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# EVALUATION OF THE ROTOR-STATOR DYNAMIC CHARACTERISTICS UNDER VARIOUS RUBBING CONDITIONS

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## ABSTRACT

Multistage discs that are welded together are a common design choice for rotor systems in aero-engines. Rotating machinery often has rotor-stator rubbing issues while in operation. Many researchers have focused on the rotor dynamics, which are affected by the mechanical characteristics of the contacting surfaces between the bolted joints as a result of friction and impact pressures during a rubbing event. Then, the vibration responses in a dual-rotor case system caused by rubbing are examined. Different rubbing vibration responses are addressed, along with the implications of rotational speed and speed ratio. When rubbing happens in a dual-rotor aero-engine, the results demonstrate that a spectrum with many frequency components will arise, with the exception of two imbalanced excitation frequencies and their numerous frequency components. In the same operating state, torsional vibration amplitude is greater than lateral vibration amplitude, and the speed ratio greatly affects the periodicity of the system's rubbing-induced motion trajectory. When the same parameters are applied in both directions, the amplitude of the rubbing-induced reactions is less when counter-rotation is used.

**Keywords:** dual-rotor-casing system, rubbing fault, finite element method, coupling dynamic, Rotating Speed

## INTRODUCTION

Due to assembly constraints, rotor systems in aero-engines are often composed of a number of substructures, each of which has a number of neighboring discs and drums. Adjacent stage discs are connected together at their joints so that the substructures may be brought closer together for power transmission and adequate rigidity. As can be seen in Figure 1, the discs that make up the multi-disc bolted joint are evenly spaced around the whole circle of the aero-engine compressor. Due to nonlinear contact at the mating interface of the bolted joint, the local stiffness at the contact interface is not linear. For this reason, the impact of the bolted joint must be included into the dynamic analysis of the rotor system with the bolted joint. In order to boost efficiency, aero-engine manufacturers have been working to decrease rotor-stator clearance over the last decade. As a result, rotor-stator rub-impact has emerged as a leading source of potential disaster. Investigation of the stability characteristics of the bolted joint rotor system incorporating multi-discs exposed to the rub-impact action is crucial for ensuring the secure operation of aero-engines. However, the authors note that there are few data on rotor dynamic simulations under rub-impact that account for the multi-disc bolted joint's local nonlinear contact interface.

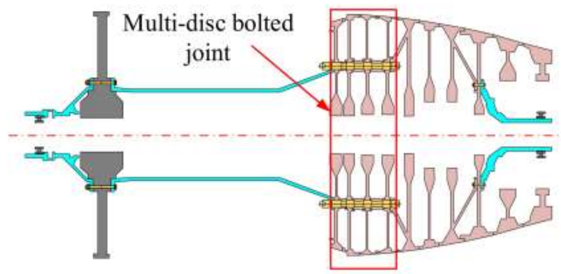


**Figure 1. Sketch of a certain type of aero-engine compressor with a multi-disc bolted joint.**

During the last several years, researchers have been looking at the impact that bolted joints inside spinning shafts have on rotor dynamics. rod fastening rotor system model was created taking into account initial deflection due to imbalanced preload and nonlinear oil-film force. After that, numerical simulation was used to look at how the imbalanced preload affected the rotor system's parametric instability. developed the rod fastening rotor system's motion equations in order to examine the impact of speed, eccentricity, and bending stiffness on the rotor system's nonlinear dynamics. All of the aforementioned research took into account the gyroscopic effect and the bending stiffness at the contact surface to refine the simulation. a mathematical model was constructed to determine the impact of disc misalignment and damping on rotor dynamics; the model used a spring with cubic stiffness to represent the contact effects at the mating interface.

The effect of joint interface assembly parameters on the natural frequency of high-pressure rotors in aero-engines was determined numerically through finite element simulation and experimental studies. These included the influence of preload, structure parameters, contact surface, and uneven preload. For rotor systems with bolted joints, we provide a data-driven modeling approach called frequency sweep modeling, and we also present an algorithm for the bolted joints called Weighted Extended Forward Orthogonal Regression. nonlinear dynamic features of a rotor system are studied using a mathematical model derived from Lagrange's equations, which takes into account the non-uniform nonlinear stiffness at the mating contact. For the well-connected case and bolt-loosening scenario, a problem of dynamic modeling and response analysis on discontinuous shafts linked by the bolted disc-drum joint has been addressed. To better understand the piecewise linear stiffness of the bolted disc-drum joint and its impact on rotor dynamics, a simple rotor with a fastened disc-drum joint was analyzed using the finite element technique. Research into the dynamic properties of rotor systems subject to the rub-impact effect has attracted a lot of attention in recent years. constructed, using the finite element modeling technique, the dynamic model of a basic rotor system taking into account the rotor-stator rubbing fault in order to examine the rubbing vibration characteristics.

