Non-Obstructive Particle Damping Experience and Capabilities

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ABSTRACT

Non-Obstructive Particle Damping (NOPD) technology is a passive vibration damping approach whereby metallic or non-metallic particles in spherical or powder form, of heavy or light consistency, and even liquid particles are placed inside cavities or attached to structures by an appropriate means at strategic locations, to absorb vibration energy.

Numerous laboratory experiments and applications on hardware have been carried out at Boeing Canoga Park (Rocketdyne). Test results are summarized in the following paragraphs to provide an overview of the technique and the effectiveness of particles as a means for damping vibrations as well as for acoustic attenuation.

Specific applications and capabilities are presented regarding some of the major test/development programs undertaken during the past years at Rocketdyne.

BACKGROUND

High amplitude structural resonance vibrations in components**/**members such as aerospace structures, aircraft and rotating machinery, result in serious problems that can lead to failure of such structural members. For undamped or very lightly damped structures, the response amplitude near resonance frequency increases drastically. If damping is made available, however, elementary analysis and experimental data show that response is, roughly, inversely proportional to the damping coefficient (Figure 1). Therefore, if design stresses are to be evaluated, the degree of uncertainties in the damping coefficient is exactly equal to the uncertainties in these stresses. Moreover, if damping values are significant, then the effect of these uncertainties in the analyses and the design are reduced.

According to one method of damping structural vibrations, a rubber-like viscoelastic material is either coated on the surface or sandwiched inside the structure. Such coatings and/or sandwiching absorb the vibration energy by flexure of the added material. While such coating/sandwiching is effective under certain conditions, they are temperature and frequency dependent, and in time they disintegrate/crack and require replacement.

There are also other damping techniques wherein energy is mainly dissipated via friction. These include friction dampers used on structures such as turbine blades, in the form of a piece of metal attached to the blade so that when the blade vibrates, the piece of metal rubs against the wall of the blade and it absorbs energy by friction. However, the disadvantages of this type of dampers are that the effectiveness degrades in time because the tightness of fit loosens. Moreover, the metal piece can break lose and enter the flow stream of the propellant and, thus, harm the turbine.

The effectiveness of damping treatments in structures is related to the amount of vibration energy converted to other forms of energy. The performance of virtually all existing damping methods is effected by environmental conditions. Vibration damping under severe temperature, pressure, or fluid flow conditions is usually handled by structural design optimization, material selection, and other measures. Systematic treatment for passive damping are unavailable for use in cryogenic or harsh environments.

There is a particular need for more effective vibration damping of aerospace and aircraft structural members, especially turbine blades.

