ULTRAGARSAS Journal, Ultrasound Institute, Kaunas, Lithuania
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ISSN 1392-2114 ULTRAGARSAS (ULTRASOUND), Vol. 62, No. 2, 2007.

Data acquisition system for air-coupled navigation study: the concept

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Abstract

The concept of the measurement system dedicated for air coupled ultrasound navigation study is presented. The proposed system is portable as it is intended for field experiments. In particular, it is planned to use it research, rapid prototyping and signal processing experiments of vehicle parking-guidance systems, transport docking platforms orientation, industrial robotic vision systems and other coordinate estimation systems. The heart of the proposed system is the main block with an USB interface for a host personal computer (PC) communication and interfaces for external sensors/actuators. It is decided to use the system with a laptop PC, as an initial data analysis and storage unit. The communication is achieved using the USB 2.0 high speed interface, which enables high bit rates for information exchange and provides the supply for the system. The main block is responsible for communicating with at computer, step motor driver control generation, of low level arbitrary waveform excitation signals, two digitally controllable time variable gain channels, simultaneous signal acquisition using two channel analog-to-digit converter, serial communication channels for power- and pre- amplifier control, serial communication channels for relative humidity, temperature, wind speed and direction measurements, digital input output interface for other tasks. The proposed system has a detachable output amplifier and a detachable preamplifier. The changeable transmission and reception units allow adaptation of the system for various research tasks.
Keywords: ultrasonic data acquisition, robotic vision, ultrasonic ranging.

Introduction

Nowadays there are many applications that require non-contact navigation systems for automotive vision applications, intelligent industrial robotic vision, docking platform orientation and etc. The essential navigation tasks can be split into two categories [1]: the obstacle-free space determination and position mapping. This means that for physical measurements the obstacle (target) location is the only task to be performed. The rest of a navigation procedure is processing of the acquired data for fusion with the known map. The target location techniques for 2D space in general can be divided into 3 groups: finding two bearing angles; finding a bearing and the range; finding two ranges. Then the only difference is the type of waves used for the mentioned tasks: visible radiation [2], infrared, microwave [3] waves and ultrasound [4]. The rigidity, simplicity of implementation and cost effectiveness makes ultrasonic navigation an attractive technique.

Product design carries two stages: modeling and experimental verification. Verification is as good as exhaustive and superior is the data collected. The number of publications on ultrasonic navigation is growing. It is always tempting to repeat these investigations in order to verify or improve the technique.

Our final goal is the design of a simple, cost effective navigation system suitable for a commercial realization. Therefore, it was decided to design the ultrasonic data acquisition system with a maximum functionality. This paper concentrates on such data acquisition system concept. The required system functions, parameters and construction requirements are defined.

The requirements definition

One of the most significant parts of the system are ultrasonic transducers. In this case the main interest is the measurement of a transmitting voltage response (TVR), receiving voltage response (RVR), radiation pattern, complex electrical impedance, and transduction AC (alternating current) response of a single transducer or a transducer pair [5].

The transmission efficiency (TVR) of an ultrasonic transducer is defined as the sound pressure produced in the center of the radiated beam (reported in dB above 1 μPa) at the indicated distance and at the given excitation voltage.

The reception efficiency (RVR) of a transducer is the output open circuit (usually simulated by 3.9kΩ load) voltage. It is given in dB relative to $1V_{RMS}$ per μPa.

The transducer directivity, or radiation pattern, is a sound pressure distribution versus observation angle α. The transducer beam width is noted as $2\theta_{0.5}$ and is measured at the half power points.

Table 1 lists parameters of the commercially available ultrasonic transducers. TVR has been is defined at the center frequency f_c, 0dB for 0.02mPa at $10V_{RMS}$ excitation at the 30 cm distance. RVR is measured at the center frequency, 0 dB correspond to 1 V_{RMS}/μbar.