The numerical simulation findings were verified by using an experimental test rig designed to mimic rotor-stator frictional properties. Study findings from numerical and experimental analysis show that the period-1 motion, period-2 motion, and period-3 motion all exist at higher operating speeds. dynamics of a magnetic liquid double suspension bearing system with a clearance rubbing defect, numerically investigated. We examined the radial shaft displacement responses and found that the rubbing frequency was proportional to the product of the fundamental frequency and the number of blades.

the computational and experimental results of fixed point rubbing on dual-rotor systems. Several observable combination frequencies may be interpreted as the specific fault frequencies. Using a dynamic model based on a comparable dual-rotor structure, we look at the bifurcation behaviors of rotor partial rub while taking into account synchronous forward and backward precession. nonlinear dynamics of the Jeffcott rotor were analyzed numerically, taking into account the fact that the rotor makes physical contact with the stationary sections. The nonlinear dynamic characteristics were studied by an experimental investigation using a rotor-stator rub-impact test rig, and the harmonic balancing technique was employed to accomplish so. explored the intricate bifurcation behavior and path to chaotic events in a large deflection rotor-bearing system hit by a rubbing defect. characteristics of dynamic response to rubbing flaws in a basic rotor casing system. Spectrums of rotor-stator rubbing were discovered to include both fundamental frequency and its harmonics, as well as sub-harmonic frequency components.

From the above studies, it is clear that parametric studies about bolted joint rotor systems under rub-impact are still insufficient, even though many researchers have begun to study the dynamic properties of the bolted joint rotor system and the nonlinear vibrations of a rotor-bearing system undergoing rubbing fault. In addition, the multi-disc bolted joint construction of the compressors used in aircraft engines has not been taken into account in the prior research. To far, research on the rubbing characteristics of bolted joint rotor systems has mostly concentrated on the way in which contact stiffness and radial clearance influence the systems' dynamic properties. This study intends to shed light on the influence of rubbing position on the rotor dynamics of a bolted joint rotor system with several discs, and is thus concerned with the structural properties of the compressor in an aero-engine. The findings may also be used to learn more about the unique features of a multi-disc bolted joint rotor system's rubbing fault's location.

Therefore, a dynamic model with twelve degrees of freedom is built in the current study to shed light on the bifurcation phenomena of a multidisc bolted joint rotor system subject to the rub-impact effect. The contact impact of the mating interface in the multi-disc bolted joint is accounted for in the modeling and analysis, which is accomplished by applying the lumped parameter based on Lagrange's equations to produce the dynamic model. Bifurcation diagrams, time-domain vibration waveforms, frequency spectra, shaft orbits, and Poincare maps all show how the rubbing position affects the dynamic behaviors of the multi-disc bolted joint rotating system. This study focuses on the aero-engine compressor's structural properties, drawing on empirical data.

The novelties of the present work are given as follows:

**(i)** A dynamic model of a multi-disc, bolted-joint rotor system that experiences a rubbing defect is constructed.

**(ii)** A multi-disc rotor system with bolted joints is investigated for how rubbing position affects the system's dynamic properties.