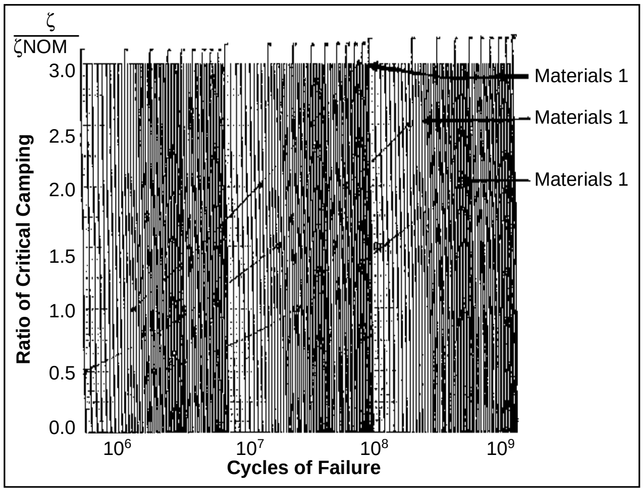

Figure 1. Damping Ratio as a Function of Cycles-to-Failure for Various Materials

DESCRIPTION OF NOPD

NOPD is a relatively new vibration damping technique entailing placement of numerous loose particles inside any cavity built-in or attached to a vibrating structure at strategic locations, based on finite element analysis. During vibration, particles interact with the walls of the cavity and one another and, thus, dissipate energy through momentum transfer and friction. Parameters like particle size, size distribution, shape, density, texture, coefficient of restitution, coefficient of friction, cavity surface area and condition, free space around the particles, vibration amplitudes and frequencies can all have significance in the damping performance. Thus, proper NOPD treatment of a structure requires careful analysis and design of cavity location, size, and shape as well as characterization of the proper particles and their fill levels for maximum damping effectiveness for a given set of vibration modes of concern. Research in this field has shown the complexity of the response of an ensemble of granular particles placed in a cavity. One major problem is that, even at microscopic levels, dissipation mechanisms in solids are poorly understood, since they depend on a large number of parameters. Thus, particle damping design tools for application on vibrating structures is not readily available [1].

NOPD may be considered as a generalization of the well-known impact damper, in that the latter only uses a single particle or mass, while in the former, numerous randomly sized particles are placed in the cavity [2]. Similar to impact dampers, particles are supposed to move out of phase with the cavity walls. Thus, the resulting impacts and the frictional forces amongst the particles and those between the particles and the walls provide the mechanisms for energy absorption. The particles in a cavity can be treated as an effective mass and, thus, have an effective velocity, equal to the mean velocity of the whole group of particles. This type of a design approach could help size any NOPD treatment configuration [3].

CURRENT RESEARCH

Particle mechanics has been investigated for several decades. The recent interest in the damping capability of particles in vibrating structures has given a boost to this area of research. Numerous organizations and universities in many countries are currently experimenting with particles for damping structural and acoustic vibrations as well as to study the various complex mechanisms of energy absorption in this robust technique. Being at least as effective as other damping techniques (e.g., viscoelastic damping), it is the only one, other than friction dampers, that can be used in harsh environmental conditions, like those attained in high-speed rotating machinery. NOPD is insensitive to temperature, unlike viscoelastic damping. Because NOPD can be integrated into existing hardware, it has also proven to be a technology that can be used to solve vibration problems in the field.

The particle-damping phenomenon is complex because of friction and the variety of other energy dissipation mechanisms involved, and because of the granular nature of the particles themselves. Friction is still a poorly understood issue. It is the macroscopic manifestation of strong surface cohesive and adhesive forces at the atomic scale; so anything beyond semi-empirical laws becomes extremely complicated. The combination of elastic, viscous, and plastic mechanisms during deformations is another difficulty. If one combines all these with the granular quality, leading to meso-scopic properties (collective behavior here does not imply macroscopic, but an intermediate stage between microscopic and macroscopic laws), we are faced with one topic that has been left unresolved for centuries.

Theoretical advances on this subject are difficult and limited to simplified systems. There is a lot of recent descriptive experimental research on instabilities because of convection, size segregation, fingering, ripple and stripe formation, and other phenomena found in granular ensembles out of equilibrium [1]. While some effects have been known for a long time, only more recently the possibility of numerically simulating the behavior of systems of granular particles has opened new ways to understand interaction-dissipation mechanisms and collective patterns of flow, energy dissipation, and dynamic regimes. Important information can be extracted from numerical simulations, which otherwise is expensive to obtain or not even available with direct, real experiments. Nowadays, systems of 10,000 particles are handled in a reasonable amount of time, by means of fast algorithms and computers, but this number can be easily increased tenfold in parallel computer architectures and the knowledge can be used for practical purposes.

Previous research work has shown that particle damping can be modeled and predicted by using numerical simulations [4]. For instance, in a simple linear model, a single cavity filled with an arbitrary number of particles, is subjected to sinusoidal forces of constant amplitude and frequency, $F_0 \sin \omega t$, and its velocity recorded to evaluate the energy dissipated per cycle. If the system were a linear damped oscillator, the friction force would be proportional to the velocity, and its evolution would be dictated by the equation of motion

$$\ddot{x} + 2b\,\dot{x}\,\omega_0^2\,x = F\frac{0}{m}\,\sin\omega t \qquad (1)$$