Table 1. **Commercially available ultrasonic transducers**

Manufacturer	Transducer	f_c, kHz	TVR, dB	RVR, dB	U_{TXmax}, V_{p-p}
Prowave	400EP900	48	100	-80	100
Prowave	400EP18D	40	100	-80	100
Sencera	EC4018	40	100	-65	100
Quantelec	SQ-40-X-10B	40	110	-70	10
Airmar	AT120	125	107	-169	800
Murata	MA40E8-2	40	106	-86	160
Murata	MA40MF14	40	103	-87	160

From Table 1 we see that the highest commercially available air-coupled transducer frequency is 125kHz. But we are aware of other researchers reporting use of 445kHz [6] 1MHz [7] or even 3MHz [8]. For transmission and reception efficiency study of the harmonic high voltage excitation source is needed [9]. It should be of known voltage and frequency. Also the known gain and a high input impedance reception channel are required. Two simultaneous sampling reception channels are required for measurements of the complex electrical impedance. For the same reason two analog-to-digit (A/D) channels are desired when measuring a complex AC response.

For investigation of a transducer directivity a step motor turn table or turntable with an encoder are needed. Such types of experiments are carried out in an echo chamber where wall-plug power is not a problem (usually available). Therefore, power supply consumption for this unit is not an essential issue. For the sake of system mobility and since this is not a frequent investigation this unit should be a detachable external module.

The environment noise should be the crucial clutter source for the navigation system operating outdoors or under industrial conditions. Therefore it is essential to carry out noise sources investigation. In order to preserve data storage space, the system should be capable of a single noise signal detection and acquisition. That is, the system should store only such signals which have passed some threshold level. In order to reduce the electrically induced noise the reception preamplifier should be an external detachable unit. The experiments have to be mobile. Hence, the power supply and size of registration equipment are important.

The classical air-coupled ultrasonic navigation system is supposed to avoid mechanical scanning – the coordinate measurement should be performed using a limited number of ranging channels. Nevertheless, there might be a need to measure the noise distribution around some machinery or at defined positions in the field. For that purpose an external scanner or encoding unit are anticipated for the system. Since this type of experiments is an alternative no special requirements for positioning device are set. The only one interface system which should be supported is a digital input output (I/O) interface for a scanner or an encoder connection.

For the object detectability evaluation the reflectivity investigation has to be carried out. The reflectivity statistics (i.e. common properties for the same object type), e.g., the angular reflectivity properties and the reflectivity frequency response for should be acquired. The reflectivity data base together with clutter records could be the base to evaluate the optimal frequency range for best detectability of objects.

Meantime, variety of publications on robust ultrasonic ranging applications has appeared [10]. The goal for a planned study is robust detection and ranging too. The experiments will definitely require an arbitrary waveform high output voltage generator. It should be capable to load desired signals from the database and suitable for excitation. At later stages the generator can be simplified switching to rectangular excitation signals. The investigation of the generator output stage effectiveness is planned. Therefore output stage must be a detachable external unit. Keeping in mind that ultrasonic field experiments will have to be carried out this external unit should use a single 12V power supply, which is usually available from accumulator batteries or car lighter.

Ultrasound speed is temperature and relative humidity dependant [11]. Measurements are also influenced by wind speed and direction. External detachable weather station is planned. The communication interface should be simple and universal.

All acquisition control should be carried out by a single software application. Application must present the acquired data as A-scans, be able to do some simple data processing like averaging, power spectrum calculation, smoothing and recorded data conversion to few most popular data file formats. The proposed functional system diagram is given in Fig. 1.

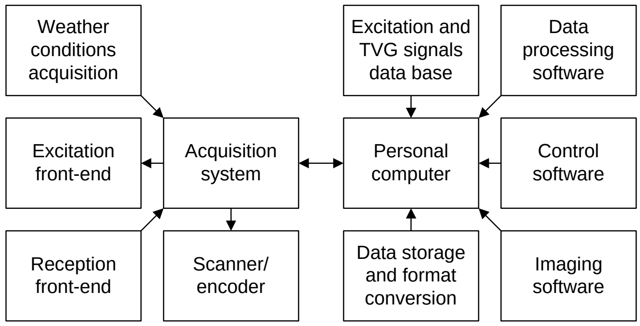

Fig. 1. **Research system functional diagram**

It consists of two parts: hardware part and the software part. Below we outline the hardware requirements.