**(iii)** The study may serve as a benchmark for identifying the rotor system of an aero-rubbing engine's location.

## LITERATURE REVIEW

**HuiMa (2015)** Through the lens of contact dynamics theory, we investigate the dynamic features of a rubbing rotor with circular and four-pin-shaped stators. Timoshenko beam is used to model the rotor system coupled to two disks and pin-shaped stators using the finite element (FE) approach. To build the dynamic model of the rotor-stator coupling system, a lumped mass model is used to represent the circular stator, and one or more point-point contact components are used to form the connection between the rotor and stator. System dynamic characteristics are analyzed by time-domain waveform, rotor orbit, normal contact/rubbing force, and stator acceleration, with the assumption that rubbing is caused by the sudden impact excitation and sudden unbalance excitation under two loading conditions (condition 1: in-phase unbalances of two disks at the first critical speed, condition 2: out-of-phase unbalances of two disks at the second critical speed). A combination of frequency components around the rotor's rotational frequency (1) and the first lateral natural frequency of the rotor-stator coupling system (fn1) can be seen as the most distinguishing feature, indicating that the rubbing caused by the sudden impact under loading condition 2 will always exist and will excite quasi-periodic motion of the rotor system. Under loading condition 1, full annular rubbing may arise as a result of a rapid imbalance excitation; four-point rubbing may dampen the sub synchronous vibration and primarily excite odd multiple frequency components.

**Di Liu (2022)** Aero-engine rotors often use joint structures like flanges with bolts and curve-couplings. When the rotor is put under a lot of stress, the joints holding it together tend to loosen, and the local deformation of those joints might cause the rotor's dynamics to become nonlinear. But although studies of bolted-joint loosening are common, reports of curve-coupling loosening in rotor systems are uncommon. In this study, we model and analyze the dynamics of loosened curve-coupled rotors. To begin, a theoretical framework is put out to characterize the nonlinear stiffness due to looseness in the joint contact. Then, the corresponding dynamic equations for a rotor with curve-coupling looseness are generated from the model. In the end, the complex nonlinear modes approach is used to investigate the modal features of the rotor with curve-coupling looseness, and steady-state response is produced by numerical methods. The findings demonstrate that eigen frequency drop in modal analysis, amplitude leap in response, and bifurcation around the critical speed may all come from the loosened joint's softer new behavior. Fault diagnostics in a loosened curvic-coupled rotor system may make use of the aforementioned dynamic properties.

**Dongxiong Wang (2022)** Magnetic suspended dual-rotor systems (MSDS) have the potential to greatly improve the efficiency of aircraft engines by doing away with the need for a lubrication and maintenance system and providing an efficient answer to the problem of vibration. Nonlinear support qualities of active magnetic bearing (AMB) have seldom been included in studies of MSDS vibration characteristics under fixed-point rubbing. Through the use of the equivalent magnetic circuit approach and subsequent verification using the finite element model, a revised EF model of the AMB is suggested in this study. We then use the Lankarani-Nikravesh model to characterize the impact force during the rubbing operation. Based on these findings, a finite element model of the rubbing dynamic is developed and then validated against published experimental data. At last, we investigate MSDS vibration properties and discover some peculiar behaviors. A large number of frequency components evenly distributed around the sum of the frequency components of the rotor's rotational speeds will be produced via fixed-point rubbing. The fractional frequency component of the MSDS second-order critical speed emerges in a certain speed range as a result of the stimulation of the AMB nonlinear EF, and this implies the possibility of instability in the system; when fixed-point rubbing occurs, the rotational speed corresponding to the initial appearance of this frequency component decreases. In the rubbing process, the maximal normal impact force falls as the proportional coefficient declines and the differential coefficient increases.

**E. P. Petrov (2019)** There are several examples of rubbing contact interactions in gas turbine engines and other rotating equipment structures, including rubbing in rotor bearings and labyrinth seals, and rubbing between spinning bladed disk casings. Including the prescribed relative motion of rubbing surfaces in addition to the motion due to vibrations of the contacting components is essential for the analysis of vibrations of structures with rubbing contacts. This necessitates the development of a mathematical model and special friction contact elements. The suggested work develops a formulation of the friction contact components, taking into account the influence of the required relative motion on the friction stick-slip transitions and, by extension, the contact interaction forces. Using the multibaryonic representation of the vibration displacements, a novel formulation is developed for the frequency domain analysis of coupled rubbing and vibrational motion. To facilitate rapid and precise computation of the multibaryonic contact interaction forces and multibaryonic tangent stiffness matrix, the formulation is constructed in a purely analytical fashion. This formulation takes into account the fact that the friction and contact stiffness coefficients rely on the amount of energy lost in high-energy rubbing contacts and, by extension, the amount of heat generated at the contact surface. A variety of test scenarios, from elementary models to a genuine large-scale blade, are used to illustrate the effectiveness of the created friction components.