The constant of the friction force, *b*, is the inverse of the amplitude of the relaxation time, and is directly associated with the energy dissipation rate and the damping ratio, $\zeta = b/\omega$. In stationary regimes, the averaged dissipated power can be written as

$$(W)_{cyc} = mbA^2\omega^2 \qquad (2)$$

where *A* is the (stationary) amplitude of motion. Even if the particles do not behave like the linear oscillator, one can compute the cycle averaged dissipated power, and define an effective damping parameter *b.* This will be the equivalent linear oscillator with the "same" damping properties, if they are evaluated with no more resolution than complete periods. The averaged energy consumption, moreover, is the quantity accessible in experiments and can be easily compared with numerical results. The study of the properties of *b* leads to the damping phase diagram and provides useful tips for damper design.

The next step is the development/use of a generalized (nonlinear) one-dimensional model. When the cavity is moving in a stationary manner at a given mode of vibration and the quantity of interest is the (time dependent) force of the particles, this force is exerted through the walls of the cavity and provides damping to the surrounding structure. The oscillator is no longer linear since a pure mode in the response (damping force) is not observed [4]. It has been shown that under horizontal (with respect to gravity) excitations, it is possible to rewrite the Fourier series in terms of an expansion of displacement and velocity terms. In this typical decomposition of nonlinear elastic and viscous terms, the system is characterized by four dynamic parameters, which depend on the amplitude and frequency of vibration, but not on time.

The dependence of particle damping on the type of particles used is known to be crucial. Very little is known, however, about the systematic connection between material characteristics and damping response. Particles are assumed to be spherical, as in most applications. However, no particle is perfectly spherical at any scale, for it contains asperities at some typical length. This leads to roughness. Roughness can be modeled either through Coulomb static friction or through a shield of smaller spheres surrounding the particle core. Many models have been used so far for normal and tangential forces. Some introduce constant restitution coefficients. Experiments have shown that normal and tangential restitution depends on the impact velocity of colliding particles and they are not constant. One exception is the pure plastic limit [5], which is poorly understood. One of the few models with a sound theoretical and experimental basis is the viscous model for normal interaction [6]. For the normal force between colliding spheres, one derives a generalization of Hertzian contact law to dissipative (viscous) interaction. The presence of asperities can alter the picture of viscous dissipation. For very hard materials and small velocities, deformations can occur that barely surpass the scale of the protuberances of the particle. Collisions do not involve the particle cores, but much smaller effective colliding particles. The overall effect is that viscous dissipation from normal interaction is dramatically reduced.

Research continues in this area. Numerous new studies are ongoing that deal with various complex aspects of particle interactions, modeling of the various mechanisms, and prediction of damping under various conditions. One such study was recently carried out that dealt with the particle damping variability under different gravitational conditions. This study addresses features similar to particle behavior under rotational conditions in turbomachinery. The results indicate that particle behavior could change as a function of g-level. Thus, there are conditions when particles behave like a solid (move in unison), like a liquid (move in waves) and like a gas (move randomly). The plot in Figure 2 shows some of these characteristics.

NOPD EXPERIENCE

Numerous laboratory test results and applications are reported in the following paragraphs (1 through 9). NOPD has been under study at Rocketdyne for the past 13 years.

1. A high-cycle fatigue (HCF) induced anomaly was discovered on the SSME liquid oxygen inlet duct. This is in the form of the letter T. HCF was causing cracks on the two flow split vanes that (analysis indicated) was caused by fluid/structure interactions and random loading phenomena. Extensive analyses were carried out to determine applicable options to resolve the anomaly. One option was added damping. Viscoelastic or other forms of damping were considered impractical. Hence, a new technique was invented that proposed filling of solid particles inside small holes drilled in the vanes to absorb the vibration energy [7]. Laboratory tests indicated a very high effectiveness under static loading conditions. A reduction in amplitude of over fivefold was measured with four 1 mm in diameter holes along the lengths of each vane that had less than 1 gm of particles.

