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ON THE EFFECT OF SELF-SYNCHRONIZATION IN THE TWIN-ENGINE GAS TURBINE POWERPLANTS

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The analysis of the dynamics of non-linear system, which can be represented by helicopter twin-engine power-plant with free turbine turbo-shaft engines, is given. The possibility of the stable synchronous motion, which leads to high vibrations, is discussed. Experimental data is given that can be explained by the phenomena of motion synchronization.

1. Introduction

High vibration sometimes happens during operation of the helicopter gas turbine power-plant that consists of a pair of free turbine engines. This vibration emerges when the engines are operating together. As a rule the vibration is unstable i.e. it springs up suddenly and disappears suddenly as well. When the engines operate at different throttle settings, the high vibration is observed only on one of them. The same happens when this engine operates alone. It was also found that the frequency of vibration coincides with that one of the engine gas generator.

For the majority of the helicopter engines the engine control system is scheduled by free turbine rpm. It means that revolutions of the gas generator rotor may float within a wide range. It may be supposed in this case that the cause of high unstable vibration in two-engine power-plants is the synchronization effect.

2. Description of synchronous motion

Synchronization phenomena and accompanying effects of vibration capture and increasing were first discussed in the famous Huygens' work about two pendulums. Being attached to an elastic beam the pendulums begin oscillate synphase after a certain period of time. The synchronization phenomenon is caused by the interaction of rotating and oscillating motions of the objects joined together with mechanical links (Blechman 1979).

It is known (Lozitsky 1992) that rotating assemblies of contemporary gas turbine engines have special arrangement for vibroisolation. However researches of the synchronization effects show that they may take place even if the connections between the objects are weak. Engines of the aircraft power-plants are connected through the engine mounts and other airplane structure components of finite elasticity.

Let's analyze the phenomena for a power-plant, which consists of a pair of gas turbine engines. The simplest scheme of connections between rotating assemblies is shown in the Figure1, where 1 is heavy frame that includes the engine cases, engine mounts and aircraft basic structure; 2 and 3 are rotating assemblies of the engines.

If two rotors are nearly at uniform motion and connections between them are weak this task may be solved using the method of small parameter. In this case the following system of equations describes the scheme shown in Figure1.

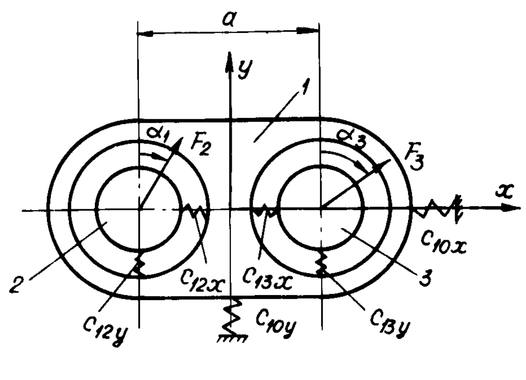

Figure 1

$$
\left.\begin{aligned}
& m_1\ddot{x}_1 + c_{10x}x_1 + c_{12x}(x_1 - x_2) + c_{13}(x_1 - x_3) = 0 \\
& m_2\ddot{x}_2 + c_{12x}(x_2 - x_1) = \\
& = F_2(\ddot{\varphi}_2 \sin\varphi_2 + \dot{\varphi}_2^2 \cos\varphi_2) - \mu\nu_2\dot{x}_2; \\
& \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\
& J_1\ddot{\varphi}_1 + c_\varphi\dot{\varphi}_1 = \mu\tau\nu_\varphi\dot{\varphi}_1 + \mu Q_\varphi - m_2e_2a(\dot{\varphi}_2^2\sin\varphi - \\
& - \ddot{\varphi}_2\cos\varphi_2) + m_3e_3a(\dot{\varphi}_3^2\sin\varphi - \ddot{\varphi}_3\cos\varphi_3); \\
& J_2\ddot{\varphi}_2 + k_2(\dot{\varphi}_2 - \omega) = \mu\phi_2; \\
& J_3\ddot{\varphi}_3 + k_3(\dot{\varphi}_3 - \omega) = \mu\phi_3.
\end{aligned}\right\} \qquad (1)
$$

Where m_i and J_i (i = 1, 2, 3) are masses and mass moments of inertia of the scheme components, c is stiffness of elastic elements connecting scheme components (designations are clear from Fig.1), $F_i = m_ie_i\omega^2$ is unbalanced force (here e_i = eccentricity, ω = circular frequency of rotation), μ is coefficient of coupling (small parameter), ν is coefficient of viscous friction, Q and ϕ are periodical functions with the period of $2\pi/\omega$. It is assumed that $c_{11} = c_{22} = c_{33}$, $c_{12} = c_{21}$ etc.

Stable regimes of synchronization can be found with a help of generating equations that can be derived from the system (1) by assuming that $\mu = 0$. In this case synchronous motions will occur according to

$$\varphi_2 = \omega t + \alpha_2 \quad \text{and} \quad \varphi_3 = \omega t + \alpha_3, \qquad (2)$$

where α_i - phase lag.