**Yang YANG (2022)** This paper's focus is on a dynamic model of a gas turbine in order to better understand its nonlinear vibration characteristic. To begin, a model for a rotor-bearing coupling using rod fastenings and fixed-point rubbing is provided; this model makes use of both fractal theory and the finite element approach. In this study, we provide a new contact force model for use in contact analysis. At the same time, the Coulomb model is used to elaborate on the frictional features. Second, the rotor system's governing equations of motion are numerically solved, and the nonlinear dynamic features are evaluated using a bifurcation diagram, Poincare map, and a time history. Third, the distribution location and quantity of contact layer as well as the contact degree of the joint interface are explored in depth, along with their possible impacts. We conclude with a comparison study of the integrated rotor and the rod fastening rotor in the presence of fixed-point rubbing.

## DYNAMIC MODEL OF DUAL-ROTOR-CASING SYSTEM

### FE model of dual-rotor-casing system

This work examines the phenomenon of rubbing in a dual-rotor-casing system. Figure 2 shows a schematic depiction of the model. One rigid compressor disc and one rigid turbine disc constitute the low-pressure (LP) and high-pressure (HP) rotor subsystems, respectively. In this case, the linear spring and damping parts stand in for the bearing. With an inter-shaft bearing linking the LP and HP rotors, two-rotor subsystem connection is a real possibility. The rotors are discretized into 19 elements and 21 nodes using finite element analysis, while the housing is discretized into 15 elements. Timoshenko beam elements are used to simulate the inner rotor, outer rotor, and housing. Each node of the LP/HP rotors has five degrees of freedom (DOFs): two lateral ($u_x$, $u_y$) and three rotational ($rot_x$, $rot_y$, $rot_z$), whereas each node of the casing has four lateral ($u_x$, $u_y$) and two rotational ($rot_x$, $rot_y$, $rot_z$) ($rot_x$, $rot_y$). In this simulation, lumped mass components are used to represent all of the disks.

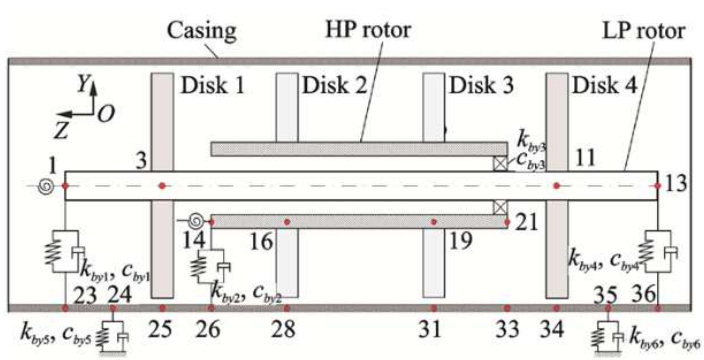


**Figure.2 Schematic of dual-rotor-casing system**

Figure 2 shows the Y-direction supporting stiffness and damping between the LP rotor and the housing, denoted by $kby_1$ and $kby_4$, and $cby_1$ and $cby_4$, respectively. The HP rotor and housing have a supporting stiffness and damping in the Y direction denoted by $kby_2$ and $cby_2$, respectively. Supporting stiffness and damping along the Y axis are denoted by $kby_3$ and $cby_3$, respectively. The Y-direction supporting stiffness and damping between the housing and the foundation are denoted by $kby_5$, $kby_6$, and $cby_5$, cby6.

### Rubbing force model

The linear spring and damping components are attached to the rigid casing to provide this constraint, but the local-contact elastic deformation due to contact force is disregarded. The rubbing action of the disk against the housing is seen in Fig.3 Assuming a static configuration, the geometric centers of the LP rotor and case are located at ($O_d$, $O_c$). Furthermore, Oc, the center of the case, is also the origin of the coordinate system. The rubbing disk radius, denoted by Rd, and the casing radius, denoted by Rc, are shown here. To be eccentric is to use the letter e. The supporting stiffness and damping in the x and y directions between the casing and the base are denoted by kcx, kcy, and ccx, ccy.

