of thermal-induced seizure. The same dynamic process observed at a frequency of 440 Hz (point E) is, however, characterized with a lower dynamic coefficient of friction $f_{fr} = 2.9$, the absence of self-excited oscillations, and the formation of athermic seizure bridges.

The plain bearings made of antifriction self-lubricating organic-fiber composite demonstrate the best dynamic characteristics (figure 4 (c)) compared to the other ones. However, the oscillation amplitude of the dynamic coefficient of friction at medium frequencies (in the frequency range from 16 to 120 Hz) increases with the number of cycles (area J). At higher vibration frequencies (from 180 to 500 Hz), in the 2nd and 200th cycles, the dynamic coefficient of friction (area G) does not exceed the coefficient of friction $f_{fr} \approx 0.063$, which corresponds to a stationary stable state. Meanwhile, with an increase in the vibration frequency, the phase argument of the delay happens with seemingly minor deviations (areas H and I).

Obviously, the frequency characteristics affect the quality of the time characteristics in transient responses. Figure 5 presents the transient response to the Heaviside function of a damper.

Large-amplitude high-frequency oscillations of the contacting friction surfaces (point B in figure 4 (a)) seriously affect the deviations 1 of the controlled variable from the stationary motion trajectory (figure 5 (a)) of the corresponding aperiodic link, a significant overshoot level $\sigma$, a low negative gradient of the output value, thus increasing the duration of transient response and reducing the effectiveness of regulation.

In the 1st ms of transient response, load and inertia forces in a damper with worn-out plain bearings made of metal-fluoroplastic tape (figure 5 (b)) results in notable convergence of friction surfaces 3 with an equivalent dynamic coefficient of friction $f_d = 0.73$. In addition, it causes friction seizure that in its turn in the 2nd ms produces stroke-type impulse 4 and deformations in the volumes of contacting friction pairs in the direction of relative sliding $v_{rel}$ (with a coefficient of friction minus 0.46). Under the influence of high-frequency vibrations, until $t (h_{max}) = 27$ ms the damper is showing maximum deviations from the stationary motion trajectory 5. In the 86th ms, the dynamic coefficient of friction is stabilized at the level of a steady state value $f_{fr} = 0.28$, which exceeds the permissible value $[f_{fr}] = 0.15$.

An insignificant dispersion of amplitude harmonics at higher frequencies of a damper with plain bearings made of antifriction self-lubricating organic-fiber composite (see G in figure 4 (c)) considerably improves transient dynamic characteristics (figure 5 (c)). In the 2nd test cycle, after reaching the first maximum $h_{max}$ (7), the dynamic coefficient of friction $f_{fr max} = 0.067$ decreases to a steady state value $f_0 = 0.058$ (8). As expected, the quality of regulation of the transient load characteristics $F_v$ is enhanced.

However, it should be noted that frictional vibrations of plain bearings in all dampers lead to the increase in the dynamic coefficient of friction at medium and high frequencies (see areas G ... I in figure 4 (c)), significant overshoot values $\sigma$, and duration $tp$ of the transient function regulation.

5. Conclusion

The evidence from the study on the dynamic quality criterion of frequency, time and elastic-dissipative characteristics of dampers with rotating friction pairs points towards the idea that, in contrast to plain bearings made of metal-fluoroplastic tape, the use of those made of antifriction self-lubricating organic-fiber composite allows increasing the stability of damper dynamic and tribological characteristics by 37%.

Under the influence of 1(t)-type stepwise effect and a positive gradient of the rate of frictional links formation at some point in time of transient responses, there is no observation of frictional link deformation, and the dynamic coefficient of friction is equal to 0 (the Tolstoi – Push effect). The subsequent increase in the dynamic coefficient of friction causes the convergence of the contacting friction surfaces, deformation in the active volumes of the friction surfaces, and an increase in contact stresses. Significant speeds of the relative slip in rotating friction pairs cause plastic deformation of the microgeometry of friction surfaces, frictional self-excited oscillations, which lead to the excitation of high-frequency forced oscillations, whose frequency equals the free oscillation frequency, and
deviation of the controlled load from the stationary motion trajectory. Due to the athermic or thermic seizure of friction surfaces, the dynamic coefficient of friction tends to infinity (the Tolstoi – Push effect).

6. Recommendations
We have succeeded in finding the alternative solution for suppressing high- and medium-frequency noise during the operation of rotating friction pairs. We have suggested to coat metal surfaces of plain bearings with an antifriction lubricant with excellent adhesive properties before their assembling. The other innovative solution is to metal-clad the surfaces of rotating friction pairs of the damper with high-damping materials. In the case of high contact stresses, these measures will increase the actual contact area of friction pairs and prevent frictional self-excited oscillations, seizure bridges, and fretting corrosion.

Our research was a useful aid when manufacturing of a prototype damper intended for testing as part of a “wing – nacelle” unit of MC-21 aircraft with imitation of the vibrations produced by a running engine.

The methodology for dynamic monitoring of friction systems could be applied to any friction unit of aircraft. Moreover, it has the potential features to make a short-term or long-term forecast of changes in its dynamic characteristics.

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Acknowledgments
This study was carried out within the framework of State Program of Russian Federation “Development of the Aviation Industry for 2013-2025” and the following research works: “Development of a Methodology for Dynamic Monitoring and Assessment of Elastic-Dissipative Characteristics of a Damper” (Codename “Dragonfly”, State Registration Number 22.05.000.001, 2017) and “Improvement of the Current Prototype of the Vibration Damper of Screw Units (SU-5, SU-6) due to Innovative Rotating Friction Pairs” (Codename “Bench-2020”, State Registration Number 22.05.000.002, 2018).