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DEPARTMENT OF THE NAVY ★ NAVAL SHIP R&D CENTER ★

ACOUSTIC RADIATION FROM A DRIVEN INFINITE PLATE BACKED BY A PARALLEL INFINITE BAFFLE

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ACOUSTIC RADIATION FROM A DRIVEN INFINITE PLATE BACKED BY A PARALLEL INFINITE BAFFLE

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Naval Ship Research and Development Center
Washington, D. C. 20007

ACOUSTIC RADIATION FROM A DRIVEN INFINITE PLATE BACKED BY A PARALLEL INFINITE BAFFLE

G. Maidanik

ABSTRACT

The far-field acoustic pressure generated by an infinite plate driven by a point and a line force are computed. This paper constitutes an extension of previous computations [G. Maidanik and E. M. Kerwin, Jr., J. Acoust. Soc. Am. 40, 1034–1038 (1966)]. The extension is in the sense that the plate considered here is backed by a fluid medium that is terminated by a parallel infinite baffle. It is shown that when the absolute value of the acoustic reflection coefficient of the baffle approaches unity, the presence of the baffle may substantially affect the far-field acoustic pressure. The far-field acoustic pressure when the spaces in the front and the back of the plate are occupied by different fluid media is briefly considered.

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Acoustic Radiation from a Driven Infinite Plate Backed by a Parallel Infinite Baffle

G. MAIDANIK

David Taylor Model Basin, Washington, D. C. 20007

The far-field acoustic pressure generated by an infinite plate driven by a point and a line force are computed. This paper constitutes an extension of previous computations [G. Maidanik and E. M. Kerwin, Jr., J. Acoust. Soc. Am. 40, 1034–1038 (1966)]. The extension is in the sense that the plate considered here is backed by a fluid medium that is terminated by a parallel infinite baffle. It is shown that when the absolute value of the acoustic reflection coefficient of the baffle approaches unity, the presence of the baffle may substantially affect the far-field acoustic pressure. The far-field acoustic pressure when the spaces in the front and the back of the plate are occupied by different fluid media is briefly considered.

INTRODUCTION

THE influence of fluid loading on the vibration and acoustic radiation from driven panellike mechanical systems has been receiving increased attention recently.[1–6] The increased interest in this subject has been chiefly motivated by the more stringent requirements placed on the performance of modern seacraft and its auxiliary equipment. It has been demonstrated that fluid loading may have substantial influence on the vibration and the acoustic radiation from most practical panellike structures when submerged in sea water. Because the influence is substantial, it is necessary to acquire a thorough understanding of the mechanism and the way the fluid makes its presence felt on the vibrational behavior of the structure; for in many cases, small-order perturbation techniques may prove inadequate. This paper is written in the hope of making some contribution towards the general understanding of the subject of fluid loading on structural systems.

In a recent paper,[1] the far-field acoustic pressure generated by a point or a line force acting on an infinite plate was computed. In these computations, the influence of fluid loading was of particular interest. The results were interpreted in terms of equivalent acoustic sources. In this paper, we wish to extend these previous computations to take account of the following changes in the mechanical system: On the back side of the plate we introduce a fluid medium which is terminated by a parallel flat infinite baffle. A sketch of this mechanical system is shown in Fig. 1. As in the previously mentioned paper,[1] the analysis is restricted to the frequency range below the critical frequency. In Sec. I, we derive the general equation describing the acoustic pressure in the space in front of the plate when the plate is driven by a general external force field. In Sec. II, we limit the analysis to a point-force drive, and we compute the far-field acoustic pressure. The far-field acoustic pressure in the cases of a rigid and a soft (pressure-release) baffle are considered as particular examples of the influence of the baffle on the radiated pressure. In Sec. III, the extension of the analysis to a line-force drive is indicated. In Sec. IV, some aspects of the extension of the formalism to moment drives are discussed. In the final section, Sec. V, the problem associated with the introduction of different fluid media in the front and the back of the plate are briefly considered.