Generating equations for the given conditions are:

$$
\left.\begin{aligned}
& m_1\ddot{x} + c_{01x}x_1 + c_{12x}(x_1 - x_2) + c_{13x}(x_1 - x_3) = 0 \\
& m_2\ddot{x}_2 + c_{12x}(x_2 - x_1) = F_2\cos(\omega t + \alpha_2); \\
& \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\
& J_1\ddot{\varphi}_1 + c_\varphi\varphi = -F_2a\cos(\omega t + \alpha_2) + F_3a\sin(\omega t + \alpha_3).
\end{aligned}\right\} \qquad (3)
$$

System of equations (3) describes motion of so called chain system. It is divided into groups of independent subsystems. In Sperling's paper (Sperling 1967) solutions of similar equations are given for some special cases.

Let's consider features of system motion in the direction x (we specially omit indexes to simplify the expression). Solution can be presented in the following form

$$x_i = \sum_{j=1}^{n} X_{ij}\cos(\omega t + \alpha_j), \qquad (4)$$

where i, j = 1,2,…, n (n = number of masses in the system), and X_{ij} are constants which satisfy the following equation

$$\sum_{i=1}^{n} a_{ik}X_{ij} = \delta_{kj}F. \qquad (5)$$

Here $j = 1,2,\ldots, n$; δ_{ij} is Kronecker's symbol and the coefficients can be found as

$$a_{ik} = a_{ki} = \begin{cases} \sum_{j=0}^{n} c_{ij} - \omega^2 m_i & \text{if } i = k \\ -c_{ik} & \text{if } i \neq k \end{cases} \tag{6}$$

2. Stability criterion for synchronous motion

It was shown (Blechman 1971) that the integral stability criterion can be used to determine steady synchronous oscillations if the system of equations has the form of

$$P_s(a_1; a_2; \ldots; a_s) = 0\,, \tag{7}$$

where $s = 1,2,\ldots, n$. The function is related with the equation (7) by the following equation:

$$\frac{\partial \mathrm{L}}{\partial a_s} = -P_s(a_1; a_2; \ldots; a_s)\,. \tag{8}$$

It may be determined by average characteristics of motion for the period. If partial frequencies two rotors are equal or close to each other the potential function may be found as the average of Lagrange's function for one period of motion (Lagrangian)

$$\Lambda = \frac{\omega}{2\pi}\int_0^{2\pi} L dt, \tag{9}$$

where $L = T - \Pi$ (T = kinetic energy and Π = potential energy).

For the projection on the x-axis L is given by

$$L = \frac{1}{2}(m_1 \dot{x}_1^2 + m_2 \dot{x}_2^2 + m_3 \dot{x}_3^2) - \frac{1}{2}c_{01}x_1^2 - c_{12}(x_2 - x_1)^2 - c_{13}(x_3 - x_1)^2\,, \tag{10}$$

and according to (4)…(6) the Lagrangian is as follows

$$\Lambda = -\frac{F^2}{2} X_{23} \cos\alpha + c, \tag{11}$$

where $\alpha = \alpha_3 - \alpha_2$ and c constant which doesn't depend from α.

To simplify the analysis it assumed that $F_2 = F_3 = F$ and $c_{01} = c_1$, $c_{12} = c_{13} = c$, $c_{02} = c_{03} = 0$ $c_{23} = 0$, $m_2 = m_3 = m$. In this case according to (5) and (6) equation (11) can be written as

$$X_{23} = \frac{p_1^4 F}{m_1(p_1^2 - \omega^2)(p_2^2 - \omega^2)} = KF\,, \tag{12}$$

where $p_1^2 = c/m$, p_2 and p_3 are the roots of equation

$$p^4 - p^2\left(\frac{c_1}{m} + \frac{c}{m} - \frac{2c}{m_1}\right) + \frac{cc_1}{mm_1} = 0. \tag{13}$$

The main condition for stability of the synphase motion of rotors ($\alpha = \alpha_3 - \alpha_2 = \pi$) is K > 0. If K < 0 the antiphase motion is stable, that is $\alpha = \alpha_3 - \alpha_2 = \pi$.

Results for a numerical sample are given in Figure 2. Calculations of synphase and antiphase stable motions have been performed using the equation (12) and (13). Since $p_3 = 0$ and $p_2 < p_1$ in this example, stable antiphase motion can be observed within the range $0 < \omega < p_2$ and $\omega > p_1$. If $p_1 < \omega < p_2$ stable synphase motion is observed. In this motion unbalanced forces are summed up and rotor vibration must increase.

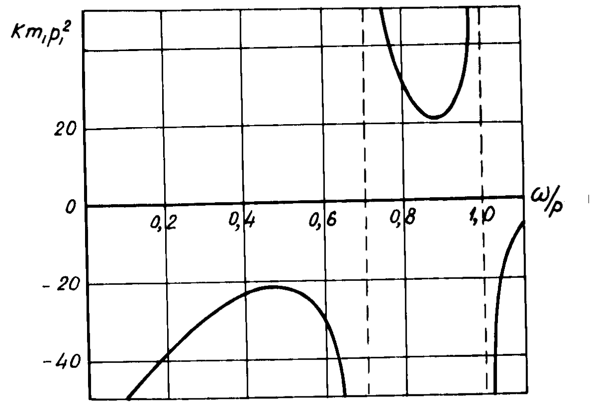

Figure 2

Strictly speaking the equation (9) is true if the system operates far from resonance. But the analysis presented in Blechman's book (1971) shows that obtained results could be extended to the zone that is close to the resonant regime. In this case small non-linear effects related with synchronization are superposed by the pulling effect caused by system stiffening.