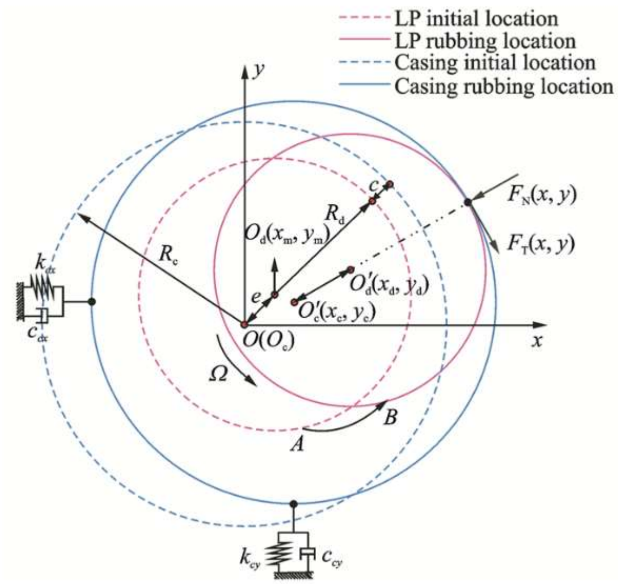


**Figure 3. Schematic diagram of rubbing between disk-casing**

**Rubbing-Induced Vibration Responses in Dual-Rotor-Casing System**

Rub-induced vibration responses of the dual-rotor-casing system are analyzed, together with the impacts of rotational speed and speed ratio. The vibration responses are studied using time-domain waveform, spectral cascades, and the frequency spectrum. It's important to remember that disk 1 only rubs against the case in a very specific area (see Fig. 4)

**Effects of rotational speed**

The vibration responses of the dual-rotor-casing system are very sensitive to rotational speed. The rubbing process demonstrates the spectrum cascades for a range of rotational speeds (800-5 800 rev/min) (see Fig. 4). Figure 4 illustrates this occurrence clearly, since the difference in LP rotor rotation speed allows it to be identified as distinct from other similar phenomena. To begin, the rubbing is minimal and sporadic in the low rotational speed range (800-2 000 rev/min). Peak values of f1 and f2 are readily apparent. Second, the amplitudes of combined frequency components are clearly discernible and rubbing becomes more prevalent at =1 700 rev/min. In addition, the excitation of 1st order natural frequency causes the spectral line of the HP rotor to form resonance (point A) and amplify. Frequencies like f2-f1, 1/2f2, 2f1-f2, 2f1, f1+f2, and 2f2 become common in the spectrum after the first critical speed. As the rotational speed increases from 2,000 to 4,000 rpm, the response values of the combined frequency components grow. At 2300 rpm, the LP rotor's spectral line develops resonance (point B), and amplitude amplification occurs owing to the stimulation of 1st order natural frequency. Extreme rubbing, an increase in combined frequencies, and excitation of the 2nd order natural frequency all take place between 4,000 and 5,800 revolutions per minute (points C and D).

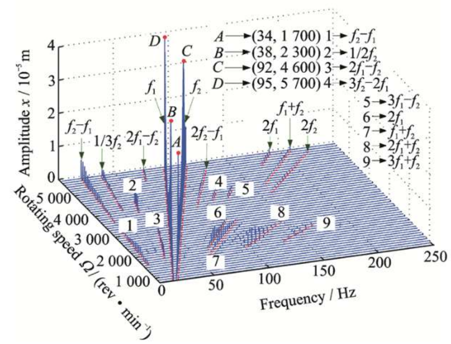


**Figure. 4 Spectrum cascades of inner rotor rubbing under different rotational speeds**

Figure 5 displays the vibration responses of the LP rotor and case at a rotational speed of =2 300 rev/min; the time domain waveform is broken in red to indicate the onset of rubbing. Both the inner rotor's and the outer casing's orbits are severely squeezed and unbalanced. More components may be seen at the response frequencies, and the amplitude of the combined frequencies is more prominent in the spectrum. On the other hand, Fig. 6 depicts the time domain waveform of the torsional displacement of the compressor disc in the LP rotor and the HP rotor. Compared to lateral displacement, the magnitude of torsional displacement is greater. Vibration responses produced by simulating the casing as a lumped mass are compared with those obtained without the casing in order to assess its influence on the rubbing-induced vibration responses (see Fig. 7).