[1] G. Maidanik and E. M. Kerwin, Jr., J. Acoust. Soc. Am. 40, 1034–1038 (1966).
[2] G. Maidanik, J. Sound Vibration 3, 288–299 (1966).
[3] M. Heckl, Acustica 13, 182 (1963).
[4] P. M. Morse and K. U. Ingard, *Encyclopedia of Physics, Acoustics I*, S. Flügge, Ed. (Springer-Verlag, Berlin, 1961), Vol. 11/1, pp. 108–126.
[5] W. Thompson, Jr. and J. V. Rattayya, J. Acoust. Soc. Am. 36, 1488–1490 (1964).
[6] The above list of references (1–5) is not meant to be exhaustive, but rather, illustrative.

I. ACOUSTIC RADIATION FROM A DRIVEN, INFINITE PLATE BACKED BY A PARALLEL INFINITE BAFFLE

We consider an infinite, homogeneous, isotropic plate lying in the x–y plane, as shown in Fig. 1. The upper side of the plate ($z>0$) is in contact with an unbounded

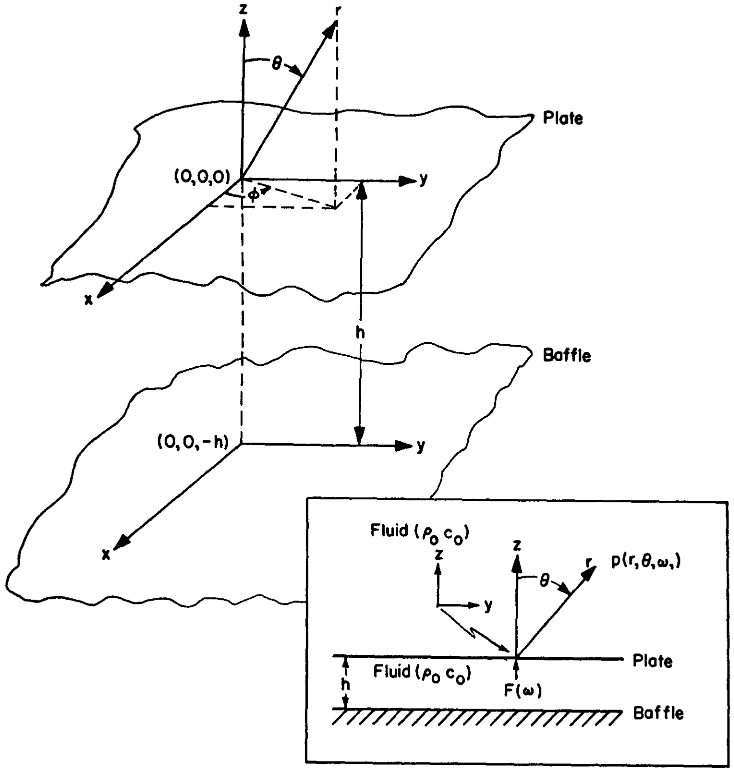

FIG. 1. Plate–baffle system and coordinate system.

fluid medium whose characteristic impedance is $\rho_0 c_0$. The back of the plate ($z<0$) is in contact with the same fluid medium, but the space is terminated by an infinite flat baffle placed at a distance h parallel to the plate as shown in Fig. 1. The equation of motion of the plate in spectral form, both in wave vector and in frequency, is[1]

$$[Z_{\mathrm{p}}(\mathbf{k},\omega)+Z_a(\mathbf{k},\omega)]V(\mathbf{k},\omega)=P(\mathbf{k},\omega), \quad (1)$$

where

$$Z_{\mathrm{p}}(\mathbf{k},\omega)=i\omega m[1-(1+i\gamma)(k/k_{\mathrm{p}})^4], \quad (2)$$

$$Z_a(\mathbf{k},\omega)=2\rho_0 c_0(k_z/k_0)^{-1}[1-R\exp(-2ihk_z)]^{-1}, \quad (3)$$

Z_{p} is the plate spectral mechanical impedance; $R(k_z/k_0,\omega)$, the acoustic reflection coefficient of the baffle; $\mathbf{k}=\{k_x,k_y\}$, the wave vector on the plate; $\frac{2}{3}\mathbf{k}_3^2=k$; $k_z=(k_0^2-k^2)^{\frac{1}{2}}$; ω, the frequency in radians per unit time; $k_0=\omega/c_0$; c_0 is the speed of sound in the fluid medium; V, the plate spectral-response velocity; P, the driving external mechanical-force spectral field; k_{p}, the wavenumber of free waves on the plate in vacuum[1]; m, the mass per unit area of the plate; and γ, the loss factor accounting for the dissipation in the plate.[1,2]