Transmission channel

Air coupled transducers require high excitation voltages in order to improve the signal-to-noise ratio (SNR) [12]. Therefore, a highest allowed voltage should be achievable. Examination of Table 1 can lead to conclusion that a required excitation voltage is up to 800 Vp-p. This requirement is only for a single transducer. The rest require excitation voltages below 160Vp-p. Therefore it is decided to set 160Vp-p excitation voltage requirement leaving the transformer matching [13] as an option for obtaining 800Vp-p voltages.

As already was indicated, excitation should be capable of arbitrary waveform, which is loadable from a local signals database. The excitation signal has to be formed by a digital-to-analog (D/A) converter. As the highest transducer frequency reported in use is 3MHz, this generator should be capable of generating such frequencies. The smoothing filter is used to complete the D/A signal conversion process by creating a more analog like continuous signal. The D/A converter output signal must be filtered by a filter before being forwarded to the output of the excitation channel. Using an easy to realize 3-rd order filter would require a 30MHz sampling frequency and 8 bit D/A converter.

The length of the excitation signal will define how narrow the bandwidth of the investigation signal can be. The transducers mentioned in [9] have 2.4 MHz bandwidth. Assuming that 1000 investigation points within the passband are needed, this would require 1 kHz excitation signal bandwidth. This will correspond to 3 ksamples deep memory buffer. Of course, for a 40 kHz transducer the sampling frequency have to be reduced accordingly. Therefore, the sampling frequency programming capability requirement is set. Since the smoothing filter for a new sampling frequency has to be changed, the need for changeable filters is indicated. Since the experiments usually are carried out for similar frequency transducers, the filter can be replaced manually. In order to have larger flexibility for more complicated experiments, the requirement of 32 k samples deep memory is defined.

Reception channel

First of all the received signal dynamic range is determined. In our case we even have transmitting and receiving efficiency for some commercially available transducers (Table 1). Combining these values with a known excitation voltage one can obtain the received signal voltage. Then these values can be combined with a noise level at the reception end to get the dynamic range.

Intensity of sound waves decreases with a distance. This signal reduction is caused by two phenomena – spherical divergence of the beam and the wave absorption in air. The absorption level at low frequencies is negligible – this can be seen from Fig.2 presenting results of data application from [14].

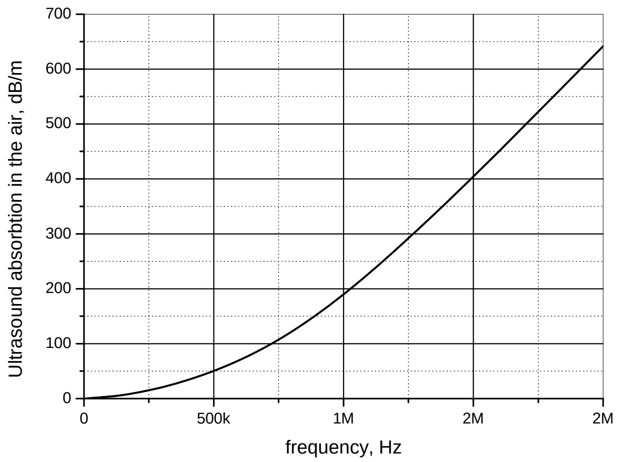

Fig. 2. **Ultrasound absorption in air at 20°C 101kPa 60%RH**

In order to calculate the received signal strength the transmission path length is used. Then if TVR and RVR are referred to 1μPa only sound pressure level (SPL) reduction due to the propagation distance have to be calculated. Since it is a pressure, the distance reduction coefficient RC is given by

$$RC = 20\lg\left(\frac{L_{REF}}{L}\right)[\text{dB}], \qquad (1)$$

where L_{REF} is the reference distance for acquired TVR and L is the transmission path length.

The voltage gain VG is calculated as:

$$VG = 20\lg\left(\frac{U_{EXC}}{U_{REF}}\right)[\text{dB}], \qquad (2)$$

where U_{REF} is the reference voltage for the acquired TVR and U_{EXC} is the excitation voltage used.

Then the corrected SPL at receiving transducer face in the case of an ideal reflection and propagation conditions is:

$$SPL_C = VTR + RC + VG\,. \qquad (3)$$

This pressure level can be converted to the RMS voltage at the receiving transducer nodes U_{RX} as:

$$U_{RX} = 10^{\frac{RVR+SPL_C}{20}}\, 0.0002\,. \qquad (4)$$

It was assumed that investigation is carried out from 5 cm to 5 m and Eq. 1-4 the received signal voltage was calculated using.