2. Two aluminum beams (24 in. by 3 in. by 3/4 in.) were manufactured. In one beam, seven equidistant holes were drilled along the length, 2 mm in diameter each. The second beam had 13 equidistant holes drilled along the width, all in the central plane of the beams. These holes were filled with various particles, at various fill levels, and numerous combinations of selective holes were experimented with, both in air and in water. Tremendous damping was achieved, over 10% of critical under certain configurations. Damping performance was found to be related to particle

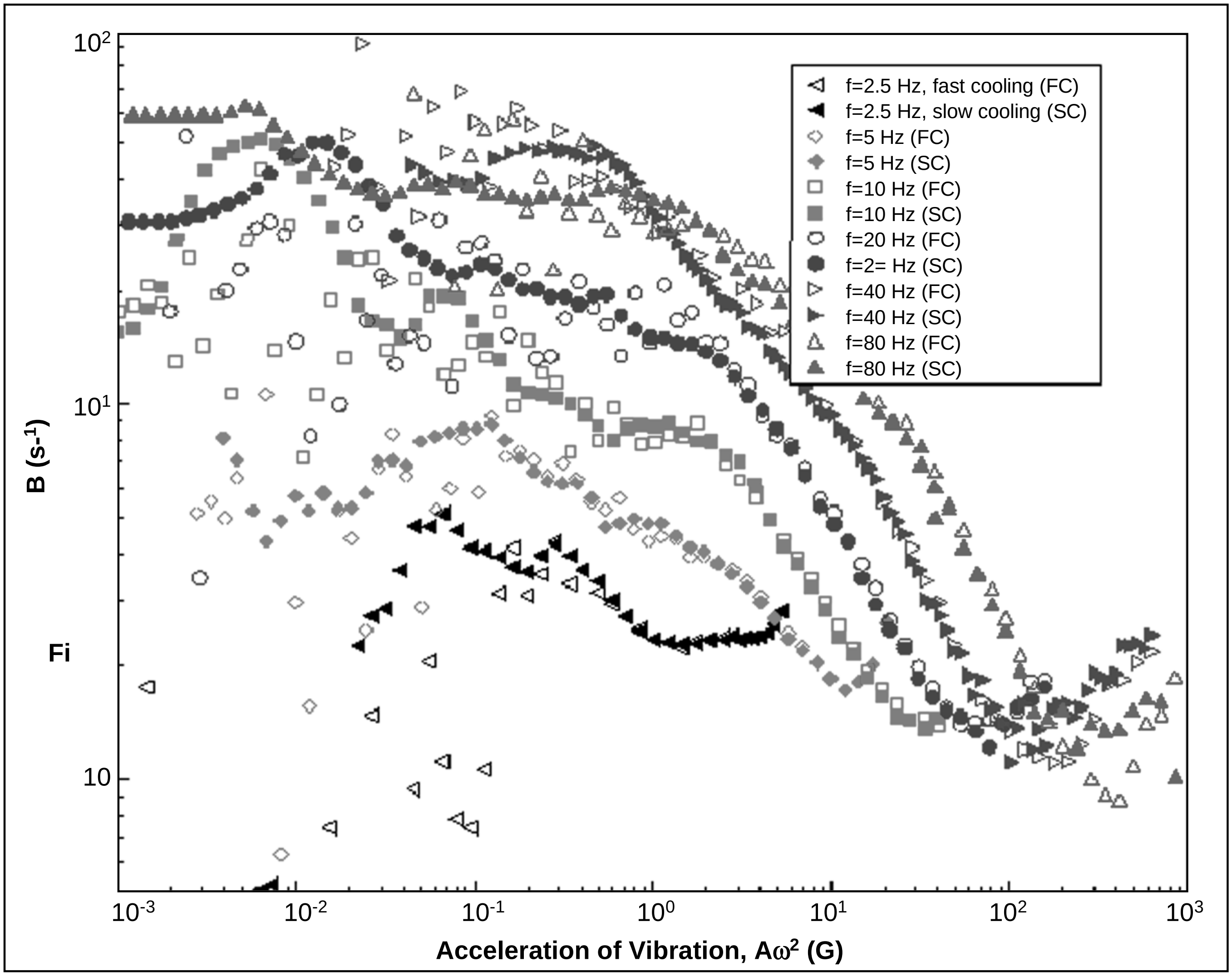

Figure 2. Damping Prediction on Parallel Computers as a Function of Acceleration (g)

size, density, shape, fill level, and amplitude of vibrations, among others.