Stiffening of the gas generator rotating assembly results from reduction of clearances in the rotor main supports, spline jamming in the shaft-coupling etc. This leads up to pulling effect during which resonant vibrations persist until pullout frequency is reached on one of the engines. Pullout frequency lies in the zone above resonance. As far as it is the zone of unstable resonant oscillation high vibrations don't appear again during the engine slowing down.

4. Experimental researches

Experimental researches were carried out on the helicopter powerplant, which included two free turbine turboshaft engines (Doroshko, 1984). The test was aimed to investigate causes of buzz, which had been noted by pilots. Vibration tests of the engines showed that one of them had high vibration during the speed acceleration (see curve 1 at the Figure 3) within the diapason from idle to approximately 275 revolutions per second (rps). Here and below the results were obtained by method of synchronous analysis of vibration signal. As the engine speed approached 275 rps the amplitude dropped down

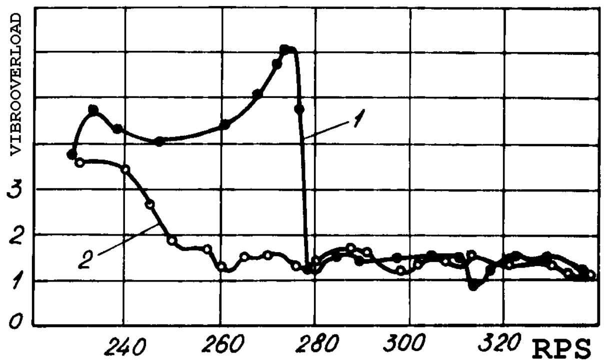

Figure 3

abruptly and remained at low level. The phenomenon was the main cause of the engine buzz. During the engine deceleration the vibration amplitude smoothly increased from low to the level of idle (curve 2).

The analysis of vibration characteristics of gas generator rotor showed that its resonant regime was below idle. When jamming occurred in the intermediate spline sleeve between turbine and compressor rotors, the stiffness of the rotating assembly increased and the resonant regime moved to the zone of higher rps. Range between idle and 275 rps was the zone of unstable vibrations. When the engine slowed down from high to low rps, the abrupt increase of the amplitude did not emerge again.

The second engine of the powerplant had typical for that engine model vibration characteristics i.e. with maximal vibration at the idle (see curve 1 in Figure 4).

When both engines operated together (that is when their regimes are equal) high vibrations were observed on both of them within the zone from idle to 275 rps (see curve 2). The vibration characteristics of the first engine did not change in this case.

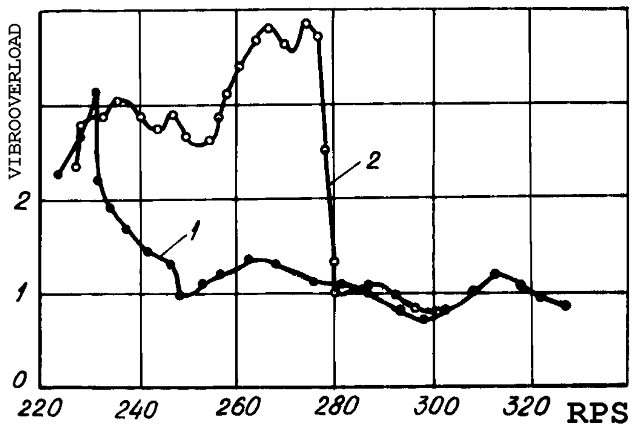

Figure 4

Calculations of the synchronization conditions showed that synphase motions were possible below the resonant rps, and within the whole operating range antiphase motions might occur. When engines operated at idle, vibration capture occurred and the engines started to support high vibrations of each other. These vibrations persisted up to the moment of the vibration fall-down on one of them. After this moment existence of synphase motions became impossible. The antiphase motions could not take place because of the relatively low vibration amplitudes. That is, with both engines operating the vibrations measured in each one were the same as if the engine operated alone. When the engines decelerated the high vibrations did not emerged again.

Difference between the speeds of the engines must be less than 5…10 rps for the synchronization to occur. Therefore the engines operating regimes set apart from each other can eliminate the effect.

5. Conclusion

High vibration of compressor rotors may appear on both engines of the helicopter power-plant, which consists of a pair of free turbine turboshafts, if one of the engines has high level of vibrations. The phenomena can occur only on rotors with indirect rotating speed control if their resonant regime is below or at the beginning of the operating range. The explanation of the phenomena can be given in terms of vibration synchronization due to frequency capture (pulling) effect. The synchronization is amplified by non-linear effect of the rotor stiffening in the rotor joint and bearings. To eliminate the effect the operating regimes of the power-plant engines must be set apart from each other.

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