It should be noted that varying the distance from 5 cm to 5 m signal level is changing 500 times. This will correspond to 54dB. Therefore, requirement for 50dB time-variable-gain amplifier (TVG) is set. The TVG is necessary to compensate a signal fade when it propagates through air. The system has to comprise two amplification stages. The first stage is intended for a static gain control, the second stage is for TVG implementation. Both stages are capable of 50dB signal gain variations. The total 100 dB gain should be available. The TVG curve is presented as a digital array, stored in a buffer memory of the TVG unit. Application of a fully digital control of the TVG law allows all necessary signal transformations – suppression of unwanted spikes, gating and extraction of low level signals.

The receiving amplifier intrinsic noise can be modeled using voltage e_n and current noise i_n sources. The voltage noise is not dependant on the source impedance, and the current noise will depend on a source impedance magnitude. The transducer itself will contribute with Nyquist noise component, proportional to the of its real part impedance. The total input referred voltage noise spectral density is [15]:

$$e_{ntot}^2 = 4kT\,\mathrm{Re}(Z_s) + |Z_s|^2 i_{n+}^2 + e_n^2\,, \qquad (5)$$

where k=1.380658·10^{-23} [J/C] is the Bolzmann constant, T is the absolute ambient temperature, the transducer impedance is noted as Z_s. The output noise can be calculated by integrating component e^2_{ntot} over a frequency range. The frequency range of 39 kHz to 43 kHz has been used. The value obtained represents the noise RMS value at the amplifier input:

$$E_{esRMS} = \sqrt{\int_{f_1}^{f_2} e_{ntrot}^2\, df}\,. \qquad (6)$$

In order to evaluate the noise level, the impedances of the several Prowave 400EP18D transducers have been measured using measurement system described in [16]. The results are presented in Fig.3.

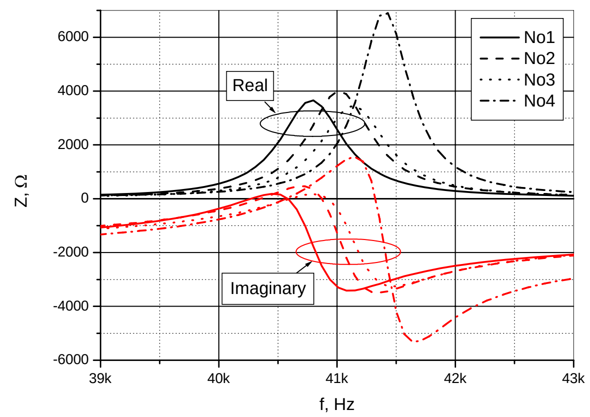

Fig. 3. **Measured complex impedance of the Prowave 400EP18D transducer**

The obtained impedance was used together with the of two candidate operational amplifiers. One (LMH6624) is presenting the lowest voltage noise, another (OPA657) is exhibiting the lowest current noise source. The obtained results for two candidate amplifiers are presented in Fig.4.

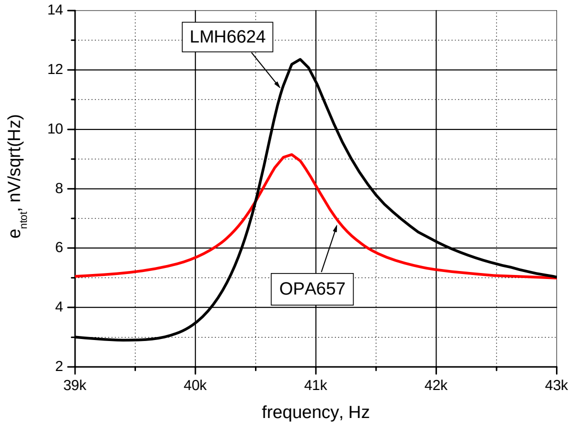

Fig. 4. **Measured Prowave 400EP18D transducer voltage noise density**

Using the calculated signal level and the noise at the input, the received signal SNR can be calculated:

$$SNR = 20\lg\left(\frac{U_{RX}}{e_{ntot}}\right). \tag{7}$$

For instance, at the 5 cm distance SNR is 86 dB and 40 dB for 5 m. Using the obtained SNR, the required number of A/D converter bits is obtained [17]:

$$b = \frac{SNR - 1.76}{6.02}. \tag{8}$$

The obtained results are presented in Fig.5.