It may be in order to make a few remarks concerning Eq. 3. This equation is derived by constructing the appropriate image system for the plate motion. The image is constructed so that both the baffle and the plate surfaces act as reflectors. The plate surface is considered as perfectly rigid (a reflection coefficient of unity according to the convention adopted in this paper). This condition is satisfied because we specify the velocity on the plate, and thus the plate is a boundary of infinite impedance for the purpose of image formation. This system of images is then considered as excitation sources acting on the plate. (The number of images is infinite, a typical image location is in a plane parallel to the plate and at a distance $2jh$ from it, where j is an integer.)

The frequency spectral acoustic pressure at the field position $\{\mathbf{x},z\}$ above the plate $[z>0]$ is given by[1]

$$p(\mathbf{x},z,\omega)=(2\pi)^{-1}\rho_0 c_0 k_0 \int_{-\infty}^{\infty}\!\!\int d\mathbf{k} \times\{k_z^{-1}\exp[-i(\mathbf{x}\cdot\mathbf{k}+zk_z)]\} \cdot[Z_{\mathrm{p}}+Z_a]^{-1}P(\mathbf{k},\omega), \quad (4)$$

where $d\mathbf{k}$ is written for $dk_x dk_y$.

The term in the integrand in the brace is the spectral component of Green's function for the acoustic field above the plate.[7] In order to compute the acoustic field in the space at the back of the plate, the appropriate spectral component of Green's function for this space should be substituted into Eq. 4 replacing the term in the brace. The appropriate Green's function is

[7] P. M. Morse and H. Feshbach, *Methods of Theoretical Physics* (McGraw-Hill Book Co., New York, 1953), Chap. 11.

computed with the plate assumed rigid. In this paper, we are not concerned with the pressure field at the back of the plate, we concentrate only on the far-field acoustic pressure in the fluid occupying the region above the plate.

II. POINT FORCE

We consider the plate to be driven by a point force (in terms of its root-mean-square amplitude) of the form $f(t)\delta(x)\delta(y)$,[1] where δ is the Dirac delta function. The spectral force field is then given by

$$P(\mathbf{k},\omega)=F(\omega)/2\pi, \tag{5}$$

where

$$f(t)=(2\pi)^{-\frac{1}{2}}\int_{-\infty}^{\infty}F(\omega)\exp(i\omega t)d\omega. \tag{6}$$

We restrict consideration to the frequency range below the critical frequency, so that $k_0/k_p \ll 1$, and to the far-field acoustic pressure for which $(x^2+y^2+z^2)k_0^2 \gg 1$.[1]

Substituting Eq. 5 into Eq. 4 and carrying out the integration in a manner similar to that employed in Ref. 1, we obtain[8]

$$p(r,\theta,\omega)=[k_0\beta F(\omega)/2\pi][r^{-1}\exp(-ik_0r)]D(\theta), \tag{7}$$

where

$$D(\theta)=\cos(\theta)[\cos(\theta)+\beta g(\theta)]^{-1}, \tag{8}$$

$$g(\theta)=2[1-R(\cos\theta,\omega)\exp(-2ihk_0\cos\theta)]^{-1}, \tag{9}$$

$$\beta=\rho_0c_0/i\omega m, \tag{10}$$

and the spherical coordinate system $\{r,\theta,\varphi\}$ is used in Eq. 7 in place of the rectangular coordinate system $\{x,y,z\}$. Because of the symmetry, Eq. 7 is independent of the angular coordinate φ.