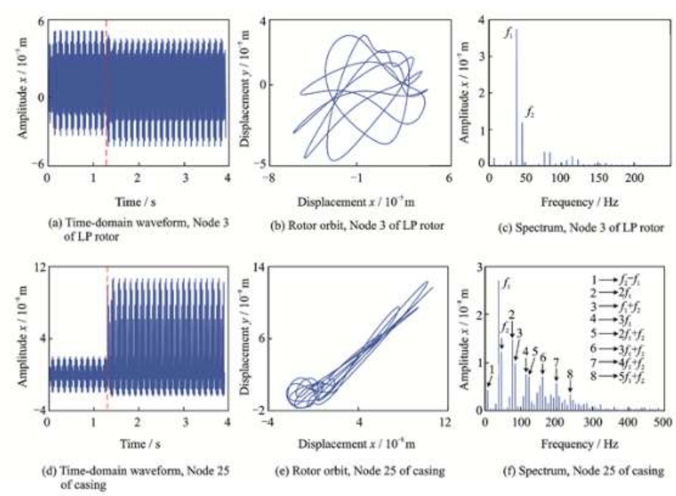

**Figure. 5 Rubbing-induced responses at Ω=2 300 rev/min**

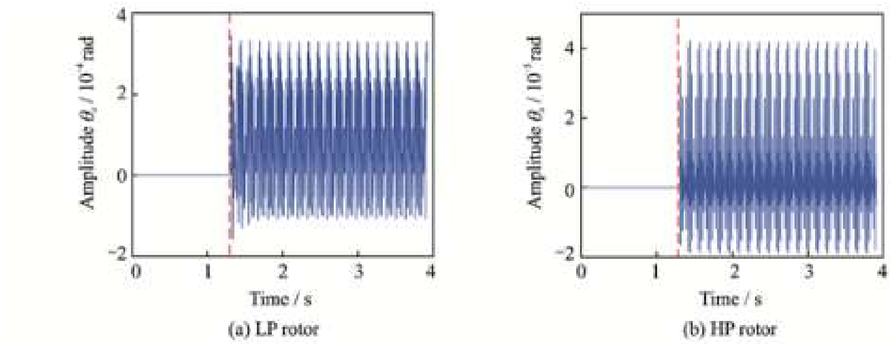


**Figure. 6 Torsional displacement at Ω=2 300 rev/min**

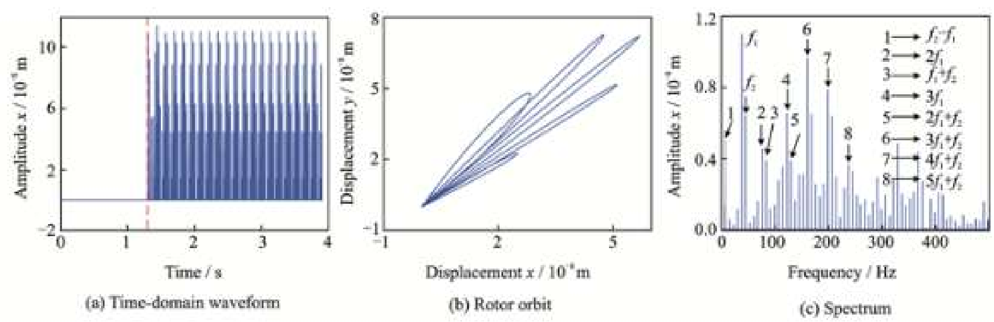


**Figure. 7 Rubbing-induced responses of mass point casing at Ω=2 300 rev/min**

## Conclusions

In this study, we use the energy theorem and Lagrange's principle to simulate a rotor system with a multi-disc bolted joint and a rubbing force on the disc. In addition, by comparing the results of the simulations performed in this study with the findings provided in the literature, the validity of the constructed model is shown. We construct a FE model of the whole dual-rotor system, including the housing. The local rubbing caused nonlinear properties of the dual-rotor-casing bearing system were examined based on shaft center orbits, time-domain waveforms, and frequency spectra. Here are a few of the major takeaways The spectrum displays not only the individual frequency components of the two imbalanced excitation frequencies but also the numerous frequency components of those frequencies when they are combined. Under rubbing circumstances torsional vibration amplitude is higher than lateral vibration amplitude. Thirdly, the dual-rotor system's periodicity is profoundly affected by the speed ratio. Under counter-rotation, the amplitudes of the rubbing-induced responses are less than those under co-rotation for the same parameters.

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