TECHNICAL NOTE:
Properties of Air Spring as a Force Generator in
Active Vibration Control Systems

IGOR BALLO*

SUMMARY

In the active vibration control systems of electropneumatic type the air spring is often used not only as the elastic element of the system, but also as the compensation force generator, which caters for improved vibro-isolating effects. To provide this function of the air spring, it is necessary to know its characteristics in sufficient detail. In this paper the procedure of experimental estimation of these characteristics is described and the result is compared with the results of estimation based on theoretical considerations. The paper is completed by the graph of both types of characteristics.

1. INTRODUCTION

As the actuator and elastic element of the active vibration control systems, an air spring is often used, into which air is fed or discharged from in such a way as to improve the vibration control effect. This air spring could be considered as a parallel combination of a passive spring and a compensation force generator, which caters for active vibro-isolating system effects whose aim is to improve the overall vibration control effect.

To facilitate proper design of the control system, which governs the inflow and outflow of the air into and out from the air spring, it is necessary to know in sufficient detail the air spring characteristics in the function of compensation force generator. In some older papers (for example [2, 3]) these characteristics were derived from general aerodynamic arguments, not taking into account some specific properties of real air springs. The result of this first

approximation was, that the improvement in vibration control effect was manifest in a rather narrow frequency band only. The use of characteristics, estimated by a procedure described below, incurred substantial widening of the frequency band where the desired vibration control effect was obtained [1].

2. AIR SPRING AS COMPENSATION FORCE GENERATOR

The construction of air springs could be different. For the sake of this paper we will assume that their principal properties for use in vibration-isolation systems are solely determined by characteristics for which the following arguments are valid. A specific type of air spring will be chosen as a typical example of all air springs. The convoluted type air spring, whose rubber body is reinforced by textile cord will be used throughout. The effective volume $v(x)$ of such an air spring could be approximated by the following formula [2]:

$$v(x) = v_0 + v_1x + v_2x^2$$  \hspace{1cm} (1)

According to the same paper the effective cross section area $s(x)$ of such an air spring could be expressed as:

$$s(x) = s_0 + s_1x + s_2x^2$$  \hspace{1cm} (2)

where the air spring compression is for positive $x$ and dilatation for negative $x$. Other symbols in equations (1) and (2) denote the properties of a particular spring.

In the state of static equilibrium the height of the air spring is $H_0$, the mass of air enclosed by the spring is $m_0$, it’s absolute pressure is $p_0$ and over-pressure is $P_{p_0}$. If, under isothermal conditions, air is admitted into the air spring or air is exhausted from the air spring into the surrounding atmosphere, an increase or decrease (i.e., change) in the internal pressure by $p_d$ is incurred. If $r$ denotes the gas constant of air and $T$ denotes the absolute temperature of the air enclosed then this process can be described in sufficient accuracy by the equation:

$$(p_0 + p_d)(v_0 + v_1x + v_2x^2) = (m_0 + m_r).rT$$  \hspace{1cm} (3)

In the static equilibrium state following relations hold:

$$p_0v_0 = m_0.rT \hspace{1cm} v_0 = s_0H_0$$  \hspace{1cm} (4a, b)
After eliminating terms related to the static position and some re-arrangement of equation (3) following equation is obtained:

\[ p_d s_0 = \frac{m_r r T}{H_0} - \frac{p_0 + p_d}{H_0} (v_1 x + v_2 x^2) \]  \hspace{1cm} (5)

On the right hand side of equation (5) two terms are present. The first one contains the amount of air in the air spring \(m_r\) and is independent of air spring deformation \(x\). In contrary, the second term depends on deformation \(x\) and is independent of the air mass \(m_r\). Hence, it is possible to assume, that the first term is concerned with the air spring function as compensation force generator, whereas the second term describes predominantly the elastic properties of the air spring.

The aim of this paper is to determine the characteristics of air spring as the compensation force generator. Therefore, the properties of the air spring around the equilibrium position, i.e., for \(x = 0\) will be further investigated. Under these circumstances, equation (5) has the form:

\[ s_0[p_d]_{x=0} = \frac{m_r r T}{H_0} \]  \hspace{1cm} (6)

The inflow and outflow of the air into and out from the air spring is governed by electro-pneumatic sliding valve, whose action is controlled by electrical voltage \(u_r\). The slide function in a real system could be described in sufficient accuracy by equation:

\[ m_r = D\{u_r\} \]  \hspace{1cm} (7)

where \(D\) is an integro-differential linear operator.

After substitution and re-arrangement equation (6) has the form:

\[ D\{u_r\} = \frac{s_0 H_0[p_d]_{x=0}}{r T} \]  \hspace{1cm} (8)

Now Fourier transform is applied onto equation (8). Under this transform the linear operator \(D\) is transformed into the frequency domain as the Frequency Response Function (FRF) \(\Psi(\omega)\) If the Fourier transforms of the dynamic variables are denoted by capital letters then for the description of FRF of the air spring as compensation force generator is following:

\[ \Psi(\omega) = \frac{[P_d]_{x=0}}{U_r} \cdot \frac{s_0 H_0}{r T} \]  \hspace{1cm} (9)
3. DETERMINATION OF THE FRF OF THE AIR SPRING AS COMPENSATION FORCE GENERATOR

As seen, equation (9) supplies a general formula for determination of the sought air spring FRF \( \Psi(\omega) \). For determination of this dynamic characteristics the ratio of Fourier transforms of the pressure changes \([P_d]_{t=0}\) and control electrical voltage \( U_r \) is decisive. This ratio could be determined best in experimental way [1, 4].

Under some specific simplifying suppositions it would be possible to derive this ratio also by theoretical considerations [2, 3], however it is clear that in this way it will not be always possible to respect specific properties of a given air spring, as it is possible by the experimental approach.

The simplest, often used case of the electropneumatic sliding valve occurs, when a linear relation between the fluid mass flow \( q \) [kg.s\(^{-1}\)] and the control voltage \( u_r \), governing the slide operation, is stipulated [2, 3, 4]:

\[
q = k_3 \cdot u_r
\]  \hspace{1cm} (10a)

The mass of air \( m_r \), transferred via the slide valve will be:

\[
m_r = \int_0^t q \cdot dt
\]  \hspace{1cm} (10b)

or, after substitution:

\[
m_r = D(u_r) = k_3 \int_0^t u_r \, dt
\]  \hspace{1cm} (11)

In same manner as before, applying the Fourier transform and some rearrangement the FRF \( \Psi(\omega) \) is obtained in following form:

\[
\Psi(\omega) = \frac{k_3}{j \omega}
\]  \hspace{1cm} (12)

4. GRAPHICAL COMPARISON OF THE EXPERIMENTALLY DETERMINED FRF AND THE SIMPLIFIED, THEORETICALLY DERIVED FRF

In the following Figure 1, two FRF courses are depicted. The first curve, denoted A, represents the FRF determined according to equation (12), whereas
curve B represents the experimentally determined characteristics. Both axis in this figure are logarithmic.

5. CONCLUSION

Based on simple theoretical reasoning the course of the frequency response curve of the air spring as compensation force generator for use in active vibro-isolating systems has been derived. According to this expression the FRF of a specific air spring was determined experimentally (curve B in Fig. 1). In the same figure the air spring FRF, derived by simplified aerodynamic reasoning is depicted too (curve A). Note the marked difference in the course of both curves, especially in the low frequency region, which is the most important one for practical application of active vibration control systems of electro-pneumatic type.

REFERENCES