The presence of the fluid medium and the baffle at the back of the plate is accounted for completely by the factor $g(\theta)$ in Eq. 7. When the baffle is removed so that the fluid medium at the back occupies the entire semi-infinite space, the factor $g(\theta)\to 2$. To obtain this result from Eq. 9, it is necessary to allow k_0 to have a small imaginary part, accounting for some losses in the fluid medium and letting $h\to\infty$. Another way is to set $R\to 0$, for if we establish an arbitrary control surface in the semi-infinite back space at the position of the baffle, the baffle so constructed would possess a reflection coefficient of zero, and $g(\theta)\to 2$. Thus, Eq. 7 reduces appropriately to those results that were previously obtained in the absence of the baffle.[1] The term $\beta g(\theta)$ in the directivity function $D(\theta)$ may still be viewed as the fluid-loading parameter[1]; this parameter may now be a function of the angle θ. When this parameter has an angular dependence, the straightforward classification of equivalent acoustic sources, the central objective in Ref. 1, can no longer be made. In the subsequent analysis we do not illustrate all the details of the modifications introduced by the presence of the baffle; rather, we consider only a few special cases.

A. Rigid Baffle

We consider the baffle to be substantially rigid so that $R\to 1$. Under this condition, the factor $g(\theta)$ becomes

$$g(\theta)\simeq 2[1-\exp(-2ihk_0\cos\theta)]^{-1}. \tag{11}$$

From Eq. 11, we deduce that for angles like $\theta_n=\cos^{-1}(\pi n/hk_0)$, where n is an integer (inclusive of zero), the factor $g(\theta)$ becomes substantially infinite. Thus, essentially no radiation to the far field can be generated at these angles at the frequency defining k_0. This result is not surprising, for the waves on the plate that would have radiated into these directions (those with wavenumbers $k_n=k_0\sin\theta_n$) experience an infinite impedance looking into the baffle, and consequently, their amplitudes are essentially zero. On the other hand, for angles like $\theta_q=\cos^{-1}[\pi(2q-1)/2hk_0]$, where q is an integer, the factor $g(\theta)$ becomes substantially unity—i.e., the factor that would have existed if the space at the back of the plate were a vacuum.[1] Again, this makes physical sense, for the waves on the plate that radiate into these directions (those with wavenumbers $k_q=k_0\sin\theta_q$) experience substantially zero impedance looking into the baffle, and consequently, their amplitudes are unaffected by the presence of the baffle and the fluid medium at the back of the plate.

Of some interest is the case where, in addition to imposing $R\to 1$, one further imposes that $2hk_0 \ll 1$—the baffle being placed close to the plate. In this case, one may further reduce Eq. 11 so that

$$g(\theta)\simeq(ihk_0\cos\theta)^{-1}, \tag{12}$$

and obtain, for the directivity function $D(\theta)$ of Eq. 7,

$$D(\theta)\simeq\cos^2\theta\left[\cos^2\theta-\left\{\frac{\rho_0c_0/hk_0}{\omega m}\right\}\right]^{-1}. \tag{13}$$

The factor in the brace in Eq. 13 is recognized as the ratio of the surface stiffness impedance of the fluid medium in the space between the baffle and the plate $(\rho_0c_0^2/ih\omega)$ to the surface mass impedance of the plate $(i\omega m)$. If this ratio is small as compared with unity, the directivity is substantially uniform, except when $\theta\to\frac{1}{2}\pi$.[1] On the other hand, if this ratio is large as compared with unity, the directivity is substantially that of $\cos^2\theta$. (Note that if $\rho_0c_0 \gtrsim \omega m$, the ratio is large, for we assumed $2hk_0 \ll 1$.) It is of interest that a resonance phenomenon can occur when $\rho_0c_0^2/h\omega^2\to\cos^2\theta$.

[8] The far-field acoustic pressure may be evaluated for the frequency range above the critical frequency. Gutin [L. Ya. Gutin, Soviet Phys.—Acoust. 4, 369–371 (1965)] has shown that such an evaluation would lead to a result where β in Eq. 10 assumes the expression $\rho_0c_0/Z_p(k_0\sin\theta,\omega)$ instead of $\rho_0c_0/i\omega m$. Unfortunately, Gutin has not discussed the condition for the validity of this expression. It appears that the condition for the far field may have to be replaced by $\gamma^2(x^2+y^2+z^2)k_0^2 \gg 1$.

Of course, $D(\theta)$ does not become infinite; one has to include higher terms in the expansion of $g(\theta)$ and to include the loss factor in the plate impedance to prevent $D(\theta)$ from becoming singular. Nevertheless, $D(\theta)$ does become relatively large if the above condition is satisfied. The phenomenon occurs when the stiffness term of the confined fluid medium combines with the mass term of the plate to form a "harmonic oscillator." When conditions are right, as specified above, this oscillator resonates.