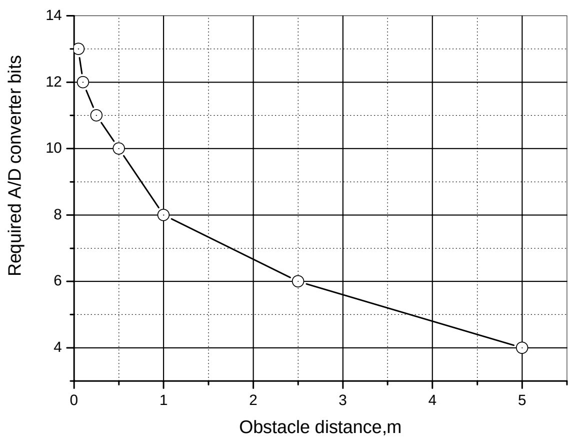

Fig. 5. **Required A/D converter bits versus obstacle distance at 40kHz**

It can be seen that only at short distances (below 1 m) a high number of A/D converter bits will be needed.

A choice of the sampling frequency is the question always arising during signal acquisition. The analog signal sampling can be presented as multiplication with *shah* function III [18] which actually is a train of impulses

$$\text{III}\left(\tfrac{t}{T}\right) = |T| \sum_{k=-\infty}^{\infty} \delta(t - kT), \tag{9}$$

where δ is the Dirac function and *T* is the sampling period. The Fourier transform of this function is also the *shah* function:

$$F\left[III\left(\tfrac{t}{T}\right)\right] = |T| \cdot III(T\omega) \tag{10}$$

Due to this multiplication in the time domain the original signal spectra is convolved with the *shah* function in the frequency domain. Therefore, all frequency components above Nyquist frequency ($f_s/2$) are aliased. In order to avoid this anti-aliasing a filter have to be used for a received signal before A/D conversion. In [17,19] recommendations for such filter are outlined. The filter stopband attenuation has to be equal to the dynamic range. Usually the A/D converter dynamic range is used, assuming that it has been matched to the signal range.

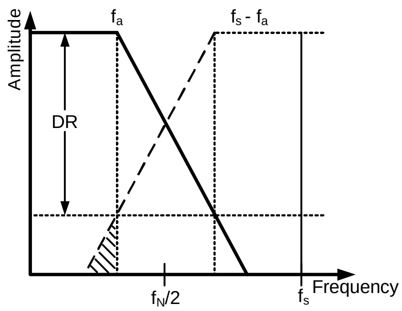

Fig. 6. **Anti-aliasing filter requirements**

As it can be seen from Fig.6 filter cut-off frequency has to be selected. Together with a filter transition band this will determine the sampling frequency and the filter order. Assuming that the 3-rd order filter can be easily realized, the 18 dB/octave transition band steepness is defined. In the discussion above it was indicated that other researchers report using 3MHz ultrasonic transducers. Therefore, the filter cut-off frequency is assigned twice the highest transducer central frequency - 6MHz. Taking the highest dynamic range of 86dB this will correspond to 192MHz sampling frequency. Such a requirement is not justified. Either the filter has to be adapted to a 40 kHz transducer or dynamic range requirements are relaxed. If 80 kHz filter is chosen, then the required sampling frequency is 5 MHz. This is still too high for 40 kHz signals: the required memory bank size will rise. One useful phenomenon usually is omitted by researches – in the case of significant oversampling and the following digital signal processing which will cause bandwidth reduction, the sampling noise is reduced. This will give a processing gain:

$$PG = 10\lg\left(\frac{f_S}{2\Delta F}\right). \tag{11}$$

This idea stands behind sigma-delta A/D converters. Example: the bandwidth of the investigated transducer is about 1 kHz and assumed the sampling frequency 200 kHz. This makes sense to use the signal processing of the received signal so after filtering the signal bandwidth ΔF is 1 kHz. Such filtering will give are 20 dB processing gain. This corresponds to relaxation of requirements given by Eq. 8 by 20 dB. This corresponds to 3 additional bits. This means that for the example given instead of 13 required bits, only 10 bits can be used. But for such example the anti-aliasing filter order is not sufficient. Iteratively solving such relationship we get that for the 6 MHz cut-off frequency and the 8 bit A/D converter the

15 MHz frequency sampling frequency is enough. This has been calculated for the case when ΔF = 4 kHz.

To have a more flexible system, the sampling frequency has to be varied according to the transducers used in the frequency range from 800 kHz to 15 MHz. In such a case changeable antialiasing filters are needed.