Response amplitude at the resonant frequencies of the beam turned out to be a function with quite a few variables. A "rule of thumb" was hard to find for design purposes. Hence, a finite element approach was developed whereby special solid (brick) elements were made to represent the holes and the particles inside them. The characteristics of damping and stiffness for the latter elements were parametrically determined for each particle used and predictions for damping were anchored on test results. The analytical model for prediction of energy dissipation was based on the Euler-Bernouli equation where the rate of change of shear along the length of the beam was taken to be equal to the loading per unit length. Also, the rate of change of the moment along the beam was considered equal to the shear. This approach was selected to design NOPD treatments.

3. The Rockwell Graphics Division had a printing problem with one of their high-speed printing presses. The printed pages had streaks of white on them because of (it was determined) the vibrations of the press cylinder under rotation. An NOPD treatment of the cylinder was designed and tested in the lab and on the printing press in its real operating conditions and the results proved effective. The design was implemented on that particular printer. The design process followed was the one described above. Namely, special solid elements for the particles in the holes were made in a finite element model of the cylinder with parametric data for their damping and stiffness values and predictions and damping design were carried out. The test results were very close to the predicted values of response amplitude for the first bending mode. Extensive testing was carried out in the Rocketdyne Engineering Development Laboratory (EDL) to compare the response amplitude of the first bending mode of the structure

4. Several other applications were also tested in EDL. The first was to resolve a truck brake failure caused by excessive vibrations during braking. The second application concerned an automotive transmission gear that was determined to have high amplitude acoustic emissions due to excessive gear vibrations. A shock absorber with particles filling the cylinder on both sides of the piston was also tested in EDL with various spherical particles. The shock mount proved to be a very effective absorber.

5. An Air Force Contract was won from the Wright Aeronautical Laboratory to evaluate NOPD application on aircraft turbine/compressor blades. As a preliminary assessment of NOPD effectiveness under rotation, it was decided to test flat titanium plates with similar frequency content as the actual blades that were to be tested in the whirligig. Thus, three pairs of plates were manufactured with dimensions of 4 in. by 4 in. by 0.155 in. The plate was made with three layers of Titanium sheets with the surface layers each of 0.150 in. thick and the plate in the middle 0.125 in. thick. The latter had 80 holes of 0.25 in. in diameter, as shown in Figure 2. These three layers were brazed together to form the plates. The plates were then tested with two configurations of NOPD treatment and one solid plate (no particles). The EDL tests indicated over 8% of critical damping of the first bending mode and similar damping values for the other modes (Figure 3). These plates were tested in the NASA Glenn Research Center whirligig facility under 10K rpm rotation and, while rotating the shaft on which the blades were attached, were excited with magnetic bearings at very low excitations levels. Unfortunately the excitation levels were over 100 times less than what the real blades would see in a real aircraft engine. Thus, the results of the whirligig tests were inconclusive. However, before going into the whirligig tests of the NOPD treatment of the real compressor blades, the contract funds ran out and the task was not completed.

6. NOPD was also successfully tested for acoustic amplitude attenuation on Delta IV components and 10 lb of particles achieved an equivalent amount of attenuation as 300 lb of blankets wrapped around the vehicle body. Several tests have also been carried out on turbine blades, which are still ongoing.