B. Soft Baffle

We consider the baffle to be substantially soft; thus $R\rightarrow -1$—the baffle being, for example, the interface of the fluid under consideration with another fluid of much lower characteristic impedance. Under this condition, the factor $g(\theta)$ becomes

$$g(\theta)\simeq 2[1+\exp(-2ihk_0\cos\theta)]^{-1}. \qquad (14)$$

From Eq. 14, we deduce that for angles like $\theta_q=\cos^{-1}[\pi(2q-1)/2hk_0]$, the factor $g(\theta)$ becomes substantially infinite; whereas for $\theta_n=\cos^{-1}(\pi n/hk_0)$, the factor $g(\theta)$ becomes substantially unity. These results are essentially the reverse of those found for the rigid case, and the physical explanation of them follows the same argument given previously.

If $2hk_0\ll 1$, $g(\theta)$ in Eq. 14 can be approximated; $g(\theta)\simeq[1-ihk_0\cos\theta]^{-1}$. When this value of $g(\theta)$ is substituted in Eq. 7, one finds that the fluid medium and the soft baffle at the back of the plate are completely accounted for by increasing the mass per unit area of the plate by $\rho_0 h$ as can be expected.

C. High Absorptive Baffle

In this case, $|R|\ll 1$, and the radiation is substantially equal to the radiation that results in the absence of the baffle with the fluid medium occupying the entire semi-infinite back space. The factor $g(\theta)\simeq 2$ in this case; this is to be expected for multiple reflection between the plate, and the baffle is substantially absent owing to the excessive absorption of acoustic energy in the baffle.

III. LINE FORCE

The computation for the far-field acoustic pressure generated by the plate when driven by a line force was made in Ref. 1. It was found that the directivity function was the same as that for the point-driven plate, except that the angle θ was to be considered as the polar angle in the plane perpendicular to the line of application of the force. Equivalent results are found when a fluid medium and a baffle are placed at the back of the plate; the directivity function remains the same in the sense just described. The far-field acoustic pressure for the line force is given by[1]

$$p(r,\theta,\omega)=-\tfrac{1}{2}k_0^{\frac{1}{2}}F_e(\omega)\beta[r^{-\frac{1}{2}}\exp(-ik_0r+\tfrac{1}{4}i\pi)]D(\theta), \qquad (15)$$

where $F_e(\omega)$ is the frequency-spectral component of the line force, r and θ are now the appropriate cylindrical coordinates,[1] and $D(\theta)$ has the same functional form as the function defined in Eq. 8. Because of the equivalence in the functional form of $D(\theta)$, in the case of a point force and a line force, the presence of the fluid medium and the baffle at the back of the plate influences the far-field acoustic pressure in precisely the same way in both cases. Therefore, the discussions in Sec. II are relevant also to a line-force-driven plate.

V. MOMENT DRIVE

The formalism, both of the point force and the line force, can be readily extended to cover point-moment and line-moment drives. If we denote by $\mathbf{e}$ the differential vector between the positions of the constituent forces that form the moment drive (for which $|\mathbf{e}|k_p\ll 1$), then the acoustic pressure at the field position $\{r,\theta,\varphi\}$ due to a moment drive is given by

$$p_m(r,\theta,\varphi,\omega)=\mathbf{e}\cdot\nabla p(r,\theta,\omega), \qquad (16)$$

where $p(r,\theta,\omega)$ is the acoustic pressure that would result if one of the constituent forces were removed. The differential operator ∇ is defined as $\nabla=\hat{x}\partial/\partial x+\hat{y}\partial/\partial y$, where $\hat{x}$ and $\hat{y}$ are unit vectors along the x axis and the y axis, respectively. If consideration is confined to the far field only, the differential operator need operate only on the exponential term $\exp(-ik_0r)$ in the expression for $p(r,\theta,\omega)$.

V. DIFFERENT FLUID MEDIA IN THE FRONT AND BACK OF THE PLATE

We briefly consider the modification to the analysis caused by introduction of different fluid media in the front and the back spaces of the plate. We denote by ρ_0c_0 the characteristic impedance of the fluid medium in the front of the plate and by ρ_1c_1 that of the fluid medium at the back of the plate. Under this condition, the only factor that has to be modified in the expression for the far-field acoustic pressure is $g(\theta)$ (see Eq. 9). This factor takes the form

$$g(\theta)=1+\frac{\rho_1c_1\cos\theta}{\rho_0c_0\cos\theta_1}\frac{1+R(\cos\theta_1,\omega)\exp(-2ihk_1\cos\theta_1)}{1-R(\cos\theta_1,\omega)\exp(-2ihk_1\cos\theta_1)}, \qquad (17)$$

where

$$k_1=\omega/c_1, \qquad (18)$$

$$\theta_1=\cos^{-1}\{1-[(c_1/c_0)\sin\theta]^2\}^{\frac{1}{2}}. \qquad (19)$$

If $c_1 > c_0$, the angle θ_1 may have a range where it is imaginary: $(\cos\theta_1 = -i\{[(c_1/c_0)\sin\theta]^2 - 1\}^{\frac{1}{2}})$. In those angular ranges where θ_1 is imaginary $[\sin^{-1}(c_0/c_1) < \theta < \frac{1}{2}\pi]$, the exponential terms in Eq. 17 are decaying terms. The reason for this is that the radiating wave components[2] in the plate that radiate in those directions of θ for which θ_1 is imaginary can generate only a near field in the fluid medium at the back of the plate; in this latter fluid medium, the corresponding wave components are nonradiating. If h is made large enough, the near field so generated does not reach far enough to be reflected; and for these wave components, multiple reflection does not take place.

It is of interest to consider the far-field acoustic pressure on both sides of the plate in the case where the baffle is moved to infinity ($h \rightarrow \infty$). The factor $g(\theta)$ then becomes simply

$$g(\theta) = [1 + (\rho_1 c_1 \cos\theta / \rho_0 c_0 \cos\theta_1)]. \tag{20}$$

It is readily verified that the far-field acoustic pressure above the plate when the plate is driven by a point force is

$$p_0(r,\theta,\omega) = \frac{k_0\rho_0 c_0}{2\pi}\frac{F(\omega)}{i\omega m}[r^{-1}\exp(-ik_0 r)] \cdot \left[\frac{\cos\theta\cos\theta_1}{\cos\theta\cos\theta_1 + (i\omega m)^{-1}\{\rho_0 c_0\cos\theta + \rho_1 c_1 \cos\theta_1\}}\right], \tag{21}$$

and at the back of the plate it is

$$p_1(r,\theta,\omega) = \frac{k_1\rho_1 c_1}{2\pi}\frac{F(\omega)}{i\omega m}[r^{-1}\exp(-ik_1 r)] \cdot \left[\frac{\cos\theta\cos\theta_0}{\cos\theta\cos\theta_0 + (i\omega m)^{-1}[\rho_0 c_0\cos\theta_0 + \rho_1 c_1 \cos\theta]}\right], \tag{22}$$

where

$$\theta_0 = \cos^{-1}\{1 - [(c_0/c_1)\sin\theta]^2\}^{\frac{1}{2}}. \tag{23}$$

It is observed that, although the volume velocities[1] on both sides of the plate are equal, the ratio of the power radiated at a given frequency into the front and the back sides of the plate cannot be simply expressed in terms of the ratio $\rho_0 c_0 k_0^2/\rho_1 c_1 k_1^2$. However, if $c_1 = c_0$ but $\rho_0 \neq \rho_1$, this power ratio is given just by ρ_0/ρ_1. The latter result is obtained because it is the ratio of the speed of sound in the fluid medium to the phase speed ω/k of the wave in the plate that determines whether the wave is a radiating or a nonradiating wave.[2] Thus, if $c_1 = c_0$, a radiating wave with respect to the front side of the plate is also a radiating wave with respect to the back side of the plate independently of the difference in the densities of the fluid media. Moreover, under this condition, the angle into which such a wave radiates in the front side of the plate is the mirror image of the angle into which this wave radiates in the back side of the plate (see Eqs. 18 and 23). Similar results are found in the case of a line-force-driven plate.

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13. ABSTRACT

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