The memory 32k samples deep have been defined for D/A converter. In order to record such long signals the A/D converter buffer length should be the same or larger.

Communication and control interfaces

All system settings and data acquisition are performed by a host personal computer PC located separately from the ultrasonic part of the system. Data transfer is performed via USB2 interface with a controller, allowing fast data transmission into a PC.

The PC connection plays a very important role as there will be a lot of data that will have to be sent from and to the host PC. The USB was selected as it is now widely used and can handle high data transfer rates (USB 2.0 up to 480Mb/s). Main – power supply has to be taken from the USB. Another benefit of using USB is that the computer can automatically detect (hot plug) and configure the system.

Conclusions

The concept is oriented for portable system therefore some quality requirements have been relaxed for the sake of system size and consumed power. It has been calculated that 8 bit D/A and A/D converters can be used. The TVG, the arbitrary waveform and acquisition channels should use at least 32 k samples deep memory. It is sufficient to have the sampling frequency variable from 800 kHz to 15 MHz.

It is decided to use the system with a laptop PC as initial data analysis and storage unit. The communication is achieved using the USB 2.0 high speed interface, which enables high data transition rates and provides power supply for the system. The system comprises a simple step motor driver control, an arbitrary waveform generator, two digitally controllable TVG channels, two simultaneous acquisition A/D channels. The proposed system has a detachable output amplifier and a detachable preamplifier to adopt the system for various research tasks.

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L. Svilainis, G. Motiejūnas

Ultragarsinei navigacijai ore reikalingų duomenų surinkimo sistemos koncepcija

Reziumė

Pateikiama duomenų surinkimo sistemos, skirtos ore dirbančių ultragarsinių navigacinių sistemų tyrimams atlikti, koncepcija. Sistema yra nešiojama ir pritaikyta eksperimentams atlikti lauke. Numatoma sistemą naudoti automobilių statymo ultragarsinės navigacijos sistemoms tirti. Transporto pozicionavimo platformų ir robotų navigacijai, koordinačių nustatymo sistemų tyrimams ir projektavimui reikalinga duomenų surinkimo sistema, kuria galima būtų siųsti norimus signalus, juos surinkti, eksperimentuoti su elektronika ir signalų apdorojimu. Sistema sudaryta iš pagrindinio bloko, turinčio USB sąsają su valdymo kompiuteriu, ir sąsajų, skirtų įjungti išorinius daviklius ar valdiklius. Nutarta kartu su sistema naudoti nešiojamąjį asmeninį kompiuterį, kuris būtų skirtas pradiniam duomenų apdorojimui ir surinktai bei apdorotai informacijai saugoti. Pasirinkta USB 2.0 komunikacijų sąsaja, kuri leidžia greitus duomenų mainus ir kartu tiekia maitinimą sistemai. Pagrindinis blokas skirtas ryšiui su kompiuteriu, taip pat žingsninio variklio valdikliui valdyti ar enkoderiui įjungti. Blokas turi laisvai pasirenkamos formos signalų šaltinį zondavimo signalams generuoti, du skaitmeniniu būdu valdomo dėsnio laike kintančio stiprinimo kanalus, dviejų kanalų signalų lygiagretųjį greitaeigį skaitmeninį analogo keitiklį. Blokas leidžia nuosekliomis sąsajomis valdyti galinio stiprinimo laipsnio ir pradinių stiprintuvų parametrus. Numatomos sąsajos, skirtos temperatūrai, santykiniam drėgnumui, vėjo greičiui ar krypčiai registruoti. Siūloma naudoti keičiamus žadinimo galinio laipsnio stiprintuvo ir pradinių stiprintuvų modulius. Tokia struktūra leidžia pritaikyti sistemą norimiems eksperimentams.

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