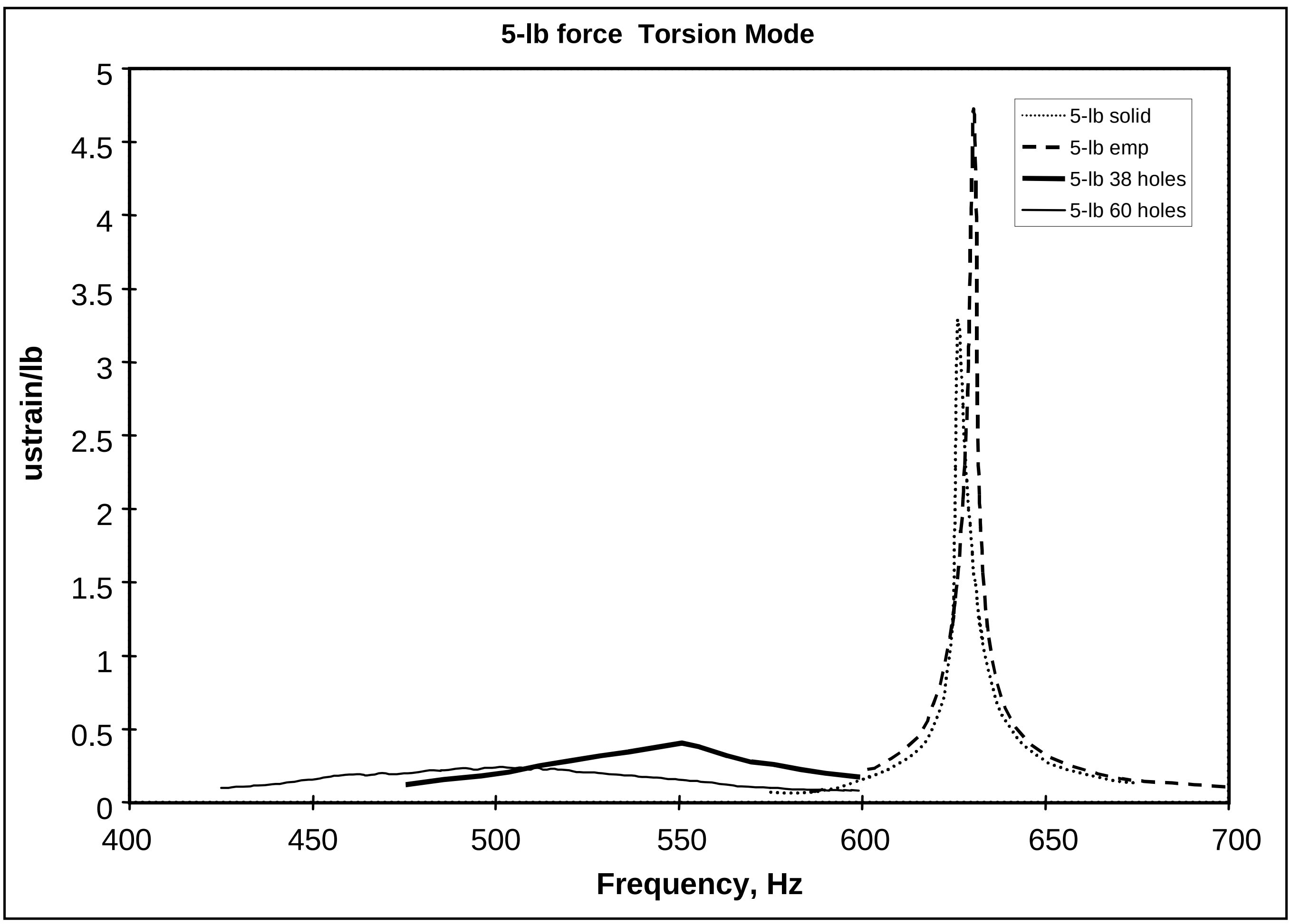

Figure 3. Plate Response to Sine Inputs of Solid, 38 and Holes Filled Configurations

CONCLUSIONS

The above summary shows that NOPD is a viable technique for vibration damping and acoustic attenuation. Extensive research has been and is being carried out in this area and continued interest in the field has gotten numerous academic, governmental, and industrial institutions involved. Currently, computer programs are available to predict damping effectiveness under various designs via finite element analysis. Moreover, advanced particle dynamic codes are also available, which can analyze the behavior and effectiveness of numerous particles (as much as 30,000) in a cavity vibrating/moving under the effect of the vibration of the structure they are housed in. These codes have been shown to predict damping effectiveness under various gravitational and other conditions